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APOLLO EXPERIENCE REPORT - CREW STATION INTEGRATION

Volume V - Lighting Considerations

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16. Abstract

The lighting requirements for the Apollo spacecraft are presented. The natural lighting factors are discussed in terms of major constraints. A general description of the external and internal lighting systems for the command and lunar modules is presented with a discussion of the primary approach and design criteria followed during development. Some of the more difficult problems encountered during the implementation of a new lighting system are reviewed.

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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 lunar landing mission of July 1969. This time period 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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APOLLO EXPERIENCE REPORT

CREW STATION INTEGRATION

VOLUME V - LIGHTING CONSIDERATIONS

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SUMMARY

The internal and external lighting for the Apollo spacecraft required a high level of quality and reliability to ensure excellent readability of the displays and controls during the mission. The lighting hardware was designed to withstand the high vibration and acceleration during launch and to function for the duration of the mission in the extreme environments of space.

The lighting system requirements were based on many studies and lighting evaluations. The Apollo lighting system consisted of two major categories: the internal lighting system, which included all integral displays and controls lighting and general interior floodlighting; and the external spacecraft lighting, which included illumination aids for rendezvous and docking, extravehicular activity, and work stations. Integral lighting refers to the methods of lighting display and control panels and instruments from within.

The general illumination in the command module was provided by fluorescent lamps and in the lunar module by incandescent lamps. For the integral displays lighting in both vehicles, electroluminescent lamps were used, which was the first application of backlighting of the complete instrument panel in spacecraft and the first extensive use of electroluminescent lighting by the aerospace industry. The external spacecraft lighting used on both the command and lunar modules consisted of orientation lights, extravehicular activity lights, and a docking floodlight located on the command module. These lights were incandescent. To aid in visual tracking, a xenon flashing light was provided on both vehicles. The docking target on the lunar module and the extravehicular activity handrails on the command module were illuminated by radioluminescent disks. For the docking target on the command module, a combination of electroluminescent and incandescent lamps was used.

Many lighting studies and mockup evaluations were conducted to assure that the lighting conditions were appropriate for adequate monitoring of subsystem performance. The type of lighting fixture, the locations, and the light intensity to be used in the two Apollo vehicles were established by the lighting studies and mockup evaluations.

The major problem encountered was with the use of electroluminescent lamps, a relatively new lighting source. Because these lamps were installed directly into the panels, sizing and shaping of the lamps to specific areas required very close manufacturing tolerances to achieve optimum light output from the displays.

The Apollo lighting system was highly successful as a result of continuous reviews and mockup evaluations of new state-of-the-art design and the capability for controlling the design interface between lamp manufacturers and hardware contractors. Also of importance was the early utilization of lighting laboratory calibrations and standardization of the light spectrum distribution within both the command and lunar modules.

INTRODUCTION

Successful execution of the Apollo lunar landing mission required that the crew properly perform a variety of visual tasks. Many of these tasks depended heavily on the performance of spacecraft illumination subsystems or devices. The lighting hardware had to function adequately for the duration of the mission in extreme environments ranging from sea-level conditions to the vacuum of deep space.

Spacecraft lighting presented problems unique in the illumination industry. For example, each pound of equipment required approximately 500 pounds of fuel for a round trip to the moon. Materials had to be qualified by numerous tests to determine that they could withstand the severity of the space-flight environment, particularly acceleration and vibration levels that obviously exceed those in most present lighting environments. Reliability and redundancy were of major importance when the level of artificial light had to range from high candlepower (for alarm lights, which had to be seen with peripheral vision during periods of high acceleration) to total darkness during space observations (requiring the elimination of sunshafting inside the vehicle). These criteria had a primary effect on the choice of lighting systems for the Apollo command and lunar modules.

APOLLO LIGHTING REQUIREMENTS

The lighting requirements for the command module (CM) and lunar module (LM) were established to maintain the eye adaptation necessary for crew tasks. Eye adaptation refers to the visual adaptation of the eye when exposed to different ambient light levels. The lighting system parameters were based on the following criteria.

1. Task analysis to define critical visual tasks

2. Vehicle design and performance

3. Internal/external illumination relationships

4. Considerations of operator fatigue

5. Optimum system performance and maximum reliability

After studies were conducted at the NASA Manned Spacecraft Center and by personnel of two contractors, and after lighting evaluations had occurred in mockups at the contractor facilities, the following items and lighting requirements were recommended and incorporated into the lighting system of the Apollo command and lunar modules.

1. White lighting, for use in cases when cone vision and color perception were needed and when the lighting power requirements had to be low

2. Integral lighting, for lighting uniformity and minimal glare

3. White electroluminescent (EL) lighting (at 0.5 ± 0.2 ft-L), for nomenclature and meters

4. Green EL lighting (at 15 ± 3 ft-L), for improved contrast in numeric readout displays

5. Incandescent master alarm warning lights (at 150 ± 50 ft-L)

   a. Caution and warning (50 ft-L)

   b. Component caution (15 ft-L)

6. Continuous dimming, to provide dark adaptation during guidance and navigation operations and to maintain legible indicators for continuous monitoring

7. Floodlighting, as orientation and backup to integral lighting

The master alarm system and the caution and warning system used incandescent lighting because of the higher light levels required.

The test evaluations and results determined the type of lighting to be used for the Apollo spacecraft. The internal and external lighting requirements, the component type, the lighting used, the luminance intensity of the lighting, and the color specification are presented in table I.

