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APOLLO EXPERIENCE REPORT - SIMULATION OF MANNED SPACE FLIGHT FOR CREW TRAINING

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16. Abstract

Through space-flight experience and the development of simulators to meet the associated training requirements, several factors have been established as fundamental for providing adequate flight simulators for crew training. The development of flight simulators from Project Mercury through the Apollo 15 mission is described in this report. The functional uses, characteristics, and development problems of the various simulators are discussed for the benefit of future programs.

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ACRONYMS

ALFA	air-lubricated free-attitude
CCA	contract change authorization
CCB	Configuration Control Board
CCP	Configuration Control Panel
CFE	contractor-furnished equipment
CM	command module
CMPS	command module procedures simulator
CMS	command module simulator
CRT	cathode-ray tube
CSM	command and service module
DCPS	dynamic crew procedures simulator
ECP	engineering change proposal
EIG	electronic image generator
EO	engineering order
FOV	field of view
GFE	Government-furnished equipment
GMS	Gemini mission simulator
KSC	Kennedy Space Center
L&A	landing and ascent
LCR	lunar module change request
LLRF	lunar landing research facility
LLTV	lunar landing training vehicle
LM	lunar module
LMPS	lunar module procedures simulator

LMS	lunar module simulator
MCC	Mission Control Center
MCR	manufacturing change request
MEP	mission effects projector
MPS	Mercury procedures simulator
MR	modification request
MSC	Manned Spacecraft Center
PDR	preliminary design review
RDS	rendezvous docking simulator
RECP	request for engineering change proposal
SCP	Simulator Control Panel
SCR	software change request
TDS	translation and docking simulator
TV	television
3-D	three dimensional

APOLLO EXPERIENCE REPORT

SIMULATION OF MANNED SPACE FLIGHT FOR CREW TRAINING

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SUMMARY

From the early phases of Project Mercury through the Gemini and Apollo Programs, flight simulators have been the key elements in the astronaut training programs. As the missions progressed in complexity, the sophistication, number, and variety of simulators employed for astronaut training were increased correspondingly. Through space-flight experience and evolution of the simulators to meet associated training requirements, several factors have been established as critical and basic for providing adequate flight simulators for crew training. Included in these factors are high-fidelity crew stations, especially in the area of controls and displays; accurate simulation of the spacecraft systems, including the guidance computer and navigation system; complete visual display systems for simulated out-the-window scenes; and certain moving-base simulators for high-fidelity training in particular portions of the missions. The significance of these factors for new programs will depend to a large degree on the mission objectives and requirements. Nevertheless, flight simulators incorporating some of these items in their design and operation will be vital in future astronaut training programs.

INTRODUCTION

In this report, "simulation" refers to the operation of trainers for instructing flight crews in the various control and monitoring procedures of manned spacecraft. The purpose of simulation for crew training is high-fidelity duplication of a wide range of inflight conditions and variables to obtain precise flight crew response to sophisticated and critical mission events. Repeated simulation exposure allows the crew to become proficient in interfacing with the flight hardware and ground-support elements, thus enhancing mission success and safety. In this context, a simulator is defined as a complex set of hardware (including computers, visual display systems, and simulated crew stations) that presents, with a high degree of accuracy, the total flight characteristics of the actual spacecraft and mission. Excluded from this classification are trainers that are full-scale spacecraft mockups designed primarily to refine crew tasks related to the handling of equipment in performing such activities as stowage, ingress and egress, maneuvering in zero-g and 1/6-g (lunar surface) conditions, handling photographic equipment, and general housekeeping within the constraints imposed by flight hardware and the space-flight environment. Although the remainder of this paper is concerned primarily with simulators, it is only proper to give recognition to these mockups that played such a significant and necessary role in complementing the simulator training for all major mission phases. A typical example was the extensive training program carried out for the Apollo lunar landing mission using full-scale mockups of the lunar module (LM) for lunar-surface training and of the command and service module (CSM) for ingress and egress and scientific instrument module training.

The topics of this report include some of the more significant aspects of space-flight simulation: crew-station fidelity, visual display requirements, moving-base simulations, and configuration management. The various topics relate primarily the experience gained in these areas of simulation since the beginning of manned space flight. It is hoped that future programs might benefit through discussion of this experience.

Credit for the separate sections of this report is given to those who, through their direct involvement with manned-space-flight simulation and training, were able to report firsthand the data contained herein. These individuals and their respective sections are as follows: C. H. Woodling and John J. Van Bockel, background and discussion; James R. Homer and John L. C. Mire, crew-station fidelity; Stanley Faber, visual display requirements; Wayne K. Williams, moving-base simulations; Charles C. Olasky, simulator configuration management; and C. H. Woodling, overall compilation and editing.

BACKGROUND

It is pertinent to preface these discussions with a listing of the crew simulators employed in support of manned space flight, to note the simulator use for training during each of the flight programs, and to discuss briefly the history of simulators from the beginning of Project Mercury.

The crew-training simulators used for Project Mercury and for the Gemini and Apollo Programs are listed in table I. These simulators are described in the appendix. The crew-training use of the various simulators throughout the flight program is presented in tables II and III. During Project Mercury and the Gemini and Apollo Programs, each crewman (on an average) spent one-third or more of the total training program time in simulations (table II). The crews of the lunar landing missions (Apollo missions 11 to 15) spent slightly more than 50 percent of their total training time in simulator training. In addition to the actual time spent in the various simulators, other training activities were accomplished in support of the simulator training. For example, the Apollo crews averaged more than 150 hours of systems briefings as a prerequisite to simulator training.

A breakdown of the simulator use by program and simulation facility is presented in table III. Progressing from Project Mercury through the Gemini Program to the Apollo Program, the number and complexity of the simulators increased. Also, it is interesting to note the increased emphasis on the mission simulators. The 708 hours spent by the crews in the Project Mercury procedures trainers represent approximately 53 percent of the total simulation time of 1330 hours. In the Gemini Program, the hours logged in the mission simulators are 67 percent of the total; and, in the Apollo Program, the command module simulator (CMS) and lunar module simulator (LMS) hours combined are 80 percent of the total of 29 967 hours spent in all Apollo simulations.

