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APOLLO EXPERIENCE REPORT - CREW STATION INTEGRATION

Volume II - Crew Station Displays and Controls

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16. Abstract In this report, the functional requirements for the Apollo displays and controls system are presented; the configuration of the displays, controls, and panels for both the command module and the lunar module are described; and the design development and operational experience of the displays and controls system are discussed. Pertinent recommendations for future displays and controls system design efforts are made.			
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FOREWORD

This technical note documents experience gained in the area of spacecraft crew station design and operations during the Apollo Program. Emphasis is given to the time period ranging from early 1964 up to, and including, the Apollo 11 lunar-landing mission of July 1969 — an era that covers three important phases of the Apollo Program: the design phase, hardware construction, and mission operations.

This technical note consists of five volumes. Volume I, "Crew Station Design and Development," gives an overview of the total crew station integration task. Volumes II, III, IV, and V are specialized volumes, each of which is devoted to a basic functional area within the Apollo crew station. The subject of each volume is indicated by its title, as follows.

Volume II, "Crew Station Displays and Controls"

Volume III, "Spacecraft Hand Controller Development"

Volume IV, "Stowage and the Support Team Concept"

Volume V, "Lighting Considerations"

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ABBREVIATIONS AND ACRONYMS

AGS	abort guidance system
CDR	commander
CM	command module
C&W	caution and warning
D&C	displays and controls
DEDA	data entry and display assembly
DSKY	display and keyboard
ECS	environmental control system
EL	electroluminescent
EMS	entry monitor system
EVA	extravehicular activity
EVVA	extravehicular visor assembly
FDAI	flight director attitude indicator
G&N	guidance and navigation
JSC	Lyndon B. Johnson Space Center
LEB	lower equipment bay
LM	lunar module
LMP	lunar module pilot
LOR	lunar orbit rendezvous
MDC	main display console
MSC	Manned Spacecraft Center
ORDEAL	orbital-rate drive, Earth and lunar
PGNCS	primary guidance, navigation, and control system
PLSS	portable life-support system

RAI	roll attitude indicator
RCS	reaction control system
RL	radioluminescent
SI	Système International d'Unités

APOLLO EXPERIENCE REPORT
CREW STATION INTEGRATION:
VOLUME II - CREW STATION DISPLAYS AND CONTROLS

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SUMMARY

The Apollo displays and controls system includes such devices as meters and switches that enable the flight crew to monitor and control the operations of the spacecraft. The Apollo displays and controls system was based on design practices and operation principles established during previous aircraft and spacecraft programs. Except for several unique devices developed for special applications, displays and controls system components were conventional in design and operation. The design development of the displays and controls system was evolutionary, and most design changes resulted from alterations in the interfacing subsystems or from the identification of new requirements. The Apollo displays and controls performed well under all mission conditions and met all design objectives.

INTRODUCTION

The discussion in this volume primarily pertains to the Apollo command module (CM) and lunar module (LM) displays and controls (D&C) requirements, configurations, and operations, as opposed to the detailed design and development of D&C hardware. Throughout the development of the Apollo spacecraft, the engineering responsibility for the D&C subsystem was essentially divided into two parts: requirements and hardware.

Requirements responsibility consisted of the definition and implementation of man/machine interface requirements; for example, control deflection characteristics, display formats, and integration of controls and displayed information. A flight-crew-support organization had the primary responsibility in this area. Hardware responsibility consisted of detailed component design, qualification testing, and test checkout. An engineering and development organization was responsible for this area.

Requirements responsibility for the portions of the Apollo D&C subsystems from the "panel out" is the area emphasized in this report. Because the two efforts (requirements and hardware) cannot be separated entirely, some hardware discussion

is included for clarity and completeness. No attempt is made to document in detail the D&C component designs, development histories, or qualification tests; however, such information may be found in the other volumes of this series. This brief documentation of what the Apollo D&C configuration was, how it was developed and operated, and how it could have been improved is intended to benefit others faced with similar problems.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Syst me International d'Unit s (SI). The SI units are written first, and the original units are written parenthetically thereafter.

DESIGN PHILOSOPHIES

An enumeration of the philosophies under which the displays and controls were developed precedes the description of the CM and the LM D&C and the discussion of their design and operation. The Apollo D&C requirements were based mostly on previous spacecraft and aircraft experience and were refined, modified, and finalized as the design evolved. The following were the most fundamental and influential requirements levied on the D&C systems.

1. No single display or control failure would jeopardize the safety of the flight crew or be cause for an abort.
2. The D&C design would allow a single crewman to fly either the CM or the LM to safety (i. e. , the LM to lunar orbit or the CM to Earth).
3. Displays and controls would be provided to enable the flight crew to control the vehicle and to manage the subsystems during all mission phases.
4. Information would be presented so as to permit rapid assessment of critical system status without resorting to extensive troubleshooting procedures to identify malfunctions.
5. Normal subsystem operation would not require continuous monitoring or control by the crewmen.
6. Displays and controls that were susceptible to damage or to inadvertent actuation as a result of normal crew operations would be guarded appropriately.
7. Existing proven design concepts would be used as much as practical.
8. The D&C of the CM and the LM would be standardized to improve crew efficiency by the elimination of conflicting designs.
9. All D&C would be designed for satisfactory operation by a pressure-suited crewman, and all D&C used during accelerated flight would be designed for operation by a pressure-suited, fully restrained crewman.

10. Primary command would be onboard the spacecraft. The capability would exist to perform the mission without dependence on ground-based information; however, the use of ground-based information to increase reliability, accuracy, or performance would not be precluded.

11. Automatic systems would be used to obtain precision, to speed response, or to relieve the crewmen of tedious tasks; but all automatic control modes would have a manual backup.

12. Initiation of any abort would be onboard, and the crewmen would have the primary responsibility.

13. Annunciator displays would be provided to indicate critical malfunctions of onboard systems. Activation of these displays would be announced to the crewmen by both visible and audible master alarm signals.

14. Displays and controls would be furnished to provide the LM with the capability for a visual or an instrument landing.

15. Crew launch-abort initiation would be based on at least two cues.

Within the aforementioned general philosophies, detailed design practices were established. The following practices evolved in the final design.

1. Time-shared displays would be used whenever the displayed parameters did not need to be monitored continuously or concurrently. This approach reduced the number of components required, conserved panel space, and facilitated crew operations by helping to group related information.

2. Percentage readouts would be used for quantity displays. Originally, consumables were to be displayed in volume or mass units, but use of this method would have required a mental calculation by the crewman to determine how usage was progressing. Percentage readouts facilitated a rapid assessment of quantity status.

3. Fixed-scale, moving-pointer meters would be the preferred and generally used type of display.

4. Status indicators would be used to indicate equipment status where such equipment was actuated by inputs from momentary toggle switches.

5. Where feasible, dual meters of the fixed-scale, moving-pointer type would use a single scale that was appropriate for both parameters displayed and that was centered between two pointers.

6. Scale graduations would generally progress by one, five, or two units, in that order of preference, or by decimal multiples.

7. Nonlinear display scales would be avoided.

8. Nomenclature would describe "what," not "how."

9. All displays, controls, and panel nomenclature would be integrally lit so as to be visible under darkened cabin conditions, such as during star sightings.

10. Time would be displayed digitally. Analog clocks and timers (similar to an aircraft 8-day clock) were originally proposed, but difficulty in reading analog clocks and timers rapidly and accurately caused the change to digital clocks.

11. Display range and readout accuracy would not exceed the needs of the flight crew to manage the spacecraft, and display scaling would not be more precise than the accuracy of the input signals.

12. Status displays would indicate equipment response and not merely control position.

13. Flight-control and navigation displays would have "fly to" pointers and symbols.

14. Displays associated with a control would be located so as to be unambiguously related to the control and visible to the crewmen while in operation.

15. Related D&C would be grouped to facilitate training and operations.

16. When operations followed a sequential or logical pattern, the D&C would be arranged to facilitate such operations.

17. When practicable, a positive indication of the loss of display power and signal would be provided.

18. Switches would be provided to deadface all crew operational power connectors to prevent the necessity for making or breaking any connections while power was applied.

CONFIGURATION DESCRIPTION

Although the general configuration of the D&C panels for the Apollo CM and LM was based on design practices established for previous aircraft and spacecraft, the configurations were, nonetheless, unique in many aspects because of the specialized mission involved. The CM was a three-man vehicle designed to be flyable during lunar orbit or emergency conditions by a single crewman. Most of the displays and controls were located on the main display console (MDC) above the couches. This location permitted easy monitoring and rapid access. The MDC was designed with the left half devoted primarily to flight-control-related D&C and the right half devoted to subsystems management D&C. Several of the spacecraft systems also had additional controls located elsewhere in the cabin. The guidance and navigation (G&N) system displays and controls used in conjunction with navigation sightings and inertial platform alignments were located in the lower equipment bay (LEB), adjacent to the G&N telescope and sextant. Manual controls for the environmental control system (ECS) that did not require frequent or time-critical manipulation were located in the left-hand equipment bay. Waste management controls and non-time-critical circuit breakers were located in the right-hand equipment bay. The general arrangement of the CM crew station is shown in figure 1.

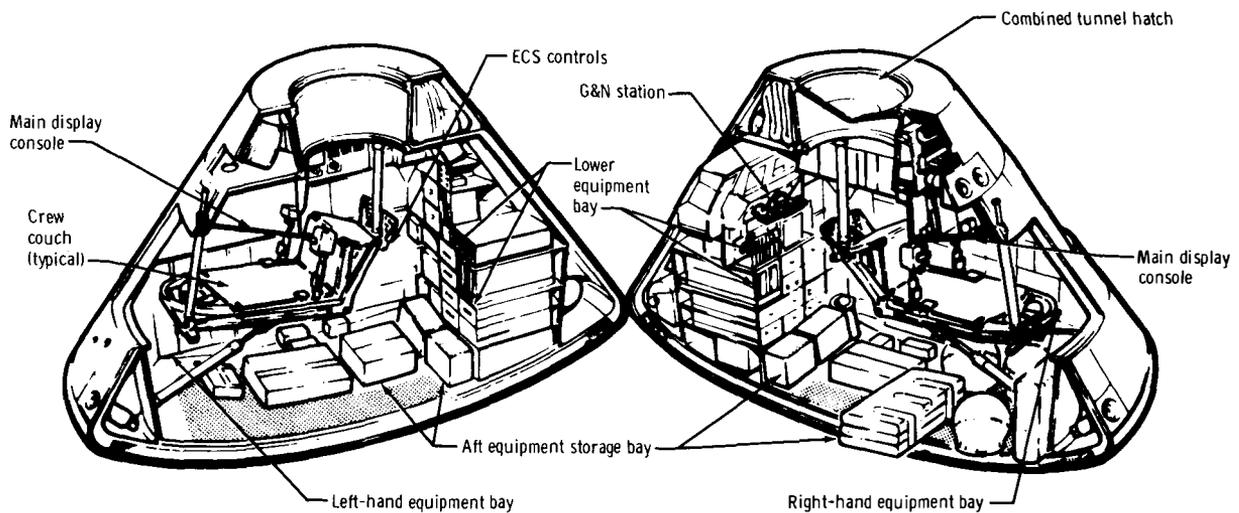


Figure 1. - The Block II CM crew station arrangement.