TABLE I. - ILLUMINATION COLOR AND BRIGHTNESS

Component	Primary lighting method	Transillumination color	Brightness at rated capacity, ft-L	Brightness adjustment, ft-L	Color under incident illumination
			Internal		
Pushbuttons — panel nomenclature displays and controls (D&C)	Integral EL preferred	White, lunar white, CIE[a] coordinates $X = 0.330 \pm 0.030$ $Y = 0.330 \pm 0.030$	0.5 ± 0.2	Continuous from 0 (0.01 minimum)	Control panels Gray 36231 Pushbuttons Background: black 37038, gray 36076 Characters: white 37875
Master alarm	Integral (incandescent)	Aviation red (per MIL-C25050A)	100^{+50}_{-20}	Fixed	Background: translucent gray 36076, white 37875 Characters: black 37038
Warning annunciators	Integral (incandescent)	Aviation red (per MIL-C25050A)	50 ± 10	Continuous from 1.5 ± 0.5	Background: translucent gray 36076, white 37875 Characters: black 37038
Caution annunciators	Integral (incandescent)	Aviation yellow (per MIL-C25050A)	50 ± 10	Continuous from 1.5 ± 0.5	Background: translucent gray 36076, white 37875 Characters: black 37038
Component caution	Integral (incandescent)	Aviation yellow (per MIL-C25050A)	15 ± 3	Continuous from 0.05 ± 0.02	Background: translucent gray/white
Status annunciator	Integral (EL or incandescent)	Aviation white	10 ± 3	Continuous from 0.02 ± 0.01	Background: translucent gray 36076, white 37875 Legend: black 37038
Advisory annunciator	Integral (EL or incandescent)	Aviation white or green	10^{+2}_{-3}	Continuous from 0.02 ± 0.01	Background: translucent gray 36076, white 37875 Legend: black 37038
Flags, two-position	Integral (EL)	White, $X = 0.330 \pm 0.030$	0.5 ± 0.2	Continuous from 0	Energized: alternate black 37038 and white 37875 striping Deenergized: gray 36231
Flags, three-position	Integral (EL)	White, $X = 0.330 + 0.030$	0.5 ± 0.2	Continuous from 0	Malfunction: red velva-glo or equivalent; if labeled; letters: black 37038 on gray 36231 Energized: alternate black 37038 and white 37875 striping Deenergized: gray 36231
Meter (color coding of lighted D&C)					
Pointers	Silhouette or EL floodlight (integral)	--	--	--	Black 37038, yellow 33538, red (rocket)
Indexes	Integral (EL)	White, $X = Y = 0.330 +$ 0.030	0.5 ± 0.2	Continuous from 0	Black 37038, white 37875
Characters	Integral (EL)	White, $X = Y = 0.330 \pm$ 0.030	0.05 ± 0.2	Continuous from 0	Black 37038, white 37875
Time-shared labels and multipliers	Integral (EL)	Green, wavelength: 5000 to 5300 Å	8 minimum	Continuous from 0	--
Range markings	Integral (incandescent)	Aviation green	20 ± 5	Continuous from 0	--
Display malfunction indicator lights	Integral (incandescent)	Aviation red (per MIL-C25050A)	20 ± 5	Continuous from $0.05 + 0.02$	Translucent gray/white
Circuit breaker	Flood	White, $X = Y = 0.300 \pm$ 0.03	0.5 ± 0.2	Continuous from 0	Background: black 37038 Characters: white 37875
Alphanumeric read-outs	Integral EL	Green, dominant wavelength: 4900 to 5300 Å	7 to 18	Continuous from $0.02 + 0.01$	Background: gray 36076

[a]International Commission on Illumination.

TABLE I. - ILLUMINATION COLOR AND BRIGHTNESS - Concluded

Component	Primary lighting method	Transillumination color	Brightness at rated capacity, ft-L	Brightness adjustment, ft-L	Color under incident illumination
		Internal			
Self-luminous devices, switchtip	Radioluminescent (RL)	Green, wavelength: $5150 {}^{+250}_{-100}$ Å	Initial, 0.1 ± 0.02 At launch, $0.05 {}^{+0.02}_{-0.03}$	Fixed	Pale green
Low-level floodlighting	Incandescent or fluorescent	White, unfiltered	5.0 ± 2	Continuous from 0	Illuminance A or better
High-level floodlighting	Incandescent or fluorescent	White, unfiltered	30 ± 10	--	--
CM utility light	Portable, incandescent	White, unfiltered	[b]0.2 minimum at 3 ft	Fixed	--
LM utility light	Portable, incandescent	White, unfiltered	[b]5.2 at 3 ft	[c]25 to 17, 15 to 7	--
		External			
Orientation lights (running):					
Port (left)	Incandescent	Aviation red	[d]0.15 minimum	Fixed	--
Starboard (right)	Incandescent	Aviation green	[d].15 minimum	Fixed	--
Aft	Incandescent	Aviation white	[d].25 minimum	Fixed	--
Bottom	Incandescent	Aviation yellow	[d].25 minimum	Fixed	--
Forward	Incandescent	Aviation yellow/white	[d].25 minimum	Fixed	--
Docking floodlight	Incandescent	White, unfiltered	[d]7500 minimum	Fixed	--
Tracking light	Xenon	White	Dependent on detection range requirement[e]	Fixed	--
Extravehicular activity lighting	Incandescent and/or RL	White Green	[b]0.6 ± 0.2 at 3 ft 0.2 ± 0.1	Fixed	--
LM docking target	RL	Green, $5150 {}^{+250}_{-100}$ Å	0.6 ± 0.1 at launch	Fixed	--
CM docking target	Background EL Cross incandescent	Green Red	High, 17 to 22 Low, 7 to 10	Two levels	--

[b]Foot-candles.

[c]Volts.

[d]Candlepower.

[e]The CM light is 160 beam c-sec, giving a detection range of 50 nautical miles; the LM light is 1000 beam c-sec, giving a detection range of 120 nautical miles.

APOLLO LIGHTING SYSTEM

The Apollo lighting system consisted of internal crew station lighting and external spacecraft lighting. The internal lighting system provided ambient light for activity in the couch and lower equipment bay; for reading panel nomenclature, indicators, and switch positions; and for tunnel activities. The spacecraft external lighting system furnished artificial light for extravehicular activity (EVA), rendezvous, docking, optical tracking, and recovery aid after splashdown.

Internal Lighting

Two types of internal lights were used on the CM and LM, and the same systems were used on both spacecraft, except where differences are noted in the following discussion. The primary lighting of the display and control (D&C) area of the Apollo spacecraft was by transillumination, which is a type of panel lighting in which the light is emitted from behind the panel (figs. 1 and 2). Apollo represents the first application in spacecraft of back illumination of the complete instrument panel (nomenclature, instruments, dials, etc.). The primary colors used on both spacecraft were white for nomenclature and instruments, green for alphanumerics, red for warning, and yellow for caution. Three methods of lighting were used within the spacecraft: self-illumination; incident-direct floodlighting, including wedge lighting of meter faces; and transillumination. In general, these three methods were used to provide lighting of indicators, controls, read-outs, displays, system switches, nomenclature, annunciator (signal device commanding attention usually by visual and auditory means) pushbuttons, and signal lights. The white nomenclature, instrument, and control lights had a maximum brightness of 0.3 to 0.7 ft-L; the green alphanumeric read-outs had a maximum brightness of 8 to 18 ft-L. The crew could dim the integral lighting system from the maximum to near zero (0.01 ft-L).

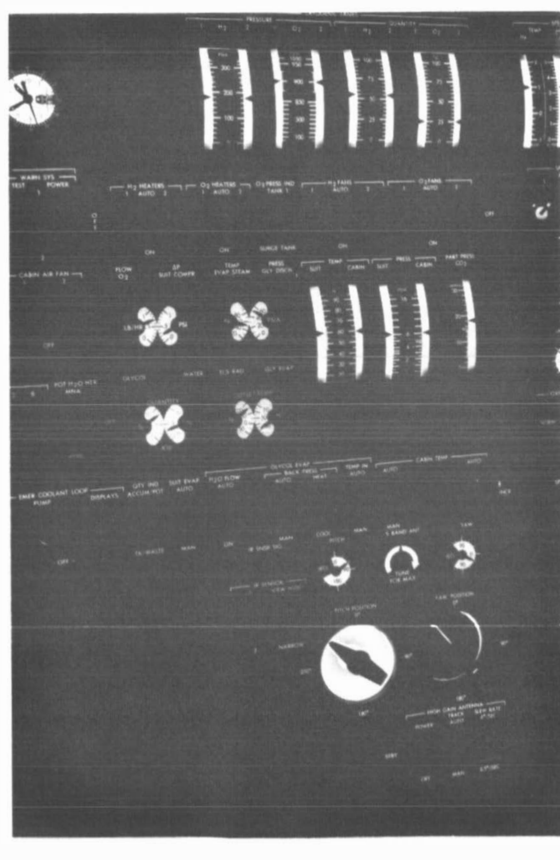


Figure 1.- Command module control and display panel lighting.