TABLE I. - FLIGHT CREW SIMULATORS

Simulator	Purpose
Mercury	
Mercury procedures simulator (2)	Primary spacecraft and mission simulator
Centrifuge (Naval Air Development Center, Johnsville, Pa.)	Moving-base simulator for launch, launch abort, and entry with associated acceleration environment
Air-lubricated free-attitude trainer	Moving-base simulator for multiple-axis pilot control tasks such as on-orbit attitude control, retrofire, and entry
Part-task trainer (2)	Retrofire and entry part-task training
Gemini	
Gemini mission simulator (2)	Primary spacecraft and mission simulator
Dynamic crew procedures simulator	Moving-base simulator for launch, launch abort, and entry
Translation and docking simulator	Moving-base simulator for formation flying and docking
Centrifuge (Naval Air Development Center, Johnsville, Pa.)	Moving-base simulator for launch, launch abort, and entry with associated acceleration environment
Apollo	
Command module simulator (3)	Primary CSM mission simulator
Lunar module simulator (2)	Primary LM mission simulator
Command module procedures simulator	Part-task procedures simulator for CSM rendezvous
Lunar module procedures simulator	Part-task procedures simulator for LM lunar descent and ascent including rendezvous
Dynamic crew procedures simulator	Moving-base simulator for launch, launch aborts, and entry
Translation and docking simulator	Moving-base simulator for LM-active formation flying and docking
Centrifuge (NASA Manned Spacecraft Center)	Moving-base simulator for launch, launch abort, and entry with associated acceleration environment
Lunar landing training vehicle (LLTV)	Free-flight training vehicle for final phase of lunar landing
Lunar landing training vehicle simulator	Familiarization with LLTV systems
Langley lunar landing research facility	Dynamic simulator (tethered) for final phase of lunar landing
Partial-gravity simulator (2)	Dynamic simulator for training in the 1/6-g lunar-surface environment

TABLE II. - SIMULATOR TRAINING SUMMARY

Program	Number of crewmen	Simulator time, hr (a)	Simulator time per crewman (average), hr	Total training program time, hr	Simulator portion of total training program time, percent
Mercury	7	1 330	190	4 038	33
Gemini	20	6 964	348	17 991	39
Apollo (through mission 15)	32	29 967	936	69 248	43
Total	59	38 261	--	91 277	42

[a] Exclusive of simulator prebriefings and postbriefings.

TABLE III. - SIMULATOR USE FOR FLIGHT CREW TRAINING

Simulator	Time per program, hr			Total time, hr
	Mercury	Gemini	Apollo (through mission 15)	
Mercury procedures simulator (2)	708	--	--	708
Air-lubricated free-attitude trainer	82	--	--	82
Multiple-axis spin test inertial facility	27	--	--	27
Part-task trainer (2)	175	--	--	175
Centrifuge	338	100	58	496
Gemini mission simulator (2)	--	4682	--	4 682
Dynamic crew procedures simulator	--	428	557	985
Translation and docking simulator	--	276	64	340
Part-task trainer	--	61	--	61
Rendezvous simulator	--	1417	--	1 417
Command module simulator (3)	--	--	14 584	14 584
Lunar module simulator (2)	--	--	10 672	10 672
Command module procedures simulator	--	--	1 008	1 008
Lunar module procedures simulator	--	--	753	753
Lunar landing training vehicle and simulator, lunar landing research facility[a]	--	--	949	949
Manned Spacecraft Center mission evaluators	--	--	146	146
Translation and docking simulator (Langley Research Center)	--	--	87	87
Contractor mission evaluators	--	--	859	859
Massachusetts Institute of Technology evaluators (2)	--	--	56	56
Full-mission engineering simulator	--	--	174	174
Simulator prebriefing and postbriefing	[b]175	[b]465	[b]703	[b]1 343
Partial-gravity simulator, mobile partial-gravity simulator	--	[b]93	[b]27	[b]120
Total	1330	6964	29 967	38 261

[a] Time computed on the basis of 2 hours logged for each LLTV flight.

[b] Not included in total simulator hours.

Classification

Simulators can be grouped into several classifications. For the purpose of this report, the following definitions will apply.

Full-mission simulator. - A full-mission simulator is a device in which all crew-related phases of the mission are consolidated into one complex. Included in this category are the Mercury procedures simulator (MPS) (fig. 1), the Gemini mission simulator (GMS) (fig. 2), the CMS (fig. 3), and the LMS (fig. 4).

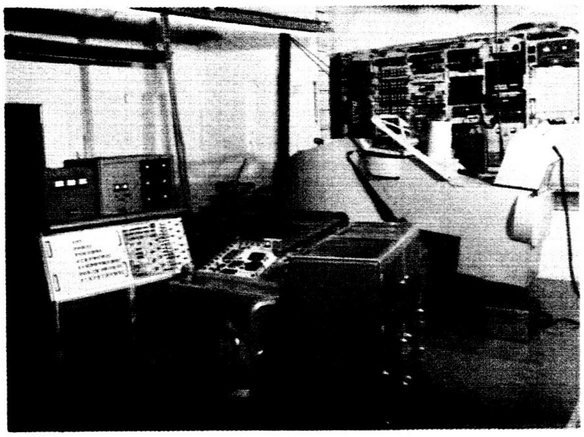

Figure 1. - Mercury procedures simulator.

Figure 2. - Gemini mission simulator.

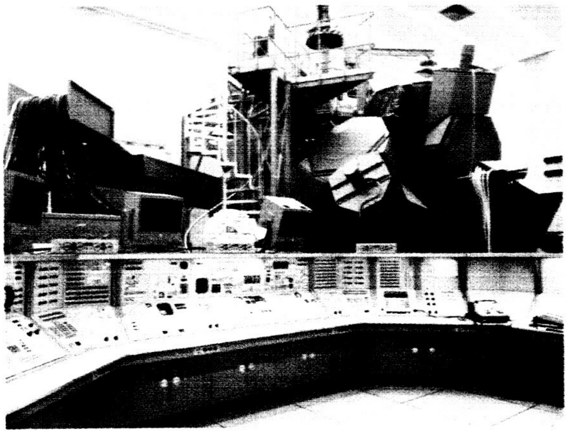

Figure 3. - Command module simulator.

Figure 4. - Lunar module simulator.

Part-task simulator. - A part-task simulator is a device in which only a portion of the mission or several major crew tasks are simulated. Fidelity in these tasks may be greater than that achieved with the mission simulator.