The LM, like the CM, was designed to be flyable in a contingency condition by a single crewman. Normal operation, however, required a two-man crew, with the commander (CDR) in the left position and the LM pilot (LMP) in the right position. The main D&C panels were canted forward and centered between the two crewmen to permit sharing and easy scanning. An alignment optical telescope between the flight stations was provided for navigational operations. The ECS and portable life-support system (PLSS) recharge stations were located immediately behind the LMP and the CDR, respectively. The general LM crew station arrangement is shown in figure 2.

A standard approach was used for locating and arranging the D&C within the CM and the LM. Flight-control displays and controls, because of their inherent critical nature and frequent use, were located in the prime panel areas. The displays and controls for all other spacecraft systems were generally grouped by system and located according to criticality, frequency of use, crew task sharing, and the most efficient use of available panel space. Assignment of D&C to (and sometimes between) particular crewmen, in general, was instituted according to standard aerospace practices. For example, on the LM, the CDR was provided with the primary flight-critical D&C. However, certain items were located for mutual access by the crewmen or were duplicated at the LMP flight station to implement copilot responsibility. The LMP stations also had subsystem-management D&C that reflected the additional flight-engineer responsibilities of the LMP. The main panels for the LM and CM are shown in figures 3 and 4, respectively. The ways in which the design philosophies were implemented and the configuration that finally evolved can be seen in some detail in these figures.

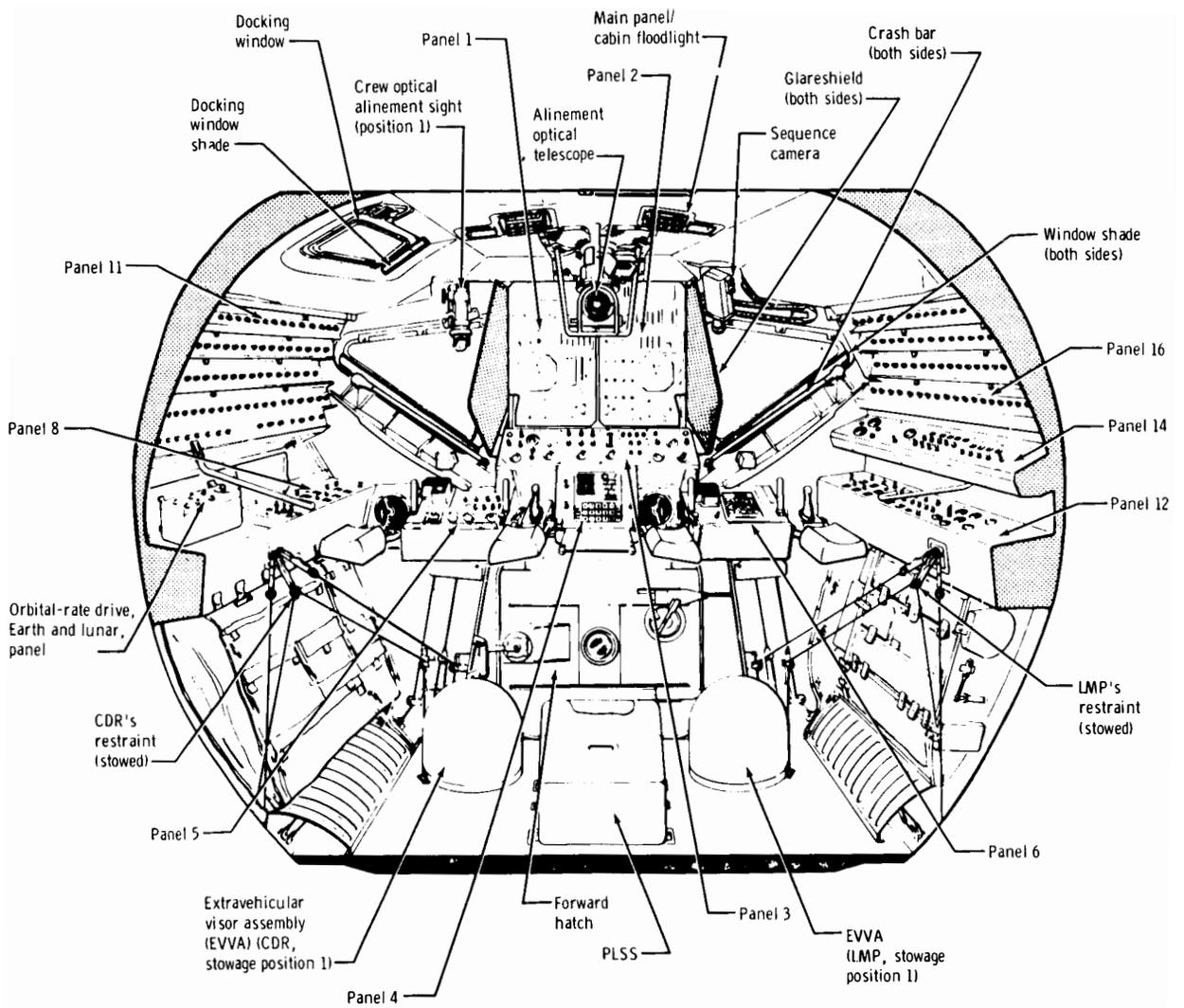


Figure 2. - The LM crew station arrangement.

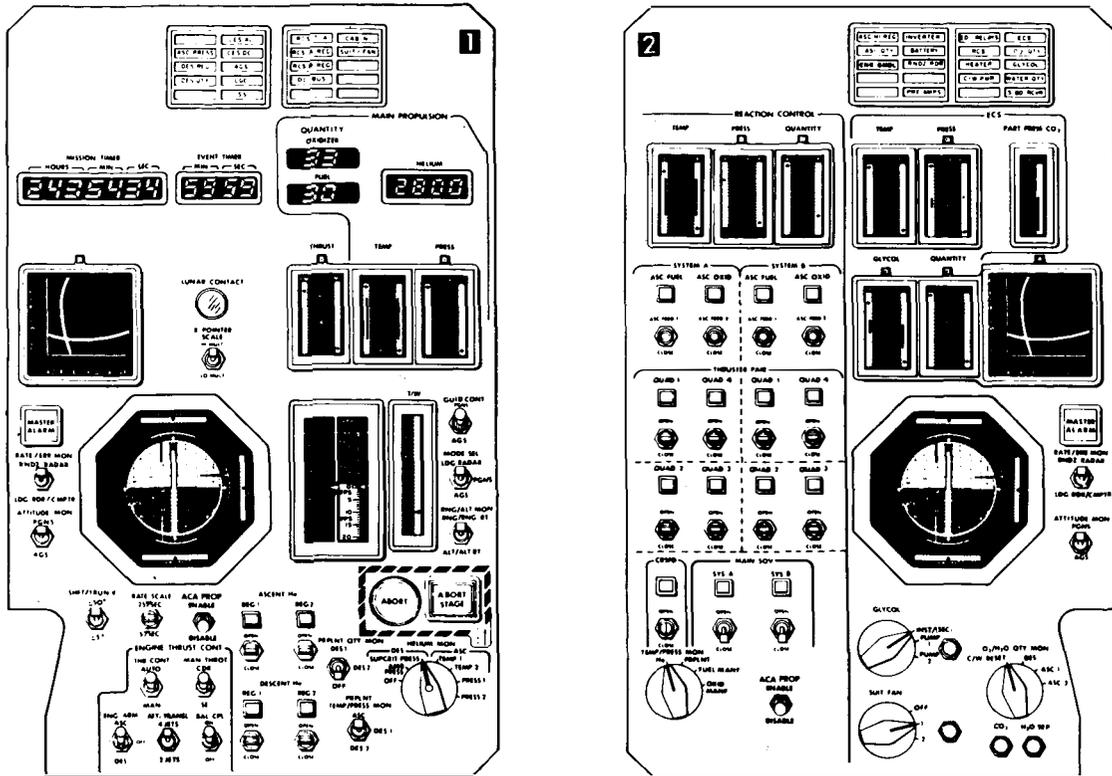


Figure 3.- The LM main panels.

The D&C components used on the Apollo spacecraft were, like the overall D&C systems configurations, similar to those used on aircraft and previous spacecraft. Unique devices, such as the entry monitor system (EMS), were developed for special applications; but, generally, the components were conventional in design and operations. The component variations that did exist were generally attributable to the addition of operational requirements, such as the use of controls while the crewman was in a pressurized suit or under zero-g conditions or the need to monitor and control during high-g or vibration conditions (or both), and to the addition of more stringent qualification requirements to achieve very high reliability under severe environmental conditions.

Controls

The control devices used in the Apollo spacecraft included toggle switches, push-button switches, rotary switches, continuously variable controls, and circuit breakers.

Toggle switches .- Toggle switches were the most frequently used control devices. The chief factors favoring their selection were that toggle switches generally required less panel space, gave a positive status indication (except for momentary switches), and were easy to actuate under a variety of flight conditions. Two- and three-position switches with various combinations of maintaining and momentary positions were used

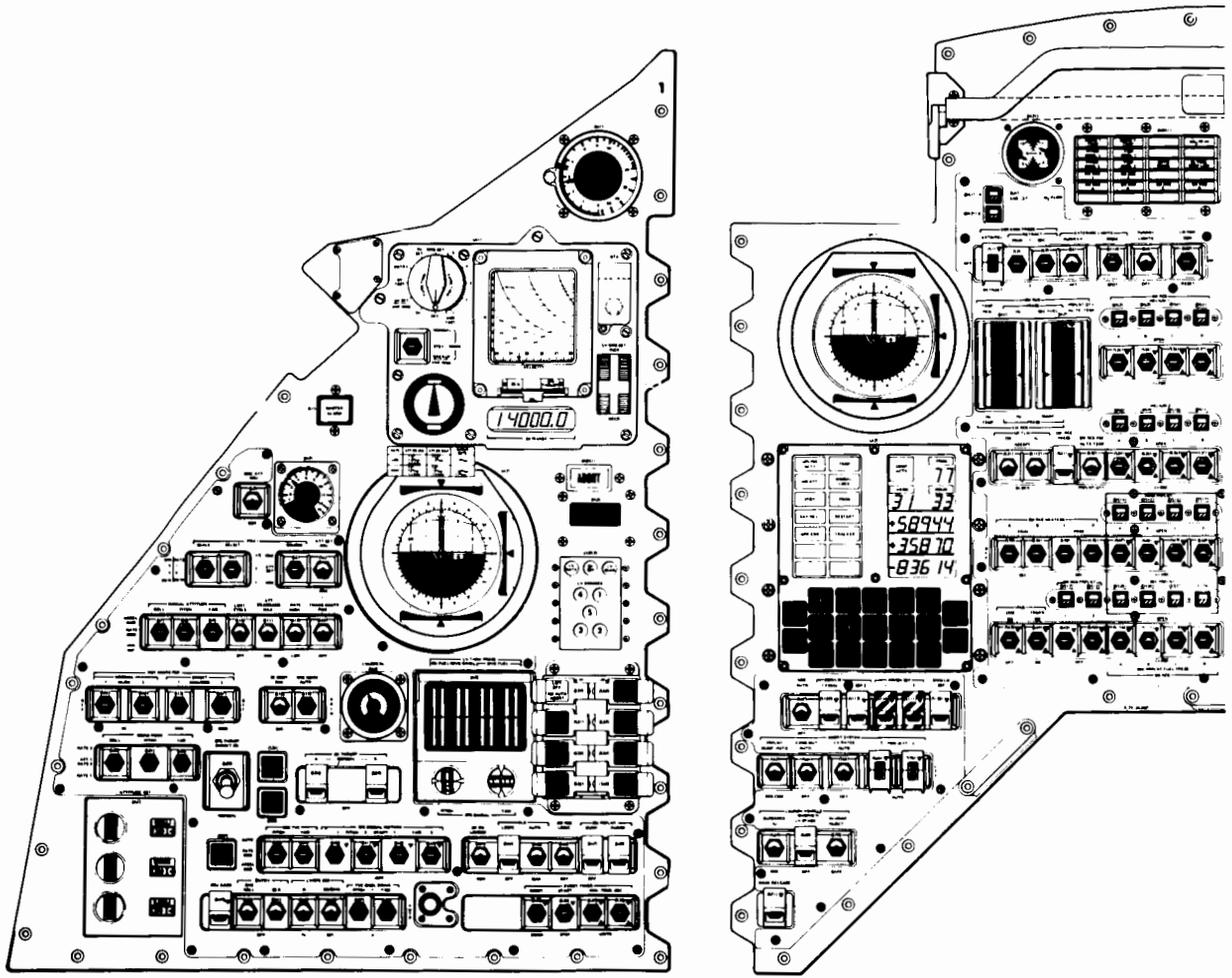


Figure 4. - The CM main display console.