The secondary lighting system on the Apollo spacecraft consisted of floodlights (figs. 2, 3, and 4). The LM floodlighting system used incandescent light and was primarily a redundant, secondary lighting system in case of panel and instrument integral lighting failure. The

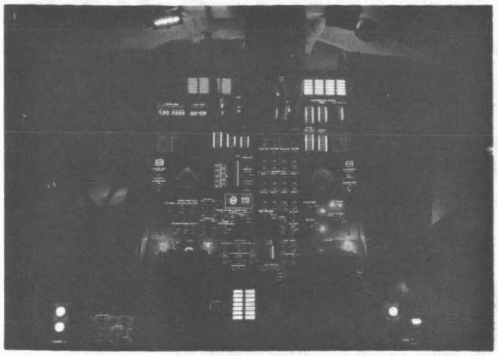


Figure 2. - Lunar module control and display panel lighting and floodlight.

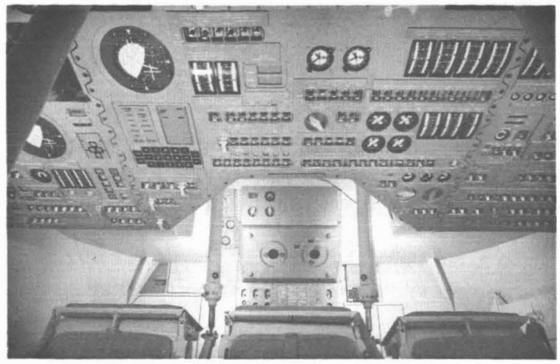


Figure 3. - Command module display panel, illuminated by floodlights.

Figure 4. - Command module floodlighting system.

illumination intensity of the display panels was relatively low but was not less than 0.2 ft-c on the main display panel. The CM floodlighting system was part of the total primary lighting system; therefore, the floodlight intensity for the CM was considerably higher than that for the LM, having a nominal brightness of 30 ft-L.

Before the adoption of the relatively new EL lighting system for the Apollo spacecraft, the relative merits of the system had to be determined. Color matching and balance had to be achieved, and minimal brightness levels had to be maintained throughout a mission.

Integral lighting. - Transillumination on D&C panels and instrument lighting in the Apollo vehicles was provided by EL lighting. Of chief concern were the behavior of the EL lamps under the effect of burning time, temperature, frequency, and voltage; the effect of manufacturing process reproducibility on such factors as lifetime, brightness, and color; and an accurate system with which to measure the effects.

The burn history of a green EL lamp used in the LM-3 vehicle is shown in figure 5. Specifying brightness, color, and minimum life is not enough; a burn-in period is required. This initial period depends on the particular manufacturer of the EL lamp and the range of lifetime curves that can be expected as a result of the degree of reproducibility of the EL-lamp manufacturing processes. A burn-in time is chosen at the point on the curve at which the slope begins to level off so that brightness stability can be expected during the mission. Because of brightness decrease, calculations are made so that, by the end of the mission, the brightness will not fall below the minimum 0.2 ft-L necessary for visual acquisition.

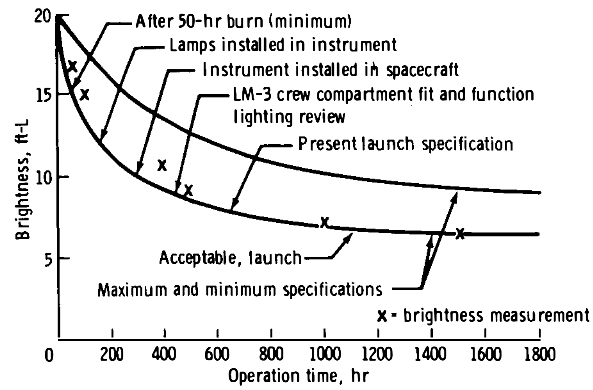


Figure 5. - Brightness aging characteristics of green EL lamps.

If the brightness values of the lamp permit, the rated voltage on the lamp may be set at some value lower than that recommended by the manufacturer. The voltage may then be increased as the lamp efficiency decreases, thereby retaining original brightness values and effectively increasing the life of the lamp. Apollo EL lighting was operated at 75 volts rms and 400 hertz, but the voltage could be increased to 115 volts.

The effect of temperature on EL lifetime was of concern in the Apollo Program because possible temperature limits for the EL lighting range from 45° to 145° F. The deterioration of EL lighting at 145° F is very rapid if the lamps are on. However, by supplementing the EL lighting with floodlighting during extreme environmental conditions, the EL lifetime can be extended throughout the mission.

The required brightness on the EL panels and instruments generally was 0.5 ± 0.2 ft-L at 75 volts rms and 400 hertz after 50 to 100 hours of burn-in time. These values were not difficult to attain, although differences between brightness measuring meters varied considerably. The brightness variations of prototype panels had ranged ±30 percent of nominal brightness over the panel. Measurements in the LM-3 to LM-5 flight vehicles reverified this range. The Apollo crews commented that the EL integral lighting was very good.

Dimming all the EL lighting with one control was neither possible nor desirable on the CM or LM. The green EL alphanumerics, which required much higher brightness for proper contrast with floodlight illumination, had to be dimmed separately. The dimming characteristics of the alphanumerics control shaft are shown in figure 6; this shaft also controlled the brightness of the annunciators through a special circuit.

Difficulty was experienced in providing proper lighting for toggle switches to be used under dark adaptation, for which most of the EL integral lighting was intended. On the CM, it was determined that edge spillover from the EL panels was sufficient for this purpose. On the LM, radioluminescent (RL) disks were mounted in the toggle switches. The radioactive source for the radioluminescence was promethium-147. The intensity of the RL lighting was 0.09 to 0.1 ft-L at launch. The half life of the RL disks was 18 months. The promethium was encapsulated inside the acrylic toggle switches. When the acrylic was changed to Kel-F, a fire-resistant material, a reaction between the Kel-F and the radioactive source developed which resulted in radioactive leakage. This condition was corrected by encapsulating the radioactive source in glass capsules and sealing the capsules into the Kel-F toggles.

The driving frequency on the EL lamp affects color and brightness. The brightness effect caused by frequency changes has been published in the manufacturers' brochures and has been proved to be linear. At 75 volts, a green EL lamp will change

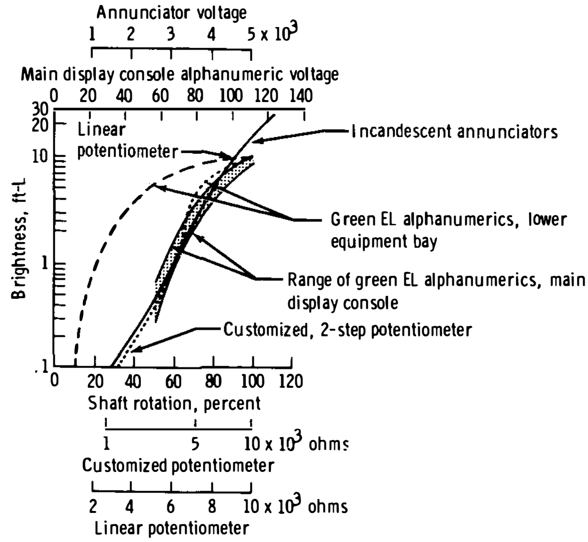


Figure 6. - Dimming characteristics of CM alphanumerics control shaft.