Moving-base simulator. - A moving-base simulator is a device in which the crew station or crewmember (or both) is subjected to some physical motion. This physical motion could be intended to give the pilot realistic cues of acceleration, velocity, or position or could be an undesirable artifact of the simulation technique. One example of a part-task and moving-base simulator is the LLTV (fig. 5), which provides a high-fidelity, six-degree-of-freedom duplication of the final lunar descent from an altitude of approximately 500 feet to touchdown.

Fixed-base simulator. - A fixed-base simulator is a device in which no physical motion is transmitted either to the crew station or to the pilot. All the dynamics of the simulation are provided through displays on the crew-station panels and by movement of out-the-window scenes.

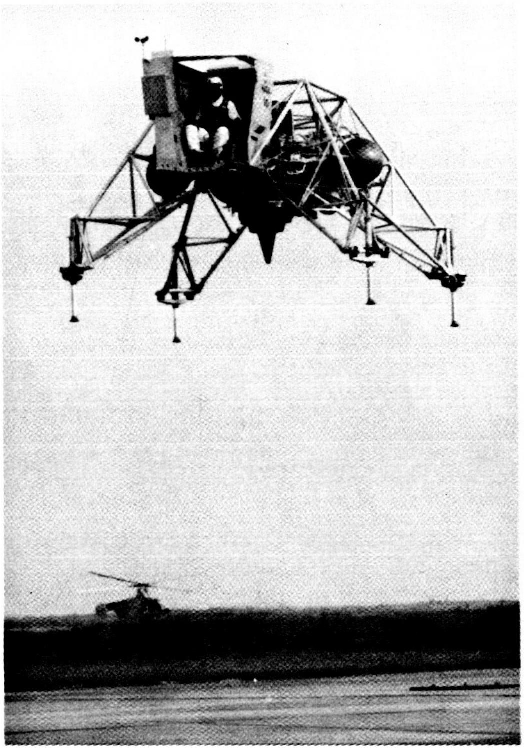

Figure 5. - Lunar landing training vehicle.

Discussion

The value of high-fidelity simulation was well known through aircraft flight experience before Project Mercury. The dependence on simulation for space mission success and crew safety generally is greater than the dependence on simulation for aircraft testing because of the natures of the two flight programs. Space-flight crews are fully committed at lift-off to an entire mission, in which a broad envelope of operational variables is exercised. Aircraft test research usually allows for a more gradual exercising of the total flight envelope through a series of "buildup" flights. Whereas the aircraft test pilot can obtain much of his training coincident with actual flight testing, the crews for space missions must receive all their training and be highly proficient in all flight tasks before the mission. Primarily for this reason, the space-flight simulators require the highest degree of fidelity of spacecraft and mission simulation. Aircraft experience was used extensively in the development and operation of the first space-flight simulator, the MPS. For the follow-on space programs, Gemini and Apollo, the major developmental impetus for the simulators was derived from space program experience.

Early in Project Mercury, the effect of space-flight environmental factors upon crew performance caused considerable concern. Consequently, training emphasized crew exposure to such conditions as high acceleration forces, zero-g conditions, heat, noise, and spacecraft tumbling motion. The Mercury astronauts received many training exercises in an attempt to duplicate these environmental conditions. Particular concern was expressed about crew capability to manually control the spacecraft during the high acceleration loads imposed during launch and entry. As a result, the Mercury astronauts participated in four centrifuge programs at the Naval Air Development Center, Johnsville, Pennsylvania. Project Mercury flight results verified that the conditions of space flight had no adverse effects on crew performance for missions as long as 22 hours in duration. Consequently, crew-training programs for the Gemini and Apollo missions deemphasized such considerations and concentrated to a great extent on the many and complex operational considerations. Project Mercury experience did point out the importance of simulating out-the-window scenes, which became even more important for the Gemini and Apollo missions. The Mercury simulators did not have adequate out-the-window displays, and a major effort to remedy this situation for the Gemini simulators was begun.

The value of high-fidelity simulators was verified throughout Project Mercury, thus establishing for the Gemini and Apollo Programs the requirement for a full-mission-simulator inventory both at the NASA Manned Spacecraft Center (MSC) and at the NASA John F. Kennedy Space Center (KSC) launch site. Operation of simulators at KSC was deemed necessary primarily because of crew participation in specific checkout tests of the spacecraft and launch vehicle at the launch site.

For each Mercury flight, full dress rehearsals (referred to as simulated network simulations) of the most significant flight phases integrating the crew, the flight plan, and the ground-support elements were accomplished as part of the preflight preparations. These simulations proved to be extremely valuable for the flight and ground crews and, consequently, were further developed and expanded for the Gemini and Apollo Programs. A simulated network simulation for the Apollo lunar landing mission involving the LMS and CMS tied in with the Mission Control Center (MCC) in Houston, Texas, required the precise coordination and synchronization of 10 large-scale digital computers. The magnitude of this phase of the simulation training program is indicated in table IV in terms of the number of days spent running full-mission simulations during the Gemini and Apollo Programs.

The Gemini Program required more sophisticated simulators than did Project Mercury, principally because of the Gemini rendezvous mission objective. Crew capability to effect the rendezvous by using primarily out-the-window information was essential to the mission and dictated that an elaborate visual system be incorporated into the Gemini mission simulators. The development and use of an advanced state-of-the-art infinity optical display system added considerably to the realism and value of simulator training for the Gemini crews.

Results of the Gemini Program indicated quite clearly that a well-defined and effective configuration management system was needed to maintain the simulators in a configuration that corresponded closely with the continuously changing spacecraft. Basically, this meant a quick-response system operated by personnel cognizant of all spacecraft changes and capable of deciding on and contracting for the necessary modifications and incorporating these into the various simulators. A configuration control panel committee, with ancillary working groups, was formed for the Gemini and Apollo Programs with good results.

TABLE IV. - SIMULATED NETWORK SIMULATIONS[a]

(a) Gemini Program

Mission	Simulation sessions, days
III	4
IV	7
V	7
VI	13
VII/VI	9
VIII	9
IX	9
X	7
XI	6
XII	7

(b) Apollo Program

Mission	Simulation sessions, days			
	CMS/MCC	LMS/MCC	CMS/LMS/MCC	Total
7	18	0	0	18
8	14	0	0	14
9	10	2	8	20
10	11	0	7	18
11	7	4	7	18
12	10	3	12	25
13	13	5	9	27
14	15	7	13	35
15	19	5	7	31

[a] This summary includes only the mission simulations involving the use of mission simulators with flight crews and does not include the many more additional days of "math model" simulations (without the mission simulators) for flight controller training.