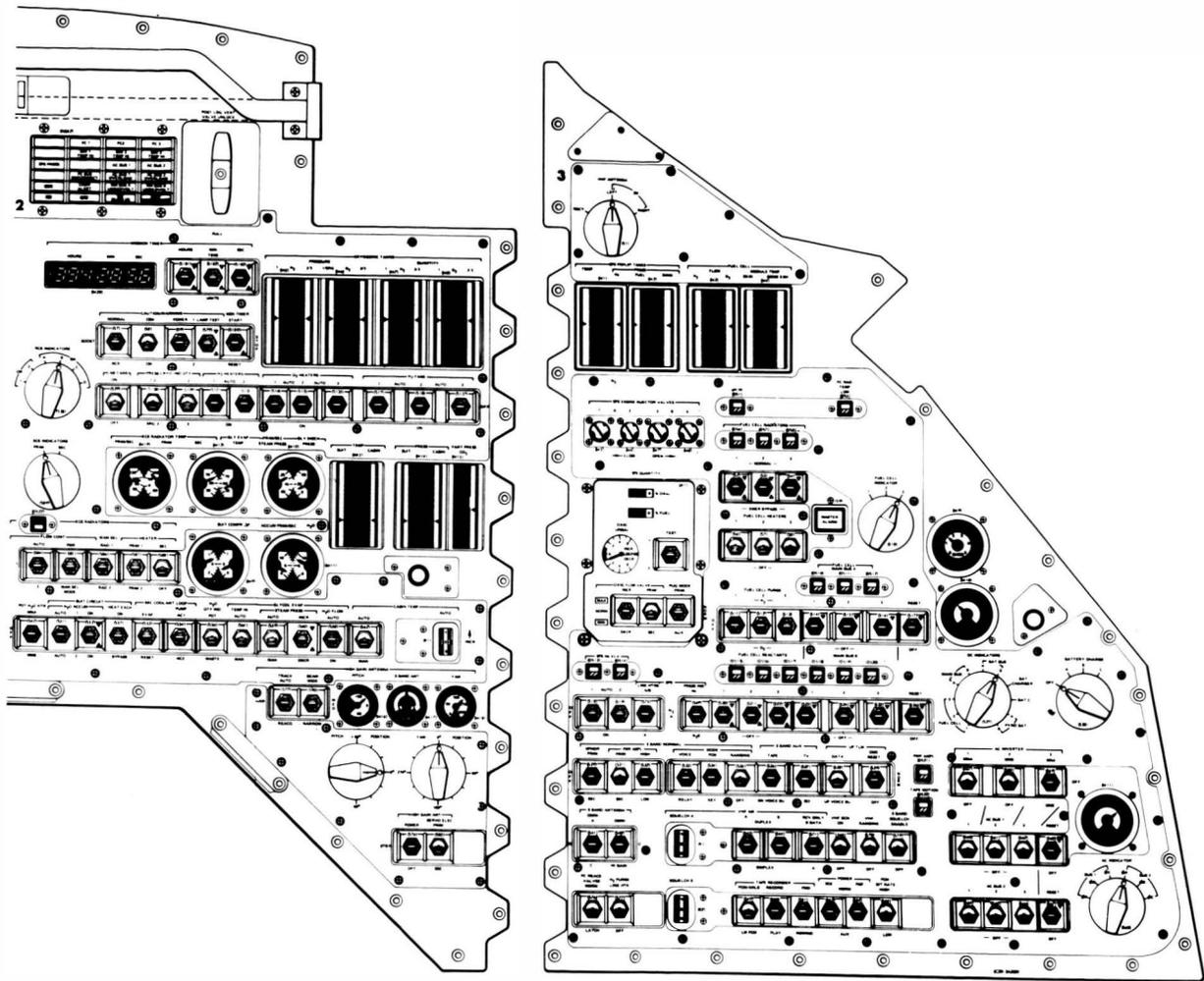


Figure 4. - Concluded.

to actuate or select operating conditions or components. A four-position (up/down, left/right) momentary switch was also used on the LM for manual positioning of the rendezvous radar antenna. Momentary positions were used to initiate a specific action requiring current for only a short time, such as jettisoning the launch-escape tower or operating a latching relay or valve.

Maintaining switches were used for most applications. An inherent advantage of the maintaining-type switch is a visual indication of switch position and, therefore, of system and vehicle configuration. The momentary-type switch, in which the handle is spring-loaded to return to another position, does not give such inherent status indication. For most functions initiated with momentary switches, such as opening a latching valve, some type of adjacent status indicator was necessary. This requirement for a status indicator to be used with most momentary toggle switches meant that an additional component and more panel space would be required than if a maintaining-type toggle switch were used. Status indicators provided with momentary switches, however, had the added advantage of providing the end-item status of the equipment being controlled, whereas a maintaining switch, in itself, gave no such information.

Most of the toggle switches used on the Apollo vehicles had a wedge-shaped tab handle that provided the crewman a large purchase area with which to actuate the switch while wearing a pressurized glove. Toggle switches that had locking mechanisms incorporated into the handle to keep the switch from being thrown inadvertently were also used. These lever-lock switches (fig. 5) had large, bat-shaped handles and were used extensively on the LM spacecraft. An additional feature of the LM toggle switches was a radioluminescent (RL) tip on both regular and lever-lock handles. The RL tips enabled quick determination of the switch position even when the cabin floodlights were dimmed. Alternate approaches were used to guard and to illuminate CM toggle switches. Command module toggle switches were recessed within a trough and guarded with adjacent wickets (fig. 6). The toggle switches were lit by spill lighting from the edge of the electroluminescent (EL) nomenclature overlay.

The operating characteristics of the toggle switches were approximately 3 to 44.5 newtons (10 to 160 ounces) of actuating force (depending on the number of poles), $34^\circ \pm 8^\circ$ of throw for two-position switches, and $17^\circ \pm 4^\circ$ of throw for three-position switches. The force values were acceptable, but a lower value for the upper limit of actuating force would have been preferable from an operational viewpoint. The possibility of increasing the deflection for three-position switches should also be considered in future designs because many of these switches have been mistakenly mispositioned or monitored (or both) on Apollo missions.

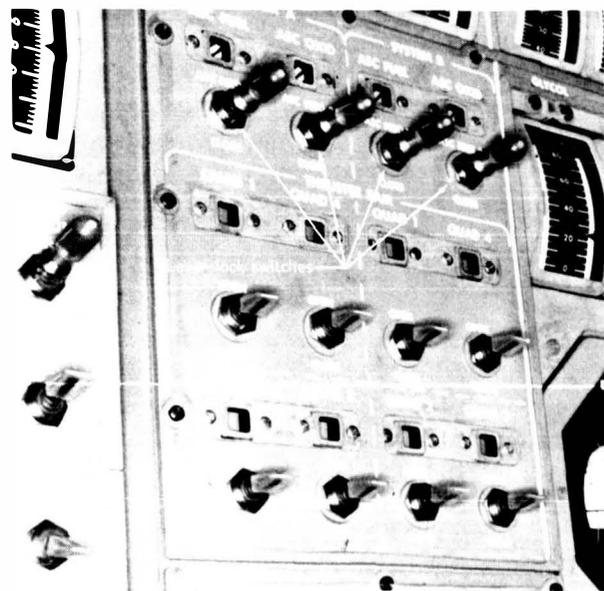


Figure 5. - Control panel showing lever-lock switches.

Pushbutton switches. - Pushbutton switches were used for applications requiring the rapid initiation of a function, for high-frequency-of-use situations, and for applications requiring a combined control/signal device. Pushbutton switches were most widely used for applications requiring the rapid initiation of a function. In the CM, pushbutton switches were used mostly as manual backup controls to initiate various sequential events during launch and entry; in the LM, they were used to back up main engine commands and to shut down the descent engine on lunar touchdown. Pushbutton switches, in a keyboard format, were used to enter data into the guidance computers. Master alarm pushbutton/signal lights in both vehicles served to indicate caution and warning (C&W) conditions and to reset the alarm circuitry.

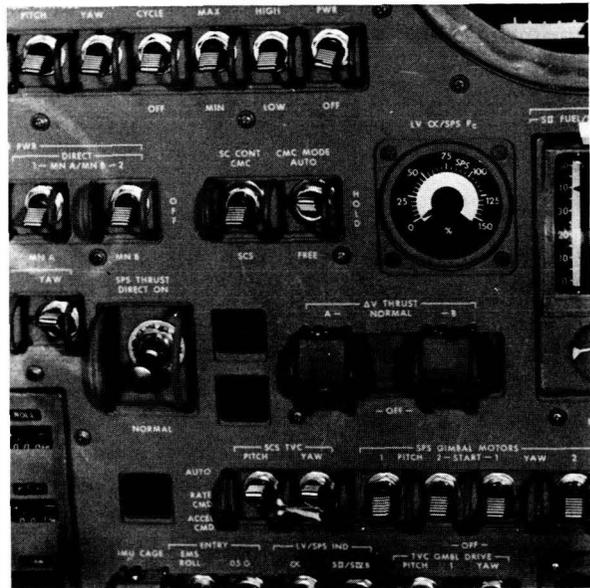


Figure 6. - Wickets guarding the CM toggle switches.

Square pushbuttons, slightly larger than those normally used in aircraft or in the Gemini spacecraft, were used for most applications. The larger size (approximately 2.03 centimeters (0.8 inch) on a side) aided actuation and permitted the use of larger legends.

Rectangular master alarm pushbutton lights, approximately 6.5 square centimeters (1 square inch) in area, were used in both the CM and the LM. Pushbutton-switch operating characteristics were 3 to 21 newtons (10 to 74 ounces) of actuating force and 0.317 to 1.5 centimeters (0.125 to 0.6 inch) of travel.