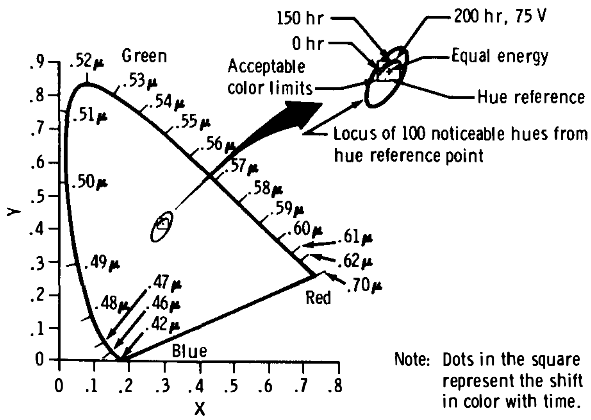


Figure 7. - Eye sensitivity to Apollo white lighting.

approximately 0.01 ft-L for a variation of 1 hertz in driving frequency. Frequency was controlled to ±7 hertz in the Apollo spacecraft. Brightness could vary initially ±0.05 ft-L, assuming a filter transmission of 70 percent. The effect of frequency variation upon the color of the EL lamps has been published in the manufacturers' brochures. With a ±7-hertz variation, the Y coordinate for the green EL lighting was expected to change by ±0.001, and the X coordinate was expected to change by much less. In this case, X and Y coordinates refer to the interaction of a point on the International Commission on Illumination (CIE) chromaticity chart that specifies the dominant wavelength of the light (no units used).

Color drift occurs during the lamp lifetime. The extent of drift by one lamp is shown in figure 7. Although it is evident that most lamps will drift beyond specified tolerances, the drift is expected to be uniform and toward the same wavelength region. Also indicated in figure 7 is the fact that, although X and Y tolerances on the white EL lighting are reasonably close to the present state of the art, visually matching the lighting hues of the different instrument vendors is nearly impossible because the human eye is extremely sensitive to color differences.

The effect of voltage variation on EL lamp brightness is an order of magnitude greater than the effect of frequency. Brightness changes at the rate of 0.025 ft-L for each volt of driving-voltage change at the 75-volt region of operation. This fact was significant primarily in the qualification and acceptance test because the accuracy of measuring the driving voltage had to be controlled carefully. Otherwise, with a measurement accuracy of ±0.02 ft-L, a ±4-volt tolerance at 75 volts would vary brightness by 0.5 ± 0.10 ft-L and thereby defeat the ±0.2-ft-L tolerance.

Inherent inefficiency of edge lighting presented some problems with brightness qualification on the face of the meters when EL lighting was used. White EL brightness at 75 volts and 400 hertz averages approximately 2 ft-L after burn-in. At least 12 square inches of EL lighting were required to obtain candlepower comparable to that of a grain-of-wheat lamp, which is a miniaturized incandescent lamp about the size of a grain of wheat.

The efficiency of EL lighting as a transilluminant on the panels averaged 15 mW/in^2 of lamp at 75 volts rms and 400 hertz, or 40 mW/in^2 at 115 volts. These figures were obtained from statistical data from all the lamps on the panels.

The most difficult problems in the use of EL panels were the shape and sizing of the EL lamps, the tolerances required by the lamp manufacturer, and the manufacturer's ability to produce lamps with unusual shapes. Generally, the lamps fell into the following four major groups.

1. The group 1 lamps were used for circuit-breaker panels and were made as long as possible and to the width required to light the legends on the panels. In some cases, the length of the lighted area exceeded the lamp manufacturer's production capability. In these cases, two or more lamps were used, and the spaces between lamps were placed to correspond with the open areas of the panel (areas without letters).

2. The group 2 lamps contained holes or cutouts to provide access areas for switches, potentiometers, and rotary devices. These lamps had to be designed to light all legends and also to allow the lamp manufacturer enough unlighted areas to hermetically seal the lamp.

3. The group 3 lamps were unusually shaped, with thin sections, thick sections, cross shapes, and L shapes, and had square or round cutouts within them.

4. The group 4 lamps were small, individual lamps, 3/16 by 7/16 inch to 1/4 by 3 inches in size.

The group 1 lamps did not present any significant problems in the design stage. Group 2 and 3 lamps required great care in locating the circuit areas or unlighted areas as well as in selecting the tolerances allowed to the lamp manufacturer. It was discovered that no attempt should be made to design lamps of less than 3/4 square inch in size in lighted areas; smaller lamps would not meet the illumination-intensity specification.

The lamp terminals presented problems; "standard" terminals were not usable for flight application because the reliability was less than desirable. The wire mesh broke quite easily and the grommets became loose, resulting in a poor electrical connection. Phosphor bronze wire mesh embedded in the lamination was used. A plastic tophat was placed on the lamination to accept the number 26 wiring, and silver threads were embedded in the phosphor to reduce line drop. As a result of EL lighting degradation with temperature increase, another problem developed with the use of EL within flight instruments. The specification on flight instruments was 160° F, but the older EL lamps were reliable only to 140° F. The lamp manufacturer modified the lamps, and they then were qualified for the 160° F temperature environment. These new lamps were used for the first time on the LM-5 flight vehicle.

The use of EL lighting for wedge lighting on instruments presented some problems. For example, problems were encountered in the lighting used in the flight director attitude indicator. When EL lighting was used to illuminate a sphere from the side, the center of the sphere remained dark, and uniform illumination was not obtained. The problem was resolved by using an EL light with a thick center and a narrowing area or wedge toward the side.

Other problems were encountered on the Apollo spacecraft, but they were similar to the problems previously discussed and, therefore, will not be mentioned in this report.

Floodlighting. - Floodlighting in the Apollo spacecraft began with the conventional incandescent source. However, subsequent vibrational and heat-dissipation tests discouraged the use of this type of lighting in the CM in favor of a more efficient and rugged type. The incandescent source was maintained in the LM, and an isolation mount was used to produce the qualification of the units under the Apollo launch vibration (fig. 8). The LM floodlighting system was composed of white incandescent lamps, as follows.

1. Overhead lights, one each above panels 1 and 2 (fig. 2)

2. Forward lights, one each above panels 5 and 6 (fig. 2)

3. Side-panel lights, a total of 31 lights above the rows of side-panel D&C

The overhead and forward lights had dimming capability; the side-panel lights did not.