Forecasts of the simulator training requirements for the Apollo Program showed that a large inventory of various types (full mission, part task, moving base) of strategically located simulators would be needed. The Apollo Program imposed severe schedule and simulator-complexity constraints; a requirement was dictated to train a large number of three-man crews within a relatively short time in sophisticated and critical mission simulators (three command module simulators and two lunar module simulators) with complete visual systems. The capability for integral operation of the simulators with each other and with the MCC in Houston also was required. The greater number of command module simulators was needed to accommodate the greater number of command-module-only flights that comprised early program concepts. In addition, certain special-purpose part-task simulators were considered necessary to provide supplementary training, to afford overall training flexibility, and to support the crew procedures development effort (an integral part of crew training). Among these special-purpose simulators were the command module procedures simulator (CMPS) (fig. 6), the lunar module procedures simulator (LMPS) (fig. 7), the Apollo translation and docking simulator (TDS) (fig. 8), and the Apollo dynamic crew procedures simulator (DCPS) (fig. 9). Perhaps the most notable special-purpose simulator was the LLTV. Because of the limitations of accurately simulating this critical phase of the lunar mission on ground-based simulators, the free-flying LLTV was employed to provide an extremely realistic dynamic simulation of the lunar approach and touchdown.

Concerning the simulators themselves, several basic decisions were made to satisfy the fidelity requirements. One of these decisions was that all spacecraft subsystems would be simulated by the computers; that is, no actual (hardware) spacecraft subsystems would be used. One area handled in a special way was simulation of the Apollo onboard guidance and navigation computer. The simulation successfully used was based on an "interpreter" concept

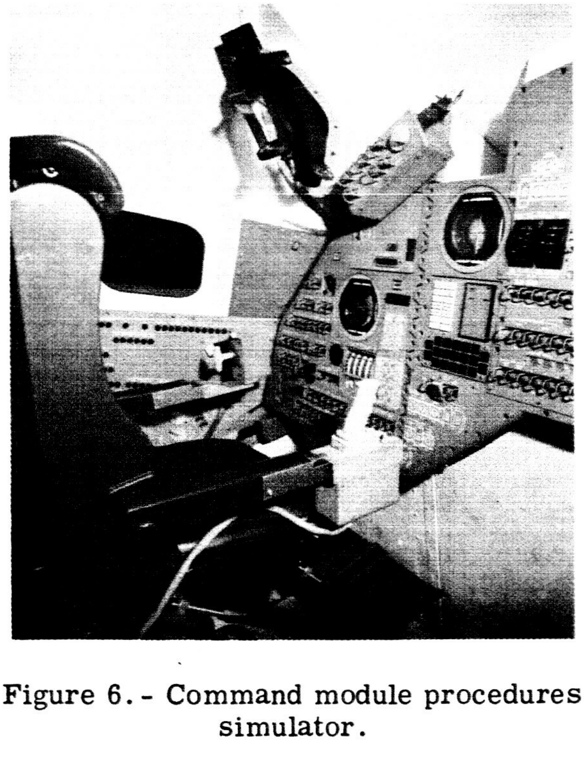

Figure 6. - Command module procedures simulator.

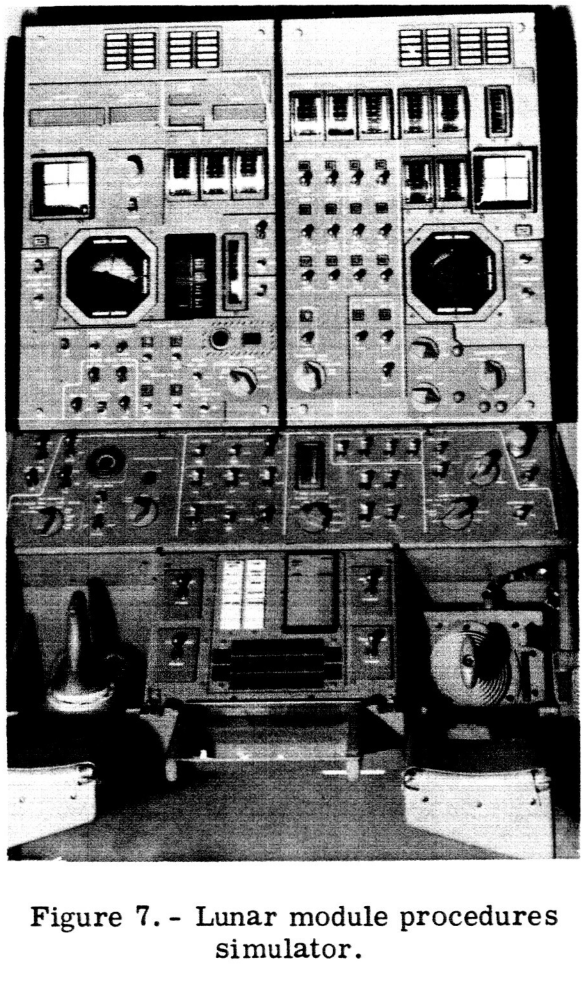

Figure 7. - Lunar module procedures simulator.

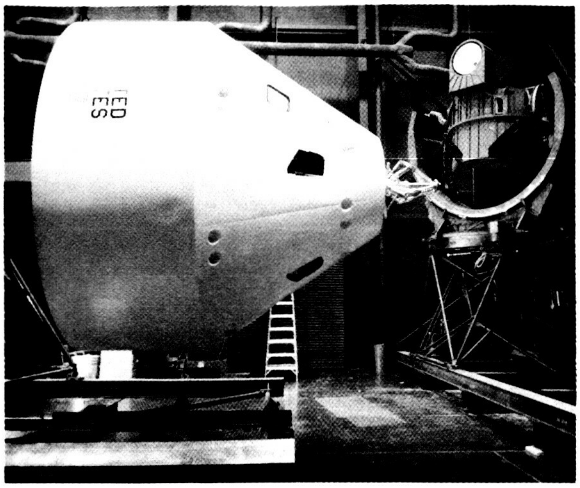

Figure 8. - Translation and docking simulator (Apollo).