Rotary switches. - Rotary switches were used when four or more detent positions were required for discrete functions, or in applications that required many poles or high-current capacities. In the latter applications, the design of a rotary switch was generally more suitable than the design of a toggle switch.

Rotary switches were highly advantageous in accomplishing numerous switching functions, but this capability in turn increased the criticality of a failure. A mechanically jammed rotary switch, for example, could inhibit all the switching functions normally performed by the control. Therefore, the LM rotary switches were positioned in the most critical detent positions before Earth launch; and, in later lunar modules, mission-critical rotary switches were replaced with (and by an additional number of) toggle switches.

A standardized rotary control knob (fig. 7) was used in both the Apollo vehicles. The knob was equipped with a circular skirt to allow for transillumination of an integral

pointer indicium. Actuating forces ranged from 8.5 to 85 centimeter-newtons (12 to 120 inch-ounces). A standard 30° spacing between adjacent positions was used for all rotary switches.

Continuously variable controls. - Continuously variable controls, such as potentiometers, rheostats, and variable transformers, were used for functions requiring precise control and adjustment of system or equipment parameters. Some of these functions included the control of lighting intensities, audio volume, and antenna positioning. Continuously variable controls were equipped with thumbwheel and rotary-switch-type knobs. Thumbwheels were used predominantly for audio controls and knobs for lighting and antenna controls. The periphery of thumbwheels was marked with integers from one to nine for indexing the control.

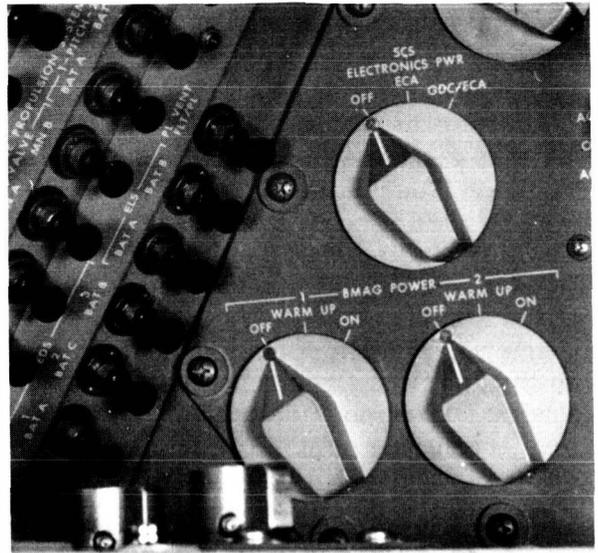


Figure 7. - Standardized rotary control knobs used in both the LM and the CM.

A slightly different type of rotary control knob was used to operate a stepper motor. Because a stepper motor has little inherent friction to maintain it at the set position, a device that would hold the control at the selected position was necessary. This locking was accomplished by the use of a knob resembling the other rotary control knobs but having an internal locking mechanism. Pushing in the top portion of the knob unlocked the control and allowed it to be positioned freely. Releasing the knob locked the stepper motor in place.

To operate continuously variable controls with rotary-switch-type knobs required a torque of 6 to 25 centimeter-newtons (8 to 36 inch-ounces). Failure to specify a lower acceptable limit for rheostat actuating torque in the LM procurement specification resulted in the delivery of several units having torques of less than 1.4 centimeter-newtons (2 inch-ounces). The addition of external friction washers between the control knob and the panel compensated for this improper torque value. Thumbwheel controls required 1.4 to 4 centimeter-newtons (2 to 6 inch-ounces) to operate. Early LM thumbwheels were also delivered with improper torque values. Because requirements documentation was misinterpreted, early thumbwheel units having torques of 14 centimeter-newtons (20 inch-ounces) and greater were delivered; but these units were used "as is" in nonflight applications. A standard 300° deflection was implemented for all continuously variable controls.

Circuit breakers. - Circuit breakers were used primarily to protect electrical circuits. Sometimes, however, circuit breakers were used as control devices; this application occurred mostly on the LM, where weight was very critical. In all these instances, though, an attempt was made to design the systems so that switching actions were limited in number and conducted under a no-load condition. Circuit breakers were procedurally used on both vehicles to disable critical circuits during periods when they were not required.

The circuit breakers used on the Apollo vehicles were the push/pull type and had a small, black knob. An aluminum band was displayed when the breaker was open. A white band originally used was deleted because the paint flaked and chaffed. Some difficulty was encountered in visually monitoring the lower contrast silver-colored bands in the lower level lighting environment of the LM. This condition resulted in the misconfiguration of certain circuit breakers by the Apollo flight crews. To avoid this situation in future programs, crew station lighting simulations should be performed to verify altered D&C color schemes.

Circuit breakers were particularly susceptible to inadvertent actuation or damage. This susceptibility was especially prevalent on the LM because of the amount of crew activity associated with lunar surface operations (e.g., backpack donning and doffing). Therefore, special precautions were taken in both vehicles to protect the circuit breakers by recessing the panels (fig. 8) or by providing barrier guards (fig. 9) or by both methods.

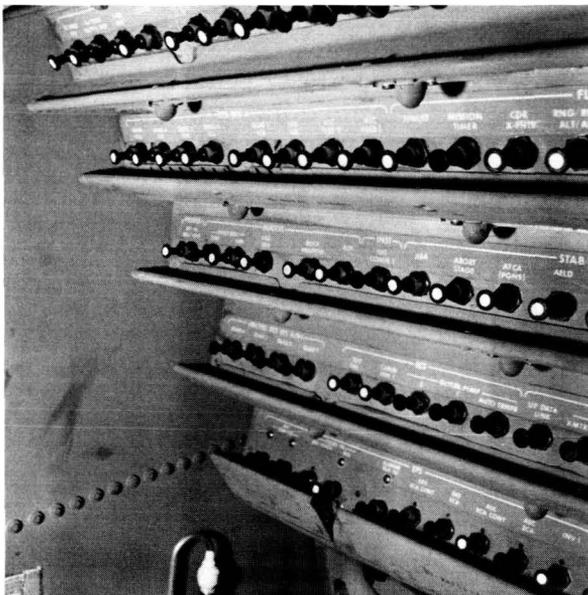


Figure 8. - Recessed panel.

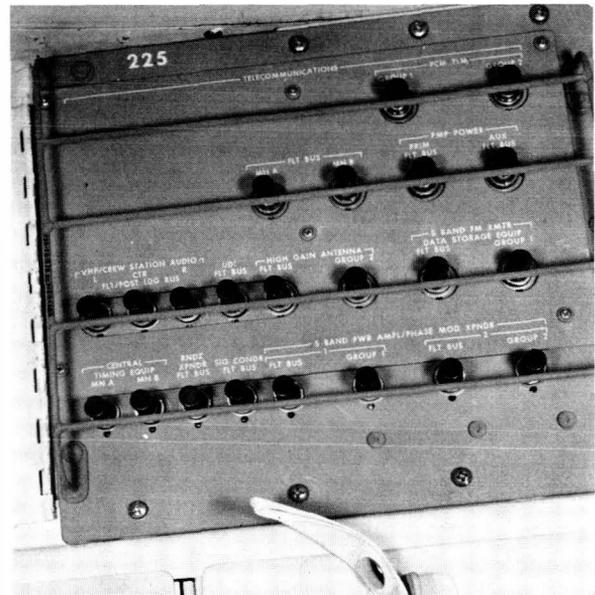


Figure 9. - Barrier guards.

All circuit breakers were the "trip free" type currently used on military aircraft; that is, a "tripped" breaker could not be manually overridden (closed). Nominally, 53.4 newtons (192 ounces) of force were required to close and 27 newtons (96 ounces) to open the circuit breakers. Total travel was approximately 0.5 centimeter (0.2 inch).

Displays

Several different types of displays and signal devices were used in the Apollo spacecraft. Among these were D'Arsonval meters, numeric displays, event indicators, annunciator lights, and several special flight instruments.

D'Arsonval meters. - The D'Arsonval meter was the predominant display instrument used in the Apollo CM spacecraft. A modified version of this type of meter, incorporating a feedback loop and termed a servometric meter, was used extensively on the LM. The basic simplicity and inherent response characteristics of the meter, its compatibility with conventional analog transducers and signal conditioners, and the extensive experience with the D'Arsonval-type movement were the primary factors in its selection as the general type of display.

Although the servometric meter provided improved accuracy and minimized vibration-induced pointer movement, the mechanism had certain undesirable features. One such feature, the necessity of providing a separate power input in addition to the signal input, required additional power, weight, wiring, and circuit breakers. Implementation of the requirement to provide a positive indication of meter failure or loss of input was also more difficult. The standard D'Arsonval meter inherently moves off scale with loss of signal and thus gives a positive failure indication. With the servometric meter, however, loss of the additional power input (or internal power) leaves the pointer at its last position. Unless the crewmen have another source of information, they are led to believe that the parameter is unchanged. This problem was circumvented in the LM by the addition of a small signal light above certain critical displays. This light illuminated whenever meter input power was interrupted. In future programs, the standard D'Arsonval movement should be used, where possible, instead of the servometric design. Servometric displays, when used, should be designed to provide a positive indication for both loss of signal and power.

The types of D'Arsonval and servometric meters used in the Apollo crew stations included single- and dual-scale vertical meters, single-scale circular meters, dual-scale semicircular meters, and cross-pointer indicators. Minimization of panel space and crew preference for vertical meters were the primary factors in the selection of the type of meters to be used. To conserve panel space (and to reduce weight and electrical connections), dual-movement meters were used, where possible, for the display of related parameters. Crew comments about the poor readability of the dual-scale, semicircular meter configuration resulted in its omission from the LM design. For the purpose of standardization, circular meters were used to display communications and electrical power systems parameters in both vehicles.

The dial faces of all D'Arsonval meters were transilluminated by the use of EL lighting. This type of meter face provided readability under a wide range of lighting conditions but did not lend itself to modification. The transilluminated markings on CM meters were produced by an etching technique, whereas a film overlay was used on the LM meters. Construction of new dial faces by either technique required a long lead time. When transilluminated meters are required for future applications, a flexible method for constructing dial faces should be adopted. Consideration should also be given to an improved method of implementing meter color bands. Color bands that denoted operating ranges, limits, and conditions were located directly on the meter

dial face in Apollo spacecraft. This method had two undesirable characteristics: meter disassembly was required to modify the color bands, and the paint on early LM meters flaked.

Numeric displays .- Numeric displays of both the electromechanical rotating drum and the electronic EL-segment type were used for certain applications in which precise quantitative data were required and trend information was not of primary importance. Among the applications were the display of mission and event times, propellant quantities, and guidance-computer parameters. Early CM numeric indicators, except the display and keyboard (DSKY) assembly, were primarily electro-mechanical. When EL lighting was selected for the later CM and LM designs, the decision was made to use EL numeric indicators exclusively in the LM and to substitute EL indicators in the CM where possible.

Event indicators .- Electromechanical event indicators, more popularly known as "flags," were used to show the status of components or system elements. Generally, these flags were used as indicators of discrete, normal events such as a valve opening or closing; but, in a few applications, they were used as malfunction indicators.