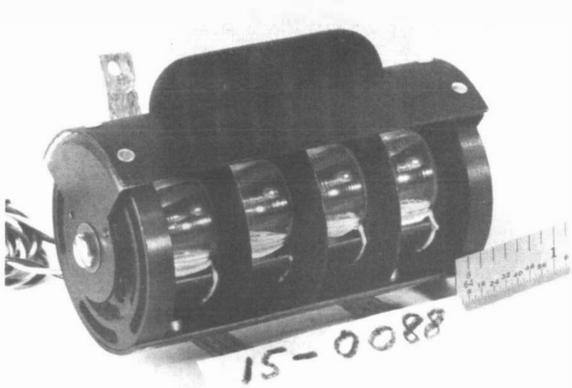


Figure 8. - Lunar module floodlight.

A tubular fluorescent lamp (fig. 4) was used in the CM. This lamp is frequency sensitive; but, through special circuits, is operable from a 28-volt dc source. A converter within the light fixture altered the 28 volts dc to ac. The electronic components were solid state to minimize weight. Noise problems (both aural and electronic) are inherent but were eliminated satisfactorily by the manufacturer.

The brightness level of the lamp was increased favorably during the 2 years of development. The initial value was greater than 2100 ft-L. This brightness was increased to 5000 ft-L by increasing efficiency and by changing tube diameter and length, which produced not only a higher level of total luminous flux output but also higher brightness levels. Specified color coordinates for the floodlights were X = 0.365 to X = 0.425 and Y = 0.365 to Y = 0.400, chosen to simulate incandescent color, which gives a natural appearance to the color of the skin.

The CM floodlights provided illumination primarily for the D&C panels and lower equipment bay and for general activity within the spacecraft. The lights were also redundant with the integral lighting. A secondary system was integrated within the primary floodlighting system for redundancy and for added illumination during high-gravity conditions. Required illumination levels approached 60 ft-c at the highlight areas of the panels, with the use of both primary and secondary systems.

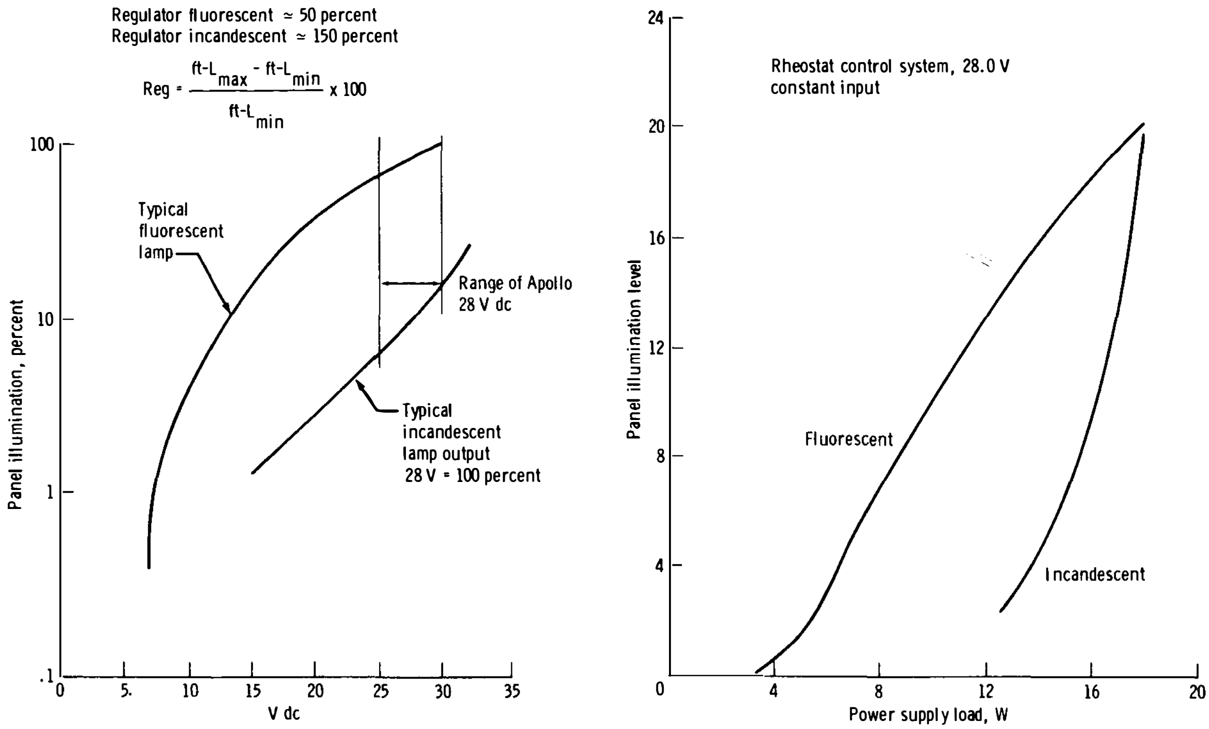
During the Apollo 9 flight, the crew objected to the high temperature of the floodlight lens. When both lamps were operating in a 5-psia zero-g environment, the lens temperature reached 170° F. An evaluation was conducted of the lens temperature effect on the crewman's touch. The results of the evaluation are summarized as follows.

Temperature	Result
130° F	Not objectionable.
145° F	Distracting thermal shock. Can be touched for 5 to 8 seconds.
170° F	Very hot, burning sensation. Can be touched for 1 to 3 seconds.

Subsequent to the touch temperature evaluation, the procedure was modified for single lamp operation, using the dual lamps only when high level illumination was required. With a single lamp operating, the lens temperature reached a maximum of 130° F. If the secondary lamp was energized while the primary was operating, the time required for the lens to reach 170° F was approximately 30 minutes. On future programs, the operational temperature of equipment that interfaces with the crew should be closely examined during preliminary design phases and followed throughout hardware development.

Dimming controls were provided for the primary floodlighting system, while an on-off control was provided for the secondary system. Dimming characteristics of a fluorescent lamp, as compared to an incandescent lamp, are shown in figure 9. The curves indicate the greater efficiency and a saturation level of light output for the fluorescent lamp. Some hysteresis in light output was experienced but was minimized by additional circuitry. The lower light level attained before extinction was approximately 0.20 percent of maximum.

Because of several special projects during the mission, floodlighting in the CM had to serve more purposes than general illumination. Because it was desirable to observe the astronauts in a zero-g environment, illumination levels for television and film cameras had to be satisfied. During television camera testing in the CM mockup, the floodlights near the face of the center astronaut "blinded" the exposure control of the television camera, and satisfactory pictures were not obtained. An automatic exposure control that was sensitive to overall scene illumination (instead of small, bright areas of the scene) was used, but at the expense of a less sensitive vidicon tube.



(a) Dimming comparisons. (b) Dimming efficiency.

Figure 9. - Dimming characteristics of fluorescent and incandescent lamps.

Tunnel lighting. - Additional floodlighting was provided to furnish ambient lighting for crew activity in the tunnel region between the docked CM and LM. The primary activity within either tunnel was hard-docked crew transfer, and removal and replacement of the docking drogue and probe.