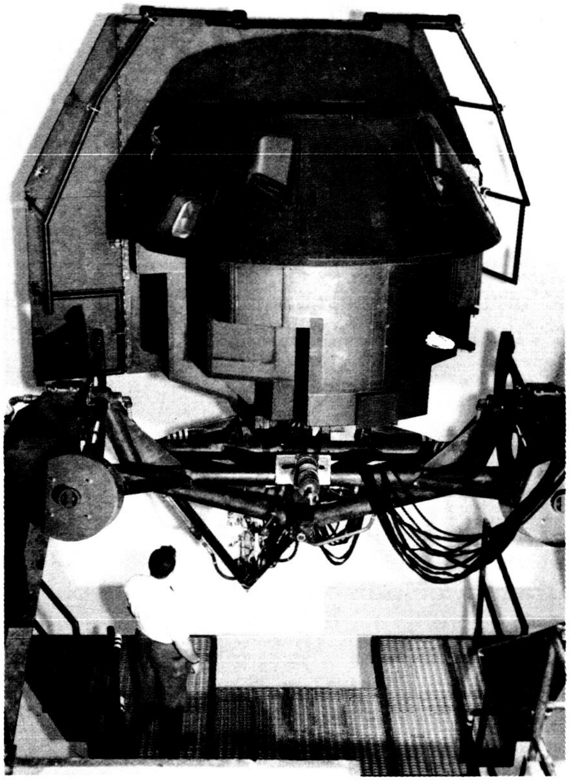

Figure 9. - Dynamic crew procedures simulator (Apollo).

in which a general-purpose digital computer was programed to accept the same program as the flight computer and to respond to spacecraft systems precisely as the flight computer would. The interpreter superseded a barely adequate, costly, and always late functional approach for simulation of the onboard computer.

Another area that required considerable updating and redesign was the difficult visual simulation of the lunar landing. As will be discussed in the section on visual display simulation, the initial concept of the LMS fell short of the realism required. An intensive development effort was undertaken to improve the visual simulation for the lunar landing and at the same time to permit timely use of the LMS for the early orbital training. This effort was successfully concluded to provide high-fidelity landing and ascent training for the first lunar landing and subsequent flights.

Although the remainder of this report is oriented toward the difficulties and experience gained through the operation of the simulator hardware, it by no means implies a lesser importance of the software systems. Indeed, a large percentage of the overall simulation effort throughout all flight programs was associated with the simulation software. For example, the Apollo lunar landing mission simulation for the CMS consisted of 750 000 words of memory residing in four large digital computers. Similarly, the LM simulation in the LMS required 600 000 words in three digital computers. At the peak of preparation for the first lunar landing mission, approximately 175 support contractor personnel were assigned to the development and control of the software systems of three command module simulators and two lunar module simulators. Another 200 contractor personnel were assigned to the hardware operations and maintenance. Simulator changes required to keep pace with the changing spacecraft and mission numbered more than 30 per month in this same time frame. Configuration management of these hardware and software systems is discussed in the section entitled "Simulator Configuration Management."

CREW-STATION FIDELITY

Various considerations for the design of the simulator crew station are described in this section. The Mercury, Gemini, and Apollo simulator crew stations, particularly those for the mission simulators, were designed and constructed with a high degree of fidelity to simulate closely both spacecraft performance and interior appearance.

Controls and Displays

The controls and display panels provide the necessary interface between the crew and the spacecraft. Only through the medium of properly designed panels and functional integration with simulated systems software can the training be performed efficiently and adequately. The controls are used to provide intelligence to the supporting computers in the form of analog voltage or discrete signal inputs. To meet crew-training requirements, it becomes necessary to simulate all known characteristics of a control switch, such as lock and spring-loaded positions, as well as the forces required to change positions. Commercial switches that look and operate like flight units usually can be procured at a fraction of the cost of the spacecraft hardware. Valves to control the flow of fluids in the actual spacecraft usually are not required in an electrically sensitive simulator. Basically, two types of valve operations require simulation. The type of valve required for adjusting the flow of a fluid is referred to as a proportional-flow valve, and the discrete detent-hold operation uses a shifting-port type of valve. The function of the proportional-flow valve is simulated by the attachment of a potentiometer to the control shaft for position sensing. Switch activation by cam and detents is used to simulate shifting-port valve action. The torque force profile can be simulated accurately by placing a frictional, adjustable sleeve around the shaft being turned.

When crew training requires a close duplication of hardware operating characteristics, the use of flight-configured hardware has provided the best results. Such components as hand controllers must duplicate as nearly as possible force profiles, dead bands, feel of multiple detents (soft stops), handle free-return characteristics, mechanical damping, and signal generation for both discrete and proportional displacement.

A wide range of commercial variable controls (such as potentiometers) that have characteristics acceptable for use without modification are available to simulate equivalent flight hardware. However, specialized assemblies consisting of a transformer element and a potentiometer or a rheostat (both of which may have certain characteristic profiles to interface delicately with an instrument or system in a balanced relationship) would be difficult to obtain unless procured from the manufacturer of the flight article. Such units usually are procured for the simulators without the flight qualification test necessary for spacecraft hardware, thereby reducing the cost of the units and shortening procurement time. Circuit breakers also require some special consideration. In simulating wiring malfunctions (resulting in high current flows) that trip respective circuit breakers, it is not practical to use spacecraft hardware that trips at relatively high currents (e.g., 100 amperes). Instead, a standardized low current (0.01 ampere on a 26-volt dc system) circuit breaker has been used throughout the simulators.

Stowage

Since the early Mercury flights, the proper location of onboard data and loose equipment has been a necessary inflight task and, therefore, a training requirement. The need for assigning every item a specific stowage location and the procedure for handling loose items could not be neglected. Ideally, flight-type equipment for stowage training is preferred. However, because of the disadvantages of the high cost of the equipment and the frequent handling under one-g conditions, actual flight equipment is seldom used for simulator stowage. For training purposes, a nonflight item serves as well if it functionally fulfills the intended use.

Lighting

Lighting of the crew compartment was not considered critical in terms of intensities and spectrum composition. Experience has shown that light levels sufficient for general illumination are satisfactory as long as the simulated intensity does not deviate appreciably (±20 percent) from the actual.