Event indicators used D'Arsonval-type meter movements consisting of a signal flag attached to the end of a pivot arm. The flag would appear in view when the device was in one energy state and would deflect from view when in the other. Two-position indicators were predominantly used throughout both vehicles. A second, three-position configuration was also used for special applications requiring the display of three separate status indications (e.g., off, on, or failure indications). In this configuration, a gray flag meant that a monitored element was operating or was not inhibited from operating (valve open, power on, etc.), a black-and-white striped indication meant that the element was deactivated or inhibited from operating (valve closed, power off, etc.), and a red indication meant that a monitored element had failed. Three-position flags were used on the LM to monitor the status of the reaction control system (RCS) thrust-chamber valves. A gray flag indicated an open valve; striped, a closed valve; and red, a failed jet. Flags were also classified according to the type of electrical actuation used. One type of indicator displayed a gray flag when energized and a striped flag when no power was applied. Another type of indicator worked in reverse. The type of flag indicator chosen for a particular application was normally the one that required the lesser operating power for the duration of the mission. For example, a "gray deenergized" flag indicator would be used to monitor a valve that was open throughout most of the mission. Although power is conserved, this scheme is operationally disadvantageous in that a deenergized indicator fails to give a positive failure indication.

In most cases in which a flag indicator was used to monitor the condition of propellant valves, the power to the flag was routed in series through valve-position-indicator switches of both the fuel and oxidizer systems. If the flag received power in the gray position, the conclusion was that both the fuel and oxidizer valves were "positively open." If the flag received power in the striped position, the conclusion was that both valves were "positively closed." Using this type of wiring logic, a positive-open flag could not provide a positive-closed indication; that is, removal of power and display of a striped flag could result from one of three conditions: fuel

valve closed, oxidizer valve closed, or both fuel and oxidizer valves closed. The opposite situation existed with positive-closed wiring logic. When mission plans and procedures began to form midway into the Apollo development, the indication was that, for certain cases, the ambiguities in determining actual valve configurations could not be tolerated. As a result, a considerable amount of rewiring was made in both the CM and the LM to interchange positive-open and positive-closed wiring logic. In future efforts, flag indicators should be powered in each active display position, where possible, to provide positive status information. When this procedure is not possible, the operational ramifications of the flag-indicator wiring logic should be carefully scrutinized.

Flags were used on Apollo spacecraft in preference to annunciator lights for general status indications. Their use conserved power, facilitated dark-adapted operations (such as star sightings), and helped to eliminate an objectionable "Christmas tree" effect. Unfortunately, the inconspicuousness of flags could also easily allow an abnormal change in the state of the monitored element to go undetected by the crewmen. Therefore, flags were generally used as status indicators and not as caution or warning indicators.

Annunciator lights. - Annunciator lights were used when a discrete, attention-getting display was required. On Apollo spacecraft, annunciator lights were generally used to provide subsystem or component malfunction information in association with the C&W system, but they were occasionally used as event indicators. The amber caution and red warning lights on both vehicles were grouped in a matrix and centrally located for easy visibility by all crewmembers. A master alarm light and an auditory alarm operated in conjunction with these lights. These alarms were activated simultaneously with the pertinent C&W light whenever an out-of-tolerance condition existed among the monitored parameters. To distinguish between CM and LM failures, two different auditory signals were used. The CM used a dual-frequency (750 and 2000 hertz) alternating tone; the LM, a single-frequency (3000 hertz) tone. The LM additionally used component caution lights, subordinate to the C&W lights, that showed which of several subsystem elements gated into a single C&W light had malfunctioned. The CM used flags for a similar function.

To avoid the distraction of constantly illuminated annunciators, both vehicles were provided with annunciator extinguishment controls. This function was accomplished in the CM by using an operating mode (acknowledge mode) that removed the lighting power from the entire C&W lamp assembly, except when the master alarm was depressed. When a C&W alarm occurred, the master alarm light and auditory alarm would activate as usual. By resetting the master alarm, the crewmen also enabled the C&W lamp power and could then observe which C&W lights were activated. An acknowledge-mode technique was not used in the LM; instead, separate controls were used to reset or inhibit the dedicated logic within the C&W electronics that enabled the power to a specific C&W annunciator.

Problems were experienced with nuisance triggering of C&W annunciators on both vehicles. Some of the false alarms were eliminated before flight by the incorporation of increased time delays within the C&W electronics. In other cases, the C&W logic of troublesome lights was completely disabled as a minimum-impact modification if alternate system information channels were available. The experience gained

in the area of Apollo C&W design indicates that the ideal C&W systems for future spacecraft would have the following capabilities: an acknowledge mode, dedicated resets/inhibits for each C&W channel, a memory or latching system for identifying the source of short-term abnormalities, a variable time delay for screening transients in individual C&W channels, and the capability to alter the alarm limits easily. For the last two features, trade-off studies should be performed to determine the advantages between onboard and ground adjustment schemes.

A special-purpose bank of annunciator lights was used on the CM to display the status of the launch vehicle during boost. Eight lights, grouped within a 5.72- by 8.26-centimeter (2.25 by 3.25 inch) area adjacent to the commander's flight instruments, provided the fundamental booster status information required by the crewmembers during launch. By means of this display, the crewmembers could determine whether or not each booster engine was developing enough thrust, whether or not the booster guidance was functioning properly, and whether or not the staging sequence was proper.

A unique annunciator was the LM lunar-contact light, which illuminated when 3-meter (10 foot) long probes on the LM landing gear contacted the lunar surface to alert the flight crew to shut down the descent engine. These two lights, installed on each side of the panel, were also provided to compensate for a possible loss of external vision because of the formation of a dustcloud caused by the landing engine thrust. Each light was round and approximately 2.5 centimeters (1 inch) in diameter. For distinction from all other annunciators, each light was equipped with a blue lens.

Special flight instruments. - Several unique displays were developed especially for Apollo spacecraft. Among these were the CM and LM flight director attitude indicator (FDAI) devices, the CM EMS, the LM range/range-rate meter, and the DSKY combinations for the primary guidance, navigation, and control system (PGNCS) computers.

Flight director attitude indicator: The FDAI, the primary flight display in both the LM and the CM, integrated into a single instrument the display of vehicle attitude, rotation rate, and attitude error. The display design was similar to that used for aircraft attitude and flight director indicators, except that attitude, errors, and rates were displayed for all three vehicle axes. Attitude was displayed on a sphere marked in an "inside looking out" fashion. Errors and rates were displayed with "fly to" needles. Attitude could be displayed to 1° , and the scaling for the error and rate needles could be changed to suit the flight situation.

Numerous changes were made to the attitude indicators before and during production and after the initial Apollo flights. Changes were made for a variety of reasons. To obtain more precise monitoring of vehicle attitude during active maneuvers, 5° yaw markings and 1° pitch markings were added. This requirement for improved attitude resolution resulted from Gemini reentry-targeting experience. At approximately the same time, as a result of recently acquired experience in both CM and LM flight simulations, astronauts expressed the desire to eliminate unnecessary dissimilarities in attitude sphere markings. The indicators in both vehicles were changed accordingly. Later, changes were made to the LM FDAI error and rate needle scaling

as a result of early Apollo flight experience. Later missions verified the belief that increased meter sensitivity would result in improved vehicle-control performance and, correspondingly, in less fuel consumption.

One of the changes made to the LM FDAI stemmed from ambiguities in interface control documents. As a result, the FDAI units were mistakenly miswired for "fly from" needle operation instead of the standard "fly to" relationship. Fortunately, this situation could be, and was, corrected by interchanging the two signal reference leads to the display. In future programs, generic functional requirements should be identified and clearly delineated at the earliest possible date. The end-to-end response between vehicle movement and display movement should be described and illustrated within pertinent program documentation.

Entry monitor system: The CM EMS was more than just a special display. The EMS was, in fact, a self-contained guidance package that allowed the crewmen to monitor, independently, the performance of the automatic PGNCs during entry and thrusting maneuvers. The EMS also displayed sufficient information to enable performance of a manual entry if a PGNCs failure occurred.

The EMS assembly (fig. 10) contained five separate displays. An entry threshold annunciator light illuminated at 0.05g to show that atmospheric deceleration had been sensed. A roll attitude indicator (RAI), a circular meter with a moving pointer, displayed roll attitude and, thus, lift-vector position throughout the entry. Two entry-corridor-verification annunciators were integral to the RAI. One of these two lights would illuminate approximately 10 seconds after the start of entry to indicate the necessity of having the lift vector up or down to accomplish a successful entry. If the upper light illuminated, the lift vector had to be up; if the lower light illuminated, the lift vector had to be down. A delta-velocity/range-to-go indicator, which was an EL numeric readout, served one of three functions depending on the positions of the mode and function switches controlling the EMS. During entry, the indicator displayed the inertial flightpath distance in nautical miles to the predicted splashdown point. For thrusting maneuvers, the indicator displayed velocity change in feet per second; for rendezvous, it displayed the range to the LM in hundredths of a nautical mile. The fifth EMS display was a scroll assembly that provided a scribed trace of acceleration as a function of inertial velocity throughout entry. The scroll had printed contour guidelines that allowed the crewmembers to monitor or control the spacecraft acceleration profile and range potential.

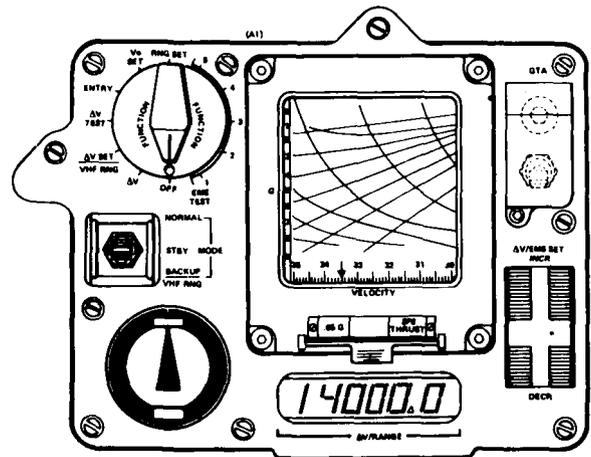


Figure 10. - Entry monitor system.

Range/range-rate meter: The LM range/range-rate meter displayed radar- and guidance-sensed ranges and range rates between the LM and the CM and between the

LM and the lunar surface. The display was a dual-scale, fixed-pointer, moving-tape indicator. Range was displayed on a moving tape located to the left of a centrally positioned fixed pointer. The range-rate tape was to the right of the pointer. This type of display was selected so that the requirements for a large data range and resolution plus trend information could be met. The indicator was one of the most complex display devices used on the Apollo spacecraft and contained approximately 500 electronic flat packs plus the mechanical drive for moving the tape. The large amount of electronic circuitry was needed to condition the various digital and analog input signals coming from several different sources and to provide malfunction-detection circuitry to monitor all signal and power inputs. As with servometric meters, special circuitry was required to provide a positive indication of loss of input power. Each of the two display tapes was approximately 3.6 meters (12 feet) long. Digital encoding with a gold-plated "gray code" on the back of the tapes provided feedback information for improved display accuracy.

Display and keyboard assembly: The displays used to communicate with the CM and LM PGNCs computers were part of an integrated DSKY assembly (fig. 11), a piece of equipment common to both Apollo vehicles. The CM had two DSKY assemblies that operated in parallel; one DSKY was located in the MDC and the other at the LEB G&N station. The LM contained a single DSKY located between the two crewmen. The DSKY consisted of two groups of displays: on the left was a group of annunciator lights that showed computer status or caution conditions; on the right were an EL numeric display and a computer-activity annunciator. The numeric display fulfilled three basic functions: display of computed data on both one-time and periodic update bases; display of data being loaded for verification by the crewman; and display of the operation (verb), the operand (noun), and the major mode (program) under which the computer was working.