Three light fixtures, mounted on opposite sides of the tunnel approximately at eye level, were used in the CM. A pair of ruggedized lamps, which were the same lamps used in the annunciators located on the main D&C panels, were used in the light fixtures. The LM tunnel lighting was provided with the LM utility light.

Utility light. - Floodlighting would not be complete without a utility light or flashlight (fig. 10). Candlepower requirements depend on the intended use of the light. Subjective tests indicated that only 0.05 ft-c was needed to perform such tasks as finding an extra pair of socks. It also was indicated that 0.3 to 0.5 ft-c is sufficient for reading panel nomenclature and that 0.1 ft-c is sufficient for equipment stowage and retrieval and for removal of screws from panels. It was assumed that the astronauts are dark adapted and want to remain that way. Too much light could destroy dark adaptation. However, reading can be accomplished with the utility light by holding the light closer to the nomenclature.

Figure 10. - Command module/lunar module utility light and penlight.

It was decided that variable intensity should not be used on the CM utility light because of heat generation and energy waste by the rheostat. The intensity of the light was 1.0 ft-c at 1 foot. Only one light per crewman was provided in the CM, with an 8-foot cable that connected to a 28-volt dc outlet.

The LM general floodlighting was too low in intensity to provide sufficient illumination for reading flight plans, star charts, navigational data, and lunar landing maps. Therefore, the LM utility light was of greater intensity than the CM utility light. The maximum intensity of the utility light was 5 ft-c at 3 feet. Again, it was decided that variable intensity should not be used. Also, it was recognized that dimming would be mandatory; therefore, a two-step discrete dimming control was added. There were two utility lights in the LM, one for each crewman. The intensity of the command pilot's light (on the left side) was 5.0 ft-c (high) and 2.0 ft-c (low) at 3 feet, while the intensity for the lunar module pilot (on the right side) was 1.5 ft-c (high) and 0.5 ft-c (low) at 3 feet. Both lights had an 8-foot cable that connected to a 28-volt dc outlet. The base of the light had a universal clamp and ball. The light could be clamped to any interior LM structure 0.5 to 1.5 inches in diameter. During LM tunnel activity, one or both of these lights could be mounted on the tunnel structure to provide tunnel illumination.

Special lighting. - Each astronaut was furnished a penlight for activity in hard-to-see areas when one or two crewmembers were maintaining dark adaptation. The distribution pattern of this light at a distance of 2 feet consisted of an uneven hotspot (8 to 40 ft-c, average 15 ft-c) approximately 4 inches in mean diameter, surrounded by a dimmer area (0.15 ft-c) at 1 foot radius that extended to approximately 8 feet in diameter.

It was discovered that the life and reliability of the penlights were not good and that the operational life would vary from a few hours to several weeks. Therefore, three lights per crewman were stowed on board for redundancy and backup in case of failure. It would not be desirable to use this same penlight in future manned missions, although the concept of providing the crewmen individual flashlights is valid. A reliable medium-intensity flashlight should be part of the crew lighting inventory on all space missions to facilitate auxiliary lighting in hard-to-illuminate areas.

Sunshafting. - The effect of sunlight entering the windows presents a problem. At first, it may seem reasonable to use the sunlight for illumination. However, further analysis reveals that sunshafting through the windows is not desirable. Sunlight is nearly parallel, similar to a spotlight. Consequently, whatever is illuminated by sunlight within the crew compartment will be illuminated to the point that everything else will be nearly silhouetted. As the spacecraft turns, the position of the illuminated spot will move, perhaps into the face of the astronaut. Dark adaptation, which is necessary in several tasks, would be impossible. Also, the heat energy introduced into the spacecraft by the sunlight would have to be dissipated. Therefore, it was decided that, under normal conditions, sunlight would be eliminated completely from the crew compartment. The elimination of sunlight was accomplished by the use of opaque window shades.

Besides being opaque, the window shades also had to be highly reflective to prevent any additional heat energy from overloading the environmental control system for the crew compartment. A highly specular reflective material is usually a material of low emissivity, so that energy that is absorbed by the shade must be emitted principally from a nonreflective surface. Thus, the equilibrium temperature of the shade should be low enough that an astronaut can touch it without harm but not so low that the shade material is rendered ineffective.

The basic window-shade concept was a 1/32-inch-thick aluminum sheet configured to the shape of the CM window. The first 0.5 inch around the periphery had a Velcro seal for attachment to the window.

External Lighting

External lighting was provided on the Apollo spacecraft for rendezvous, stationkeeping, docking, optical tracking, EVA, and contingency extravehicular transfer.

Rendezvous and docking lighting.- The rendezvous and docking maneuver required interface lighting between the LM and the CM. External lighting (figs. 11 and 12) was used for detection, illumination, and attitude orientation. All of the lighting aids had been proved successful for rendezvous and docking during the Gemini Program. Both the LM and CM were equipped with a flashing xenon light. The light on the CM was mounted on the service module (SM) in the positive Z axis and 12° toward the positive Y axis (fig. 11). The cone of radiation was ± 60° (120°), which placed the upper edge of the cone parallel to the SM mold line. The intensity was 160 beam candle-second (c-sec)/flash. The unit, beam c-sec/flash, refers to the integrated intensity of a flashing-type lamp. At 60 nautical miles, the light is equivalent in brightness to a third-magnitude star. It could be detected with optical aids at 160 nautical miles. This light was a modification of the light used on the Gemini Agena Target Vehicle. To provide the longer visual range necessary, the light intensity was increased by changing the cone of radiation from ±80° (160°) to ±60° (120°) and increasing the voltage input to the light from 32 to 55 volts.

The LM tracking light was mounted between the two forward windows (fig. 12). This light must be acquired at a range of 400 nautical miles using the sextant. The tracking-light flash rate was 60 flashes/min, with a pulse width of 20 milliseconds. The light intensity was rated at 1000 beam c-sec/flash. Three range-detection evaluations were conducted on a prototype light to verify the maximum range. Two evaluations were conducted on the ground using neutral-density goggles to simulate ranges from 1 to 150 nautical miles. The third evaluation was conducted in an aircraft flight evaluation at an altitude of 25 000 feet. These evaluations confirmed that the light would be detected at 130 nautical miles visually and at 420 nautical miles with the aid of the CM sextant. On two Apollo flights, failures of the light occurred. The problem was

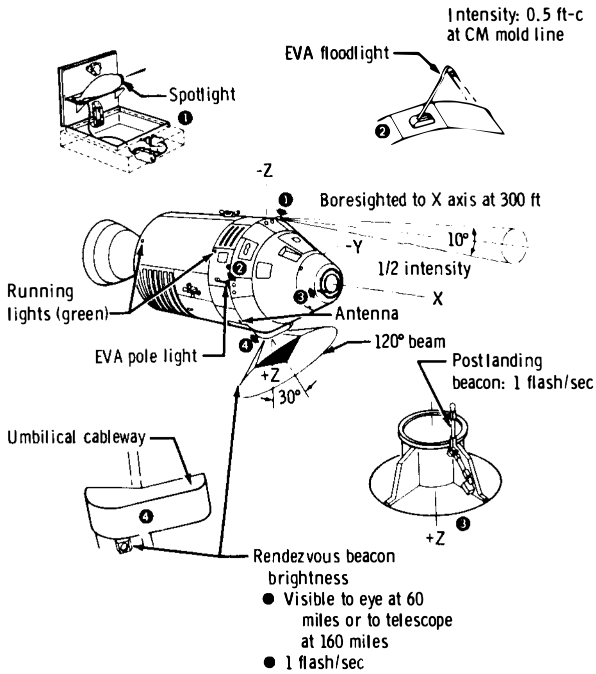


Figure 11. - Command and service module external lighting system.