Because of the use of optical eyepieces (telescope and sextant) for navigational sighting in the Apollo spacecraft, the floodlight intensity settings were usually low, which caused some difficulty in reading the meters. As a consequence, all simulator meters were lighted integrally, and panel nomenclature was blacklighted with electroluminescent elements, as in the spacecraft.

Aural Cues

Audible cues are simulated and presented to the flight crews whenever applicable during the training exercise. On the Apollo mission simulators (CMS and LMS), such cues as booster thrust, cabin decompression, and the firing of pyrotechnic devices and attitude-control jets are simulated. Noise levels in the communication channels as well as ambient noise are simulated and transmitted to the flight crews through headsets and through concealed loudspeakers within the crew stations.

Aural cues are generated by various means, such as a low-frequency reverberation that feeds into a summing amplifier. The signal output (simulated aural cue) of the summing amplifier then is fed through a voltage-controlled attenuator to a summing amplifier and then to the loudspeaker in the mission simulator cockpit. The instructor at his station is included in this loop to enable him to control the amplitude of the sound manually with a decibel-control potentiometer.

Markings and Nomenclature

All controls and displays, stowage areas, and other hardware must be properly marked with the same nomenclature used in the flight spacecraft. Nomenclature is especially important during the early phases of crew training to aid in system operations. However, in time, the crewmembers rarely resort to reading nomenclature because they become so familiar with the location and function of each control or display that reading is unnecessary.

Space Suit and Cabin Environment Requirement

In the various simulators, suited operation throughout all phases of flight, yet with the capability for the crew to train unsuited for comfort, has been emphasized. The crew-station environment is maintained at ambient pressure with circulated, temperature-regulated air. All the controls for the crew-station environment are manual, and the systems are purely simulator oriented. The crew-station-environment parameters of temperature, humidity, and noise level are electrically monitored at the instructor-operator station. The crew-station cabin-temperature and cabin-pressure meters display simulated values in accordance with the flight profile; that is, while on the launch pad, the simulated cabin pressure is 14.5 psi and decreases proportionately during launch, settling at 5.0 psi for orbit conditions.

A realistic simulation of suited conditions is provided. The use of fully pressurized suits provides the proper constraints for controlling the simulator with rigid-suit conditions. Great care always has been taken to prevent the possibility of a rapid pressure buildup in the simulator suit loops. The CMS suit loop has a motor-driven pressure control that varies the airflow at a fixed rate of 2 psi/min, reaching 3.75 psig for hard-suit and 0.25 psig for soft-suit conditions with constant airflows under either manual or automatic (computer) control.

Crew Couches

Exact replicas of the crew couches have been used in the simulators to provide proper body restraint, correct reach patterns, and accurate couch-manipulation capability.

Crew-Station Hardware

Simulator crew-station hardware is discussed in two categories: contractor-furnished equipment (CFE) and Government-furnished equipment (GFE).

Contractor-furnished equipment. - The contractor in this case usually was the prime spacecraft contractor. The spacecraft contractor has several avenues open to provide hardware for the simulators. If it is not practicable to simulate the spacecraft components, actual spacecraft hardware is supplied. Such components as attitude controller assemblies, thrust and translation controller assemblies, attitude indicators, and polycarbonate cover assemblies are examples of actual spacecraft items procured directly from the prime contractor. Much of the CFE for the simulators is manufactured on the production line at the same time the spacecraft parts are fabricated. Simulator parts made in this manner are identical to spacecraft hardware.

In many cases, simulator parts do not require the sophisticated design or the rigid tolerances demanded for the spacecraft. The frequent use of rejected spacecraft parts on the simulators results in cost savings. During the Apollo Program, the spacecraft contractor maintained another manufacturing capability commonly referred to as the "model" shop. The personnel in this shop usually work from engineering design sketches to fabricate prototype units for spacecraft qualification tests. The model shop is often used to fabricate simulator hardware. Components made in this shop for the simulators do not have to meet the stringent spacecraft specifications. Occasionally, hardware for the simulators is made from initial design sketches to meet the desired leadtime necessary to support crew-training exercises. Various other contractor sources of simulator hardware are available, including the simulator manufacturer.

Government-furnished equipment. - Simulator parts can be made at MSC. This source of fabricated hardware is generally the preferred route, on a cost basis. Federal stock provides a prime source for standard off-the-shelf items for installation and maintenance work.

A substantial amount of loose hardware is provided to the spacecraft simulator as GFE. Optical sights, suit hoses, backpacks, and most of the stowed items are provided by the supplying organization at MSC. Some units are included in the simulators on a permanent basis, but other units are furnished by the suppliers as required for the training exercises. Other hardware, such as hand controllers and attitude indicators, is provided for the simulators by the contractors who supply these items for the spacecraft.

Concluding Remarks

A high degree of crew-station fidelity, particularly in the full-mission simulators, is necessary for accurate simulation of spacecraft performance and mission characteristics. In addition to a complete simulation of the spacecraft controls and displays, such items as stowage provisions, lighting, aural cues, and crew hardware are extremely important in providing this required fidelity.

VISUAL DISPLAY SIMULATION

Early in the evolution of manned space flight, the requirement for a window in the spacecraft was identified. Although the window served several purposes, the most important was as a backup attitude reference. Experience in aircraft control tasks and during early space flight had established that training was necessary to enable the crewmember to correlate his out-the-window references with his instruments. The various techniques used to produce the simulated out-the-window scenes throughout Project Mercury and the Gemini and Apollo Programs are described in this section.

Display System

The first element of a visual simulation system is the display system, the element into which an image is projected for viewing by the crew. The determining factors of this element are the apparent distance to the image being viewed and the field of view (FOV) of the window. A general requirement is that all images appear at infinity as they do in reality. For docking, the simulation requirement was that the image appear to approach the crewmember as in the actual situation. Field-of-view requirements were based on the particular spacecraft window being simulated, with some allowance for pilot eye or head movement. The Mercury spacecraft requirement was a 60° FOV, although that of the Apollo LM (the largest requirement) was a 110° FOV as measured at the eye.

All mission simulators used an infinity display system. Figure 10 is a schematic of a typical window system using reflective optics techniques. To satisfy the docking display requirement, the display or output tube was moved from its infinity position. Approximately 4 inches of movement of the display tube made the image appear to move from infinity to 8 feet from the viewer.