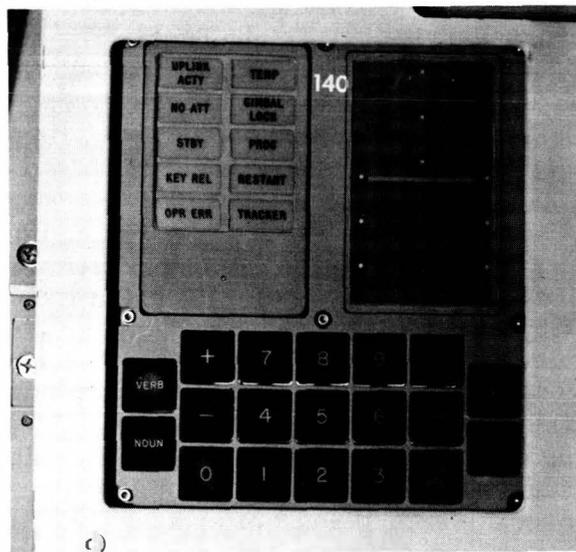


Figure 11. - Apollo display and keyboard.

The data being entered into or read from the computers were displayed on three five-digit registers. The verb, noun, and program displays were two-digit read-outs showing the code numbers for the action being performed. For example, program 52 was used to realine the inertial platform; verb 25 meant load the data in registers 1 to 3; and noun 35 was the time from an event in hours (register 1), minutes (register 2), and seconds (register 3). The EL-segmented alphanumeric displays were used for the data registers.

The LM included a dedicated keyboard for communication with the abort guidance system (AGS) and the AGS computer. Whereas the PGNCs DSKY was intended and designed for general use, the AGS data entry and display assembly (DEDA) was designed

as a special-purpose device to be limited to the displaying and processing of AGS abort-related parameters. Therefore, a single-address register, a data register, and an "operator error" annunciator light were adequate. An LM DEDA is illustrated in figure 12.

DESIGN DEVELOPMENT

Generally, the D&C design development was an evolutionary process that followed the development of the overall CM and LM vehicles. After the initial designs were completed, most of the factors that shaped and modified the D&C were generated outside the subsystem, primarily from changes in interfacing subsystems or from revised operational techniques. The development paths and milestones for both the CM and the LM D&C were similar (although on different schedules), and the chronologies of both vehicles were essentially the same as for the respective crew stations.

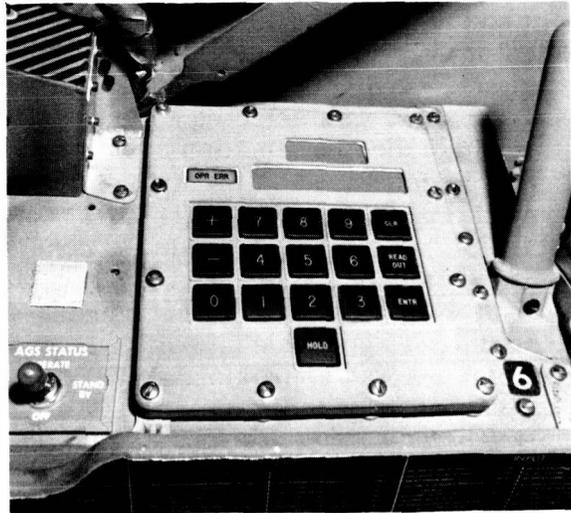


Figure 12. - The LM data entry and display assembly.

Command Module

Early in the Apollo Program, pushbutton switches were proposed for extensive use in the CM; however, pushbuttons were not used as the general switch type for a number of reasons. One reason was that, for a two-state function, a pushbutton generally required more panel space than a toggle switch. Second, the designs of pushbutton switches were more complicated than the designs of toggle switches. Third, the design of a maintaining type of pushbutton was additionally complicated because the pushbutton required the use of a relatively complicated internal or external latching mechanism or the use of external latching relays. A fourth disadvantage of pushbutton switches was the problem of a "Christmas tree" effect created by pushbuttons equipped with integral status lights. Constantly illuminated signal lights are distracting, tend to mask other important signal lights, and result in unwanted reflections in the spacecraft windows. Therefore, the toggle switch, instead of the pushbutton, was chosen as the general switch type for Apollo spacecraft.

At the time of the initial CM design, the decision to use the lunar orbit rendezvous (LOR) mode of operation had not been made. After the selection of the LOR mode with a separate LM, the CM had to be provided with the added capabilities for docking and crew transfer. As the design development proceeded, the need arose to reduce the CM weight, to improve reliability, and to incorporate numerous system modifications that early experience had shown to be necessary. The lunar-mission spacecraft that incorporated all these changes and added capabilities were designated Block II spacecraft. The initial Block I design was continued, but strictly as research and development spacecraft for Earth-orbital tests.

The Block II design point was one of the few times that truly major changes were made in the CM D&C configuration. Because weight had to be reduced and because the concept of in-flight maintenance had been deleted, the panel structure and wiring were totally revised. The 20 small, sheet metal panels making up the MDC on Block I were replaced by 3 large, machined panels for Block II, and the service loops on the panel wiring harnesses were eliminated. (Subsequent experience has shown that retaining the service loops or having rear service access to the panels would have been a major benefit to ground modifications and checkout operations.) The EL integral panel and display lighting were also added for Block II; only the FDAI (which was incandescent) in Block I was integrally lit. The layout of the D&C was also revised extensively to accommodate the numerous subsystems changes.

The following detail changes to the D&C configurations resulted from the Block II redesign.

1. The FDAI was redesigned and repackaged to incorporate EL integral lighting and a single reference index. (The Block I FDAI had two reference symbols because the vehicle and navigation axes did not coincide.) A second FDAI was also added for redundancy and operational flexibility.

2. Displays and controls were added to accommodate the newly acquired high-gain antenna and docking-probe systems.

3. The crew control of the stabilization and control system was changed from a mode-selection scheme to a function-selection arrangement. This change improved overall system reliability and provided additional operational flexibility. More switches were required for function selection because this scheme allowed manual and alternate selection of individual system components or functions. For example, the earlier mode-selection scheme had automatic FDAI error-needle scaling on the basis of preselected values. However, the function-selection arrangement incorporated a scaling switch that permitted the crewmen to select the scaling desired for a particular operation. Although function selection unquestionably gave greater flexibility, the approach also had two undesirable side effects. First, this approach increased the number of switches that had to be positioned and monitored; second, increasing the number of switches increased task times, complicated training, and raised the possibility of inadvertent or improper switch combinations. The principal advantage of the function-selection scheme may have been its capability to accommodate changes in vehicle flying techniques. By contrast, most features of the mode-selection scheme were hardwired into the system.

4. Flag event indicators that worked in conjunction with switches were moved from below the switch to above the switch so that the operator's hand did not block visibility during operations.

5. The EMS development was continued strictly as a Block II item, and the device was deleted from Block I spacecraft.

The deletion of the in-flight-maintenance concept also meant that an elaborate in-flight test system would no longer be required; therefore, the system was reduced to a single voltmeter and two multiposition switches. This systems test meter, as it came to be called, was used to check out certain equipment and monitor parameters

that had low criticality or that required a very low checking frequency. The positions of one rotary switch were identified with letters and the other with numbers. The meter displayed test values between 0 and 5 volts. A decal that identified (1) the parameter displayed with a given switch position; (2) the nominal, maximum, and minimum meter readings; and (3) the corresponding engineering units for the voltage readouts was provided for use with the systems test panel.

After the Apollo CM fire, many changes were made in a relatively short time. The primary impact on the D&C was that certain ECS controls were relocated to improve crew access. Holes were added to most D&C panels as ports for insertion of a fire extinguisher nozzle in the unlikely event that a fire erupted behind the panel. The flammable plastic control knobs were also replaced with metal knobs.

Several individual changes in the D&C occurred as the design evolved. The first change involved the nucleonics quantity measuring system developed for the service module and LM reaction control system. This gaging system consisted of many small radioactive sources placed externally on one side of an RCS tank and a scintillator-photomultiplier counter placed on the other side. The idea was that the propellant would scatter or absorb radiation at a rate proportional to the quantity remaining in the tank. This quantity would then be displayed on a digital readout. A Nixie tube display was baselined for the CM — the only spacecraft application of such a display. Unfortunately, problems were encountered in the development program; the cost increased, and the system was canceled. As a result, an indirect quantity gaging system had to be used. A pressure/temperature ratio transducer monitored the RCS helium tank that supplied propellant pressurization. The output of this transducer drove an analog meter that was calibrated to read the corresponding propellant quantity.

Problems in the development of toggle switches caused changes in vendors, redesigns, and numerous refinements in screening processes. One result of these problems was a requirement to provide redundant parallel switches, each having redundant contacts wired in series parallel fashion, for the most critical pyrotechnic functions on the command and service module spacecraft.

Another significant D&C development was the addition of the orbital-rate drive, Earth and lunar (ORDEAL), assembly to the CM and the LM. Because the Apollo spacecraft was conceived primarily as a nonorbital vehicle, its guidance and control scheme was based on a strictly inertial reference system without any capability for a local-vertical or a local-horizontal orbital mode. Gemini experience, however, showed that the crewmen required a rapid and accurate method for determining the angle between the relative line of sight and the local horizontal during rendezvous maneuvers. When the requirement was firmly established, the CM and LM designs had progressed too far to enable incorporating the requirement easily or cheaply into the existing systems. To fulfill this need, the ORDEAL was designed as a black box with integral controls that could literally be hung on the wall and wired to drive the FDAI at an orbital rate. The ORDEAL box installed in the CM is illustrated in figure 13.

Lunar Module

After the initial design was finalized, the LM did not undergo a major redesign such as the CM block changes. The major development change to the LM D&C consisted of replacement of fuel cells and associated cryogenic supplies with batteries. The displays and controls associated with a battery are much less numerous than those for a fuel cell and cryogenic system; thus, the net result of this change was to simplify the LM D&C.



Figure 13. - The ORDEAL assembly.

An interesting LM D&C component development was that of the cross-pointer indicator. This instrument provided simultaneous display of forward and lateral velocities during landing and of line-of-sight azimuth and elevation angles for rendezvous.

The initial proposal was that the display be an EL grid and that the drive signals be digital. Advantages of this implementation were improved system accuracy and elimination of parallax. After much study, however, the analog-meter cross pointer was retained because of the impact of converting to an all-digital system.

Similarly, feasibility studies and simulations were conducted to analyze the desirability of using digitally driven attitude indicators. Problems of attitude-sphere response and information lag were identified, and this concept was therefore dismissed. Apollo software, it should be noted, was generally limited to outputting information at a rate of 10 times per second. With the miniaturization of software logic, the state-of-the-art "refresh" techniques, and the advances in display designs that currently exist, digital displays would now possibly be feasible.