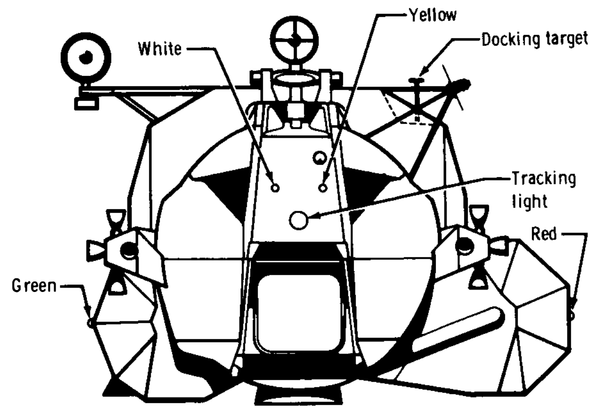


Figure 12. - Lunar module external lights, forward view.

insufficient protection at the lamp terminals, which resulted in corona and burning out the terminals. This problem was solved by providing better environmental protection to the lamp terminals and reducing the input voltage.

For orientation and altitude alinement at a distance of 1 mile to 500 feet, running lights were used on both the LM and CM (figs. 11 and 12). The color coding was the same as standard aircraft coding. There were eight running lights mounted on the CM/SM system. The four front lights were mounted on the CM adapter section, aft of the CM adapter/SM separation point. The four rear lights were located near the rear bulkhead of the SM. The following were the locations, colors, and intensities of the eight SM lights.

Color	Number of lights	Minimum intensity, cp	Location
Yellow	4	0.23	Bottom
Red	2	.15	Left side
Green	2	.15	Right side

The light fixtures consisted of five grain-of-wheat lamps enclosed within a lensed housing.

The same type of lights and color coding for orientation and altitude alinement were used on the LM, except that there were no lights at the bottom. The LM also had running lights fore and aft. The following were the locations, colors, and intensities.

Color	Number of lights	Minimum intensity, cp	Location
White	1	0.23	Aft
White	1	.23	Forward
Yellow	1	.23	Forward

There was concern about the color discrimination range of the running lights and about whether the crewmen could actually make positive discriminations between the red and yellow colors at 1000 feet. Therefore, tests were conducted at the Federal Aviation Administration fog chamber located in Oakland, California, to confirm that the running lights could be detected. The results of the test showed that the lights were detected at 2000 feet and colors could be discriminated at 1000 feet.

During the stationkeeping phase of the rendezvous and docking maneuver (500 to 50 feet), the crew must be presented a three-dimensional view of the passive vehicle. A spacecraft docking floodlight (fig. 11) was added to the CM to provide illumination of the passive LM during CM-active rendezvous. The light intensity was 8000-beam candlepower. The light was located on the EVA compartment door on the SM behind the command module pilot. The light illuminated the LM docking interface with 0.03 ft-c at 500 feet. The usable distance for stationkeeping was 500 to 50 feet.

The docking floodlight was originally the basic light used on the Gemini spacecraft. It was discovered early in the qualifications testing that the lamp and transformer mounting would not tolerate the high vibrations that were characteristic of an Apollo launch. Therefore, the light had to be mounted on a special isolation system to attenuate the vibration.

The docked CM/LM and the crewmen's line of sight were not coincident. Therefore, optical sights and suitable targets were provided to give cues for the docking maneuver from close range (75 to 50 feet) to soft dock (figs. 13 to 15). The crewman optical alinement sight (COAS) was a columniated reticle similar to a gunsight used on aircraft and was attached to the rendezvous window before the final docking maneuver.

The target in the CM was attached to the right rendezvous window before the docking maneuver. The LM target was fix-mounted outside the spacecraft. The targets provide a cue for the COAS. In this manner, proper orientation and spacecraft alinement were provided for docking. The CM target consisted of a base 8 inches in diameter and lighted by a green EL lamp, with a red incandescent cross placed 4 inches in front of the base to provide a three-dimensional effect. The cross was resolvable at 75 feet. The brightness of the target was 28 ft-L on high intensity and 17 ft-L on low intensity.

The LM target was twice the size of the CM target and was illuminated by RL disks. The disks were 5/8 inch in diameter with a 1/2-inch-diameter circular area of illumination. The intensity of the disks was 0.8 ft-L at time of launch. The half life of the RL disk was 18 months.

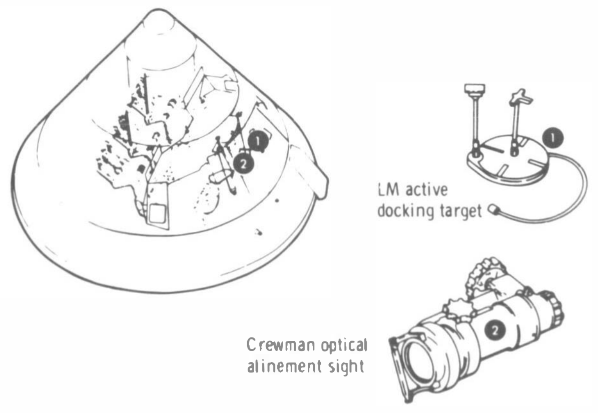


Figure 13.- Command module sighting aids.

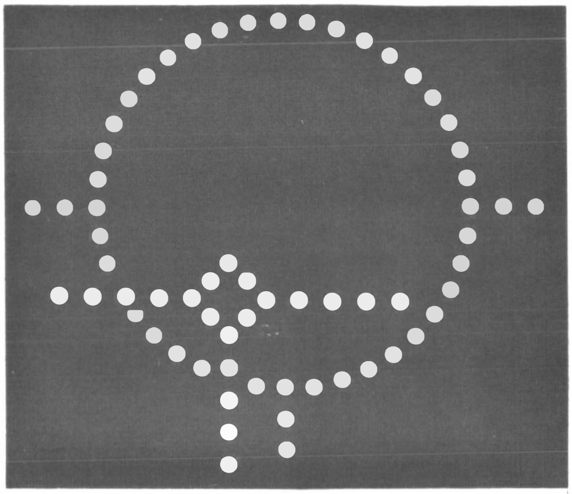


Figure 14.- Lunar module docking target.

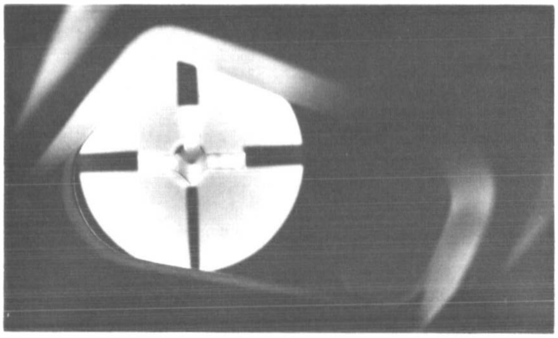


Figure 15.- Command module docking target.