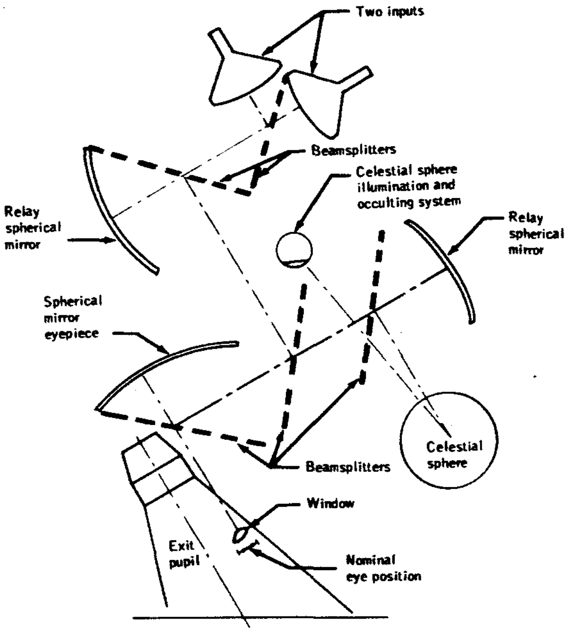

Figure 10. - Typical reflective infinity display system.

The infinity image system has the desirable characteristic that, as the crewman moves his head, the item being viewed appears to move correctly. Conversely, because of parallax, viewer head motion grossly affects what is seen with direct-view, screen-type systems; therefore, the viewer must hold his head relatively still to resolve properly the source of the observed motion.

Specifications for the FOV could not have been met without some design compromises. In the Mercury and Gemini simulators, the FOV requirements (60° and 88°, respectively) for completely filled window scenes were met as long as the pilot maintained his eyes within an area defined as the exit pupil. This was not a severe constraint in these simulators, because of the relatively limited head freedom. In the CMS, location of the exit pupil at the window allowed unlimited viewing except as constrained by the physical characteristics of the spacecraft. The design FOV was 90°. The exit pupil for the side windows was not quite as large as the windows; however, the small dark bands outside the exit pupil were hardly noticeable and were not a serious problem.

In the LMS, the large FOV, coupled with a large window (17 by 22 inches to extreme apexes) and almost total freedom of the crewman to position his head, required the greatest compromise. The first compromise was to place the exit pupil in the area of the crewman's design eyepoint (i.e., the normal eye position). From this design eyepoint, the crewman could move approximately 4 inches in any direction with no loss of display. The second compromise was to point the axis of the forward-window display down to feature the landing scene at the expense of the upward scene. In the actual spacecraft, the crewman can look up approximately 20° from the design eyepoint, and even more by hunching down. In the simulator, the crewman was limited to less than 10°. Even with this compromise, the bottom apex of the LM window was blank as viewed from forward eyepoints. Because these adjustments were chosen very carefully against anticipated use of the window, the limitations have had no adverse effect on training.

The infinity display systems used with the mission simulators produced the desired effects as long as proper consideration was given to mission simulation requirements. These systems did have some drawbacks. Relatively high cost (30 to 40 percent of total mission simulator cost), large physical sizes, ghost images, extremely low light transmission, and backlight scatter were the most significant. Since the initial application of the infinity optics technique to simulation, additional development has resulted in reductions of cost and size. These new systems are of both refractive and reflective types. The refractive types tend to be brighter, although with some loss in image quality, than the reflective types.

Celestial Simulation

Simulation of the stars was predicted on both navigational and attitude-reference requirements. In orbital flight, these requirements are intermixed because the pilot must know his location to use the stars as an attitude reference. In simulation of the star field, consideration was given to the number and relative brightness of the stars selected and to the static and dynamic accuracies required. The number of stars chosen for all projects to date is approximately 1000, consisting of all those brighter than a +5 magnitude. The logic of selecting this number was that the navigation stars and the constellations used for identifying them are all brighter than the fifth magnitude. One other factor in this selection was that fifth magnitude stars are the dimmest generally visible to the unaided eye from the ground.

In training crews for constellation recognition, variations in brightness, at least to the whole magnitude, must be simulated. The specifications required at least seven discrete levels (+5 to -1), with correct relative brightness between levels desirable but not mandatory. The specifications also required that this variation be in the true brightness of the star, not as produced by merely increasing light-source sizes.

Static positional accuracy specifications were dictated by the need to identify constellations. It was determined that the appearance of constellations changes significantly with even minor positional errors. Furthermore, if the stars were to be used in a navigational task, an instrument such as a sextant would be necessary and an accuracy compatible with the instrument was required. To reduce cost, star positional requirements were moderated to 1 milliradian (approximately 0.06°) for all navigation stars and 0.5° for all other stars. Specifications also required that if the constellation appeared incorrect with a 0.5° error in a given star location, the positional accuracy for that star must be tightened to that of the navigation star.

The specified dynamic positional accuracy also required compromise, as the requirement was complicated by the large range of vehicle angular motions possible in a spacecraft. Pilot-controlled rates range up to 20 deg/sec, with uncontrolled vehicle angular rates of 50 to 60 deg/sec possible. Although a perfectly stationary spacecraft is not possible, rates can be as low as 0.1 deg/min for small spacecraft motions. From his stable and vibrationless viewing position, the crewman could detect such small motion. The final specifications derived for all spacecraft simulation programs required as smooth a low-speed drive as could be produced and permitted lags in position at angular rates above 15 deg/sec. Stepping motions that were detectable by the crewmembers were deemed unacceptable.

In all simulators, the same basic technique was used to produce the star displays. Approximately 1000 individual stars were simulated by small, highly reflective steel balls set into the surface of a (celestial) sphere. When the highly polished balls were illuminated by a point source of light, they reflected the point of light, the relative brightness being a function of the size and coating of the balls. Balls as small as 0.1 inch and as large as 0.8 inch in diameter have been used. Mirror surfaces concentric with the celestial sphere were used to keep the individual balls in focus over the FOV of the window. This technique produced excellent representations of the star field. The only anomaly noted on the display was a halo created by some of the coated balls. Unfortunately, in the LMS the halo stars were all navigation stars, and the halo made recognition relatively easy. Therefore, the use of coatings to simulate various magnitudes is not recommended.