Special problems were encountered with the LM engine-stop pushbutton switch. On several occasions during ground checkout operations, this switch was inadvertently reset from the "on" state (engine off) to the "off" state (engine on). If this condition had occurred during lunar touchdown, the result could have been catastrophic. To avoid such a catastrophe, an external "positive actuation device" was added to the pushbutton to hold the switch in the internally latched position. Unfortunately, numerous problems were experienced with the device itself, but these were resolved before the first lunar landing. In future efforts, the use of maintaining-type pushbuttons for accomplishing critical switching functions should generally be avoided.

Standardization

The principles of commonality and standardization of equipment received much emphasis early in the Apollo Program. As a result, commonality studies were conducted to examine the feasibility of using Gemini hardware or other common hardware (or both) in both Apollo vehicles. The results of these studies indicated that the different development schedules and different environment requirements of the three vehicles eliminated the use of most common hardware. Therefore, the initial CM and

LM D&C designs did not include a single piece of equipment that was common to both vehicles. Later in the program, however, the operational advantage of a standard DSKY configuration became apparent, and a common (although not interchangeable) DSKY was procured for use in both the CM and the LM. For similar reasons, when the requirement for the ORDEAL was later identified, common equipment was procured from a single source. Later in the program, toggle switches, circuit breakers, and mission timers also became common equipment because of problems in the hardware being procured from Apollo vendors.

The goal of functional standardization was ultimately achieved by two methods. First, interface control documents were established among the prime vehicle contractors, the G&N systems contractor, and the NASA Lyndon B. Johnson Space Center (JSC) (formerly the Manned Spacecraft Center (MSC)). These documents formally defined and standardized the basic D&C functional requirements to eliminate conflicting design features. Among the items standardized were panel controls, display faces, annunciators and flag indicators, nomenclature, markings and colors, and lighting. These documents established a basic compatibility "ballpark" in which detail designing could be done. The second factor in achieving standardization — less formal than the first but just as important and effective, especially in day-to-day work in specific details — was that the D&C efforts for both the CM and the LM were monitored by the same group at MSC. This arrangement encouraged and facilitated constant communication between the cognizant engineers and helped to achieve further compatibility in the CM and LM D&C designs.

For future efforts, a set of D&C functional requirements specifications has been prepared. These documents, based on manned spacecraft experience to date, include a compilation of requirements from the Apollo interface control documents and applicable military standards. The intent of these specifications is to identify basic considerations, criteria, parameters, and values of benefit to D&C systems designers, and to maximize crew efficiency by standardizing functional characteristics and thereby reducing the possibility of ambiguity. These specifications cover the basic entities of displays and controls including lighting; nomenclature, markings, and color; abbreviations; displays; and controls.

OPERATIONAL EXPERIENCE

The first five manned Apollo missions (Apollo 7 to 11) provided more than 1000 hours of flight operations; the D&C subsystems, as a whole, worked well and met all design objectives during these missions. Flight crews reported that the displays provided the required information and were read easily even under the most severe environmental conditions, that the markings and nomenclature were satisfactory, and that the controls gave the needed command capabilities and were operated easily. Many of the D&C anomalies reported on Apollo flights were not directly attributable to the D&C equipment itself but to anomalies within interfacing equipment (e.g., instrumentation). Discussions of these types of anomalies have generally been omitted in this report.

In a sense, operational experience with the D&C system began well before the first manned Apollo flights. Valuable knowledge of D&C subsystem performance was

gained both from unmanned orbital flights and from manned thermal-vacuum chamber tests. Unmanned developmental command modules were equipped with sequence cameras that photographed portions of the MDC and obtained forward-window views during some of the critical mission phases (such as entry). Verification of the flight performance of certain critical displays was believed to be a contributing factor to manned Apollo missions.

Mission AS-202 was one of the early unmanned flights that provided operational experience. Postflight examination of telemetry data and of in-flight motion pictures of the panels revealed that most of the displays operated normally. The data also indicated that those displays that did not respond as expected were actually only reflecting problems in the subsystems. For example, an improper FDAI attitude indication that existed throughout the flight was caused by an alignment error in the platform, and a fuel cell C&W annunciator illuminated because of a low oxygen flow rate.

Because LM vehicles could not be recovered, the LM panels were not photographed in flight. A study conducted to determine the feasibility of using the Apollo television camera for real-time D&C assessment proved this approach to be impractical, primarily because of the unavailability of communications channels and receiving stations.

Manned thermal-vacuum chamber tests were performed for both the CM and the LM by using special test spacecraft. These tests permitted a combined environmental and operational assessment of the Apollo D&C. In conjunction with the primary duty of man-rating the spacecraft, astronauts manning the vehicles during these tests assessed the following D&C areas: readability of displays and accessibility of controls, torques and forces required to actuate controls, interference with D&C panels during normal operations, comparison of onboard display readings with telemetry and control-room readings, operation of the C&W system, and general acceptability of lighting. With few exceptions, the displays and controls for both vehicles were found to be acceptable. These tests were especially helpful because they enabled determination of operational quirks within the D&C and vehicle subsystems. Numerous problems with transient and false C&W alarms were encountered. As a result, significant changes were made to C&W systems within the flight vehicles. In other cases, procedural workarounds were established.

Apollo 7 Mission

The primary purpose of the Apollo 7 mission, the first manned CM flight, was to check out and gain experience with the spacecraft systems. At the postflight debriefing, the crewmembers reported that, in general, the D&C configuration and operations were very satisfactory. Control forces and torques were found to be satisfactory under all the differing acceleration conditions and were great enough to preclude inadvertent control actuations. The displays were readable, but several meters were found to be less accurate than had been anticipated. A problem with washout of the EL readouts of the EMS, the DSKY, and the mission timer was also experienced. Sun shafting, particularly through the side hatch window, occasionally made these displays unreadable. As corrective action, portable shades were provided to shield these displays on later missions. The panel nomenclature and markings were reported to be satisfactory, and the EL panels provided excellent readability even in a darkened cabin.

The Apollo 7 flight crew found that the frequency of timing operations warranted an additional timer for use by the crewman who occupied the right-hand couch. The use of either another event timer or a "kitchen timer" was suggested. An evaluation of the impact of adding another event timer resulted in provision of a kitchen-type timer for subsequent missions. A new nonflammable case was made, and the timer was tested to ensure that there was no harmful outgassing. This modified household timer proved to be especially useful because of its portability, lack of interfaces, and built-in signal bell.

Two D&C hardware failures were experienced on the Apollo 7 mission. A crack developed in the optical glass window of both mission timers, and the EMS delta-velocity/range-to-go display malfunctioned before lift-off. Fortunately, the mission-timer glass did not come loose, and timer operation was unaffected. Postflight investigations revealed that the cracking resulted from stress induced in the glass during manufacturing. The nature of the failure did not warrant redesign of the timers; but, to compensate for this type of failure on later missions, transparent tape was installed over the display windows of both mission timers to prevent the release of glass particles within the crew compartment. Loose particles constitute a special danger in a zero-g condition because these particles float freely within the cabin and can easily be ingested by the crewmen. Investigations after the mission disclosed that the EMS failure was apparently caused by a poor solder connection and a poor wire-crimp connection within the EMS.

Apollo 8 Mission

The Apollo 8 mission was the second manned flight and the first manned lunar orbit mission. Again, the crewmembers reported that the displays and controls were very satisfactory. The kitchen-type timer recommended after the Apollo 7 mission proved to be very useful, particularly for timing fuel cell purges. However, the panel shades that were provided to prevent washout of the EL numerics were generally ineffective. The best solution was to shade the displays with one hand during the occasional periods when washout occurred.

Before the flight, the Apollo 8 crewmembers wrote various supplemental systems information on the D&C panels. This additional information proved to be very useful to the crewmembers during the flight. As a result, a system was established for subsequent missions in which, shortly before flight, operational information of a supplemental or "memory jogger" nature was collected from the crewmembers and was verified, documented, and placed on metal foil decals that were then added to the spacecraft panels. Examples of these decals are illustrated in figure 14.

Only one D&C-associated hardware problem occurred during this flight — four times during the mission, abnormal indications existed on the delta-velocity counter or the scroll display. Postflight investigations disclosed a bubble in the accelerometer that could have caused some of the problems. The remainder of the anomalies resulted from using the EMS to monitor small accrued velocities, a job for which it was not designed. However, a procedural workaround was developed so that, on subsequent missions, the EMS could be used for such monitoring, if desired.

Apollo 9 Mission

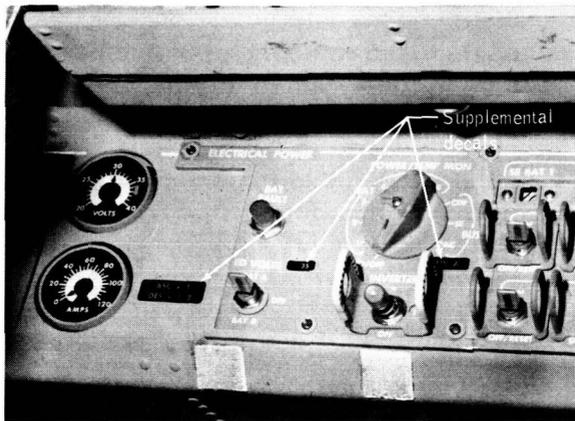


Figure 14. - Supplemental decals.

The Apollo 9 mission, the first manned LM flight and the first joint CM and LM mission, was intended both to qualify the LM spacecraft and to demonstrate, in Earth orbit, combined LM/CM operations. Although the D&C for both vehicles functioned satisfactorily, several problems occurred, chiefly in the CM.

During the first scheduled LM/CM separation (undocking), the "probe extend/release" switch was actuated, but the vehicles did not physically unlatch until the third attempt. Then, on retracting the probe in preparation for redocking, the

status indicators showed that the probe latches were not cocked for docking. Cycling the docking probe produced the proper indications, and docking was completed satisfactorily. Indications were that these anomalies did not result from any control or probe failure but from a procedural problem caused by not holding the probe switch in the "extend/release" position long enough to complete the release and latch-cocking sequences. For subsequent flights, the operational procedures were changed to reflect this operating time, and the problem was not repeated.

Some of the Apollo 9 docking problems could have possibly been avoided if the crewmembers had been provided with additional docking system information. A two-position (gray/striped) flag indicator was used to monitor all docking-probe operations. This approach inherently limited the amount of information that could be displayed and easily led to confusion because the meaning of the displayed indication was different at different times in the operating sequence. In the future, if status information is needed to monitor docking or other multiposition mechanical systems, consideration should be given to providing a discrete indicator for each event in the system operating sequence.

Several C&W system anomalies occurred during the Apollo 9 mission. On three occasions, a C&W master alarm occurred without the illumination of any C&W annunciator and without the identification of any out-of-tolerance condition. In-flight and postflight analysis revealed that these unexplained alarms were probably caused by externally induced transients rather than by malfunctions within the C&W electronics. A problem was also encountered with certain service propulsion system C&W circuits. On eight occasions during the three firings of the service propulsion engine, a C&W light indicated an excessive unbalance in the propellant quantities. Two of the eight failure indications were found to be caused by actual unbalances, but the remainder were attributed to either an unexpectedly long propellant settling time or a bias in the quantity measuring system. Analysis of all the flight data showed that balancing the propellant usage was not as critical as had been anticipated. To avoid numerous nuisance alarms, this C&W function was disabled on succeeding spacecraft.