The primary docking procedure was performed using sunlight reflections. All of the previously mentioned artificial illumination sources, excluding target, were used to provide visual aid to the crewmen during darkside contingency docking. The basic rendezvous and docking maneuver techniques were developed and verified during the Gemini Program. These techniques were used for docking the command and service module (CSM)/LM. One major change to the CSM/LM vehicle was the external thermal control coating and the increased geometrical complexity of the vehicle shapes. Both the CM and LM thermal control coatings were highly specular; for example, the CM was covered with aluminized Mylar and the LM with anodized aluminum. Coupling these vehicle reflection characteristics with the operational visual environment, where the incident light from the solar disk is collimated, the visually perceived details of the two vehicles change markedly as the relative positions of the viewed vehicle change in relation to the sun and the observer. These characteristics required definition for docking as a function of target vehicle and illumination environment relationships to determine limiting conditions for astronaut visual capabilities. The extreme complexity of the photometric phenomena involved in the docking maneuver suggested that simulation using vehicle models and a simulated solar source would be necessary to define the visual environment. Therefore, a contract was negotiated to conduct an Apollo illumination environment simulation. The study was divided into three major phases.

Phase I:

1. CSM/Saturn IVB (S-IVB) separation and turnaround, and CSM/LM docking and LM withdrawal from the S-IVB

2. CSM/LM docking at various solar incidence angles and viewing angles

3. Operational requirements for photographing the LM on the lunar surface

Phase II:

1. Apollo Lunar Surface Experiments Package (ALSEP) deployment

2. ALSEP visual "near-field" work area

Phase III:

1. Visual detection of the sunlit CSM and LM

2. Lunar horizon visibility

These studies provided the following support to the Apollo mission operation.

1. Removed the original sun constraint for LM withdrawal

2. Established a set of sun constraints where high reflective illumination would be a visual problem during docking

3. Provided the basis to establish sun/vehicle reflection conditions to demonstrate and explain the COAS washout problem that occurred on Apollo 9, resulting in a modification to the COAS (The Apollo 9 COAS problem is discussed in detail in later paragraphs.)

4. Provided information for the logical selection of the lunar surface modeling material used for the LM landing and ascent simulator

5. Established the exposure required for LM lunar surface photography, which reduced the original number of photographs of each area of the LM from four to two exposures

6. Provided the Apollo 11 and 12 crews with a set of training photographs

7. Resulted in two minor hardware changes to the ALSEP to establish maximum meter bezel heights for shadowing constraints and to establish reflectivity requirements for the modular equipment stowage assembly and ALSEP decals

8. Resulted in the relocation of the bubble on the passive seismograph

9. Provided maximum distance from which a sunlit vehicle may be detected, which provided backup navigational guidance data by optical tracking of the LM using sunlit reflections off the thermal control coatings during LM descent, ascent, and rendezvous

10. Established the range of LM specular reflectivity from the lunar surface so that specific access times could be determined for orbiting CSM sightings

The Apollo 9 rendezvous and docking profile was performed with spacecraft attitudes and sun angles that produced very bright specular reflections off the CM. This reflected glare impinged directly on the LM window and into the LM COAS, washing out the illuminated reticle. Two conditions that attributed to the washout of the reticle were the following.

1. The intensity of the COAS had been reduced by 90 percent with the addition of an internal neutral density filter.

2. Specular reflections off the CM caused excessive glare that impinged on the LM COAS optics with a flare ratio in excess of the design limits.

The intensity of the COAS was originally 1000 ft-L or more. This brightness would guarantee visibility against a background brightness of 10 000 ft-L. The Apollo 9 COAS full intensity was between 50 to 90 ft-L, which was too low to provide proper brightness compatibility between the COAS and the specular glare from the passive vehicle. This situation resulted in the crewman not being able to see the reticle against the brighter glare off the passive vehicle. Subsequent to the Apollo 9 experience, two changes were made, one in the design of the COAS and one in procedure.

1. The COAS was modified by removing the internal filter and remounting it outside the COAS and by providing a means of removing the filter in the event a brighter reticle is necessary. This change increased the full brightness of the reticle to 1000 ft-L.

2. Procedurally, if the docking profile dictates such a condition as occurred on Apollo 9, a passive or active vehicle roll attitude change will be initiated to preclude specular glare in the direction of the docking window of the active vehicle.

Extravehicular lighting. - Scheduled and contingency EVA operations required special extravehicular lighting. A single floodlight used to illuminate the CM/LM external area was mounted on the CM (fig. 16). The light was positioned between the right rendezvous window and side window by a 24-inch pole, mounted to the SM, that was extended automatically after the boost protective cover was jettisoned. The light fixture was the same as that used for the running lights except that the color filters had been removed. The light was oriented to illuminate the CM hatch, right-side EVA handrails, and LM EVA transfer handrails. The illumination of this light was 0.2 to 0.5 ft-c

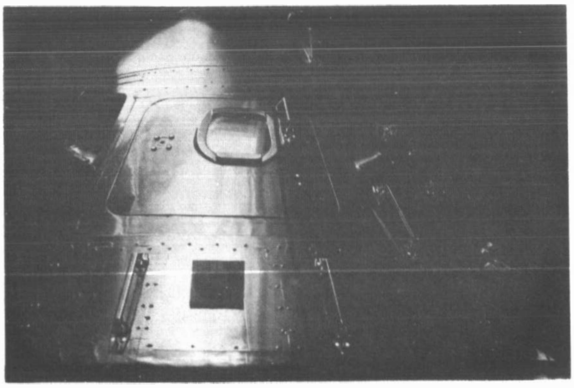


Figure 16. - Extravehicular activity light and handrail identification light.

on the CM mold line. This light also served as a docking floodlight to illuminate the CSM for LM active docking.

To aid the EVA astronaut in locomotion about the exterior of the CM/LM was a series of EVA handrails. Radioluminescent disks were used to aid the crew in locating the handrails as well as the environmental control system exterior dump valve and hatch-opening mechanism and handle. These disks were the same as those used on the LM target. The location of the disk on the EVA handrails is shown in figure 16. Two disks are mounted at each end on the handrail base.

CONCLUDING REMARKS

The following are the four types of lighting used on the Apollo lunar landing mission.

1. Fluorescent (with dimming capability achieved by varying voltage, frequency, and wave shape)

2. Incandescent (with and without dimming capability)

3. Electroluminescent (with dimming capability, ac voltage control)

4. Radioluminescent (such as promethium-147)

A conservative approach has been used in developing spacecraft lighting to satisfy Apollo illumination requirements. Although other ideas were considered, the primary design criteria for the Apollo lighting systems were reliability, crew safety, and minimization of spacecraft weight. Proven methods of illumination consistent with established aviation standards have been implemented when possible.

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National Aeronautics and Space Administration
Houston, Texas, November 9, 1972
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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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