A chronic difficulty in the simulation of stars was in the dynamic drives of the celestial spheres. Smooth, stepless servomechanism drives that hold positional calibrations have not been obtainable, and only continuous maintenance and adjustment have produced acceptable operation. This problem has not been limited to the servos and torque motors but has been noted in the entire chain, from the equations of motion, through the digital conversion equipment, to the spheres. The problem has become more acute with each new program, because the range of dynamic motion produced by crew action and under crew control has increased from approximately 10 deg/sec for the Mercury spacecraft to approximately 20 deg/sec for the LM. Although, in the past, continual maintenance and frequent calibration have tended to minimize the impact of the servomechanism problems, additional research in product improvement as well as improved mathematical and computational techniques should be continued.

In addition to the window and the unity-power telescope, the command module (CM) required simulation of a 28-power, 2° FOV sextant. This optical instrument directly interfaced with the onboard guidance computer for navigational procedures. The requirement for the sextant simulation was to produce the Apollo navigation stars (56 in number) with correct background stars, as well as to provide earth or moon limb at various altitudes. Static accuracies were the same as specified for the spacecraft, that is, 10 arc seconds. The dynamic accuracy requirements of the sextant simulation were not high, because all tracking and marking tasks were performed at very low scene dynamic rates. The sextant simulation was produced by using a single extremely accurately positioned navigation star in one optical leg and a selection of as many as 90 slides of star fields, limbs, and landmarks in a second leg. A pattern generator and filters were used to produce the background fields for the navigation star. Pairs of rhombic prisms were used to produce the motions in both legs. The two legs were combined into a single image by a beamsplitter assembly. For most Apollo training, five slides covering the most-used navigation stars were used in the second leg. In operation, if either leg were more than 1° off the intended line of sight, the sextant simulation was turned off.

Difficulties encountered in the sextant simulation were similar to those with the celestial sphere. That is, producing smooth motion at the extremely low rate used in taking navigation marks was not always obtainable in the simulator operation. Another difficulty was encountered with the initial simulator design requirement for updating the background field. Various changes in the Apollo navigation stars occurred since the beginning of the program. The method of generation of background stars made it too expensive to update to new background star fields, and the background-star generator was not used. As a result, it was not possible for the crewmember to identify the particular navigation star in the sextant. Fortunately, this turned out to be only a minor limitation. The accuracy and stability of the actual spacecraft guidance, navigation, and stabilization systems were quite good, and the inflight procedures were developed to make most effective use of this spacecraft capability. That is, the spacecraft crewmember was not required to identify a navigation star with the sextant, because his onboard guidance computer programs ensured that the navigation star was always within 0.5° of predicted value.

Far Bodies

For the purpose of this discussion, far bodies are identified as the distant moon, earth, sun, and planets, that is, all those bodies in the solar system that subtend an angle of approximately 0.5° from the viewpoint. These far bodies were simulated for navigational reference and for added realism. In the Apollo simulation program, they were deemed important enough to be included. For the sun, the specifications were for position, size, and high relative brightness in the windows when the individual window was pointed toward the sun. The requirements for distant earth and moon were for position, brightness compatible with star simulation, and apparent size change as a function of range to each body. In addition, simulation of the sun terminator on the far body was desirable. The tolerances on these requirements were not tight. Simulation of the larger planets, although desirable for navigational reference, was not mandatory.

As noted previously, these effects were not included in the Mercury and Gemini simulators. In the Gemini simulator, the sun in the window or, rather, the total washout of the scene caused by the sun in the window was simulated by video flooding the television (TV) cathode-ray tube (CRT).

The sun simulation in the CMS used arc lamps to produce a 0.5° spot of light in each of the windows. Although these lamps did not duplicate the exact sun brightness, the simulation was sufficient to wash out the stars and other dim images and served to remind the crew to maneuver to some other attitude if they desired to perform any out-the-window visual tasks.

With the LMS, a high level of sun brightness was not required, and the sun was simulated by a small disk attached to the celestial sphere. By this means, the desired effect was provided at much smaller computation and hardware cost than in the CMS. Sun lighting (or sun shafting) in the crew station was not provided in either the CMS or the LMS. Although this omission in the simulation has resulted in the crews' using spacecraft lights in the simulators that are not normally required in flight, the problem has not been a major one.

The simulation of the distant moon and earth in the Apollo mission simulators also fell short of the original specifications. In the CMS, a direct-view film system with 28 discrete phases of the distant moon was defined. Because these images were too small to be reproduced on film, the technique has been abandoned. For most CM simulation work, the sun simulator was used to represent the distant body. In the LMS, a technique similar to the LMS sun simulation was used, but the disk was somewhat less reflective than the solar disk. By shaping the disk, the phases of the moon or earth also were presented. The distant earth and distant moon were moved or manually adjusted to provide for movement of the distant body relative to the stars, changes in sun terminator on the body, and changes in relative size with variation in distance.

In summary, the far-body simulation requirements have been modified to be consistent with crew-training needs and state-of-the-art hardware. The requirements for far-body simulation from the eyepoint are summarized as follows:

1. Position tolerance — Tolerance should be ±7° for general realism, ±1° for navigational reference.

2. Size tolerance — Tolerance should be ±0.25°.

3. Brightness — Order of relative brightness should be sun, moon, and earth; all should appear brighter than the brightest stars.

4. Phase (solar terminator) — Phase is desirable, but not mandatory.

5. Dynamics — Far body should have no apparent motion relative to the star for spacecraft-attitude motion simulation. Far body should move with respect to the stars for long-term emphemeris effects; however, step changes are acceptable.

6. Washout and sun shafting — Washout and sun shafting are desirable.

The CM sextant (previously described) contained a set of slides of the distant earth and of the distant moon. These slides reproduced the effect of the terminator on the moon for all 28 days of the lunar month and on the earth for those days the CM would be in lunar orbit. This slide technique proved acceptable.

Target Vehicle for Rendezvous

The target-vehicle simulation was split into two parts: long distance, where the target-vehicle attitude is not important (e.g., rendezvous); and short distance, where the vehicle attitude in addition to the range becomes important (e.g., stationkeeping). The switchover point was defined as 2 miles, or where the target vehicle would subtend an angle less than 0.2°.

The target vehicle for distant rendezvous does not require attitude information. The two requirements are position in the window and relative brightness with range. For tracking in darkness, the spot of light was required to blink to simulate a flashing beacon. For daylight tracking, the spot should be steady to simulate reflected sunlight. Other factors are an accuracy of ±1° on position, minimum brightness equivalent to a fifth-magnitude star