One minor problem experienced on the Apollo 9 mission was directly attributable to an error in panel markings. Problems in repressurizing the surge tank resulted

from a 20° misalignment between the ECS panel markings and the control-valve detent position. The control position indexes had simply been mislocated during manufacturing, and the error was not detected before flight.

As on earlier missions, a problem with the Apollo 9 EMS was experienced. The scroll assembly failed to scribe a trace of acceleration as a function of inertial velocity during entry. Postflight testing disclosed that the environmental seal for the scroll assembly had a large leak. The scroll coating was susceptible to moisture, and a subsequent slow drying would cause the coat to harden. Apparently, ambient air leaking through the broken seal provided the moisture, and the 10-day mission at a 34 470-N/m² (5 psia) cabin pressure provided a slow vacuum drying that hardened the coating so that the scribe did not provide a trace. Special photographic techniques revealed that the stylus had traced properly on the film.

Three D&C-related problems occurred in the LM used for the Apollo 9 mission. Because the LM did not return to the Earth, as did the CM, a rigorous postflight analysis similar to the type conducted for the CM was not possible. Precise identification of the cause of an anomaly was therefore often impossible. Problems were experienced with the AGS keyboard, the C&W system, and the range indicator. When the "clear" pushbutton on the AGS keyboard was operated, the operator-error light illuminated on a number of occasions. Four or five additional switch activations were then required to extinguish the light. (The light would extinguish momentarily with each subsequent switch activation.) This problem was attributed to the improper operation of one of the two microswitches contained in the pushbutton. Simultaneous activation of both switches was required to extinguish an operator-error light. The condition was accepted on the Apollo 10 mission. However, for Apollo 11 and subsequent missions, a wiring change was made so that activation of either switch within the "clear" pushbutton would deactivate the operator-error light.

A second LM problem was the illumination of an AGS failure light. Subsequent system performance and the normalcy of instrumented system parameters reduced the probability of an actual AGS failure. The conclusion was that the alarm was probably caused either by a short-circuited or broken wire between the AGS, signal conditioning, and C&W equipment or by a failure in the signal conditioning or C&W equipment.

The LM range indicator also caused some problems, not because it failed but because it behaved differently than the meters on which the crewmembers had trained in the mission simulators. In flight, the tape responded in irregular steps, whereas the simulator displays exhibited a smooth slewing of the tape. The action of the flight display was normal and was caused by two factors: the digital nature of the input signals and drive mechanism and, the more influencing factor, the use of different scale units among the four input sources to the meter. The internal scale factor was applied according to both the source selected and the portion of the range tape being used. The simulator displays were basically analog instruments and, because of existing software limitations, had not been programmed to respond like the actual units. Unfortunately, because of the limited number of opportunities to observe integrated range-indicator operation before flight, the Apollo 9 crewmen initially interpreted the digital response of the range indicator to be abnormal. To avoid this situation in future efforts, a list describing any static or dynamic differences that exist between flight vehicles, crew trainers, and simulators should be maintained.

Apollo 10 Mission

The Apollo 10 mission, the first lunar flight of the complete Apollo system, was intended to verify all aspects of the lunar-landing mission, except for the actual LM landing, lunar surface operations, and ascent. The D&C of both vehicles again performed well with only a few minor problems.

Three D&C-related problems were encountered in the CM. The launch vehicle annunciator assembly operated intermittently during prelaunch checkout. Each of the eight status lights in the annunciator assembly had two redundant lamps, and one lamp in each of four different indicators operated intermittently. Results of postflight analysis showed that each of these lamps had cold solder joints.

A second problem existed with the digital event timer. On one occasion, the timer advanced 2 minutes; on other occasions, the timer failed to advance the tens-of-seconds count. The failure of the event timer in the tens-of-seconds count was found to be caused by contamination of an electrical contact when a motor gear rubbed against a display wheel and flaked the paint. The 2-minute jump could not be reproduced and was thought to have been caused by electrical noise to which the timer had proved to be sensitive.

The third CM D&C failure concerned the EMS. After successful completion of the preentry test, the stylus of the scroll assembly stopped scribing. When the scroll was slewed back and forth, the stylus cut through the emulsion and then performed normally throughout entry. Investigations disclosed that the base of the emulsion used on the scroll was a latex rubber and soap mixture. The formula for the commercially prepared soap used in the mixture had been changed, and the new formula caused a chemical reaction with the film and hardened the emulsion. Lack of time prevented making any change for the next mission; however, a decision was made that, for succeeding vehicles, either the scroll emulsion base would be made from the original soap compound or a pressure-sensitive scroll, which had been recently qualified, would be used.

Several D&C-related problems were encountered on the Apollo 10 LM. The first problem occurred when the LM was initially manned. The glycol temperature indicator displayed zero with the water/glycol pump switch in the pump 2 position. When the switch was in the pump 1 position, the temperature display was normal. Because the configuration was such that a jumper wire connected the pump 1 and pump 2 contacts so that the primary glycol temperature was displayed when the switch was in either position, it was assumed that either the jumper broke or complete contact was not made when the switch was in the pump 2 position.

The second problem concerned several master alarms that occurred during the descent-engine phasing maneuver. The first alarm, which occurred concurrently with engine ignition, indicated a low descent-propellant quantity. The low-level indication was proved erroneous and was believed to have been caused by a gas bubble that, in zero-g, uncovered the low-level sensor in the propellant tank. The C&W electronics system was designed such that, once a low level was detected, the circuit would latch and the descent low-propellant light would remain illuminated until reset manually by the flight crew. When the light was activated on the Apollo 10 mission, however, it failed to remain illuminated. Telemetry showed a constant low-level condition, an

indication that there was also an intermittent open circuit downstream of the telemetry point. To prevent the recurrence of nuisance master alarms on subsequent flights, the descent-propellant low-quantity input to the master alarm was eliminated on the Apollo 11 LM and subsequent vehicles. A second reason for disabling this light was that activation of the light caused by a true low-quantity condition might prove distracting to the crewmembers during the final phase of lunar landing. A decision was made that alternate onboard displays and telemetry would be ample for monitoring propellant quantities.

The final D&C-related problem was associated with what was probably the most harrowing experience of the flight. Shortly before and during the LM staging sequence, vehicle gyrations were experienced at rates as great as 19 deg/sec in pitch and 25 deg/sec in roll and yaw. Telemetry and vehicle response indicated that, coincident with the maneuvers, the abort guidance mode switch was moved from the attitude-hold position to the automatic position. As a result, the guidance system subsequently, and correctly, generated steering commands to point the Z-axis of the LM at the CM instead of maintaining the existing attitude. The crewmembers, thinking that they had reselected the semiautomatic attitude-hold mode, did not anticipate the automatic maneuver and, subsequently, attempted to override it. Fortunately, the crewmen were able to restabilize the vehicle and complete the rendezvous maneuver. After an extensive investigation, the conclusion was that the primary cause of the problem was the occurrence of an erroneous signal output from the yaw-axis rate gyro. In responding to the rate gyro error, a crewman probably inadvertently placed the mode switch in the automatic position and, thus, caused the large vehicle movements. This situation could possibly have been avoided by the use of larger toggle switch displacement angles (i. e., by providing better switch-position indexing). For future efforts, displacement angles that are greater than the 17° used on Apollo missions should be provided.

Apollo 11 Mission

The Apollo 11 mission was the first lunar-landing mission. With it, the basic goal of the Apollo Program — landing man on the Moon and returning him safely to Earth — was accomplished. Once more, both spacecraft performed well, and only a few relatively minor D&C problems occurred.

The CM had two problems with the D&C. The first concerned the mission timer, which ran slowly and developed cracks in the glass face. Both these problems had occurred previously and were attributed to electromagnetic interference and to manufacturing-induced stresses, respectively. Because of the history of problems and the failure of the identical LM timer during this mission, a redesigned timer was procured for use on future CM and LM vehicles.

The other CM D&C problem was the failure to illuminate an EL segment on the EMS delta-velocity/range counter. This failure was believed to have been caused by the misrouting of logic control wires across a terminal strip having sharp wire ends. These sharp ends punctured the wiring insulation and caused short circuits to ground. The numerous successful operations experienced until that time indicated that the

failure was probably neither a generic nor a design problem. To lessen the probability of a repeat failure, all test and checkout procedures were examined to determine whether or not improvements could be made toward further ensuring the proper operations of all EL segments.

Three D&C-related anomalies were encountered in the LM. The first occurred shortly after touchdown when the mission timer stopped and could not be restarted. Power to the timer was turned off. Approximately 11 hours later, the crewmen successfully restarted the timer. The timer functioned normally for the remainder of the mission. Previous experience with the timers indicated that the most probable cause of failure was a cracked solder joint caused by differential thermal expansion within the cordwood construction of the timer. Because the existing timers were not suitable for redesign, new timers, which were mechanically and electronically interchangeable with the existing ones, were designed for both the LM and the CM. These new timers were installed on the Apollo 13 spacecraft and subsequent vehicles. A timer of the earlier design was flown on the Apollo 12 spacecraft because of schedule considerations.

The second LM D&C failure was of an EL segment in the AGS DEDA. The segment failure made it impossible to differentiate between a "3" and a "9" on the third digit of the display. This failure did not make the DEDA unusable but did cause some ambiguity in the readout. The exact cause of the failure could not be determined, but the conclusions and recommendations were the same as for the similar CM EL failure discussed previously.

The third LM D&C anomaly did not result in any operational degradation but was potentially the most hazardous situation. On completion of the lunar surface extravehicular activity (EVA), the crewmen discovered that the knob of the engine-arm circuit breaker was broken off and that two other breakers had been closed. Fortunately, the damage did not prevent closing of the engine-arm circuit breaker for ascent, but loss of the knob did mean that the breaker could not have been manually opened if required. The most probable cause of the damage was an impact from the oxygen purge system of the extravehicular mobility unit during EVA preparation. Postflight investigations in an LM mockup demonstrated the possibility of such an impact, even though the LM circuit breaker panels were terraced by design to provide protection. For the Apollo 12 LM and succeeding lunar modules, an extended barrier guard was added to the edge of the circuit breaker terraces.

CONCLUDING REMARKS

Proven aerospace design practices and components, which were modified only as required to meet the unique aspects of the Apollo missions, were used in the development of the Apollo displays and controls system. Although a few display and control malfunctions occurred on each flight, none of these failures placed either the crewmen or the mission in jeopardy. The redundancy designed into the displays and controls system ensured both crew safety and mission success in all cases. Generally, the performance of the displays and controls system was excellent.

The Apollo experience was an indication that most of the Apollo displays and controls philosophies and designs would be applicable to future vehicles, and their use would facilitate both development and operations. Recommendations for improvements and the identification of problem areas are made throughout this report. Three of the more significant recommendations follow.

1. The displacement of toggle switches should be increased from the nominal 17° used on Apollo spacecraft.
2. Flag indicators should be powered in each active position whenever possible.
3. Service wire loops or access to the rear of displays and controls panels should be provided to aid checkout and maintenance.

To aid in future design efforts, a series of displays and controls functional requirements specification documents has been prepared and is available from the NASA Lyndon B. Johnson Space Center (formerly the Manned Spacecraft Center). These specifications, based on manned spacecraft experience to date, cover the basic considerations, criteria, and parameters of benefit to a displays and controls systems designer.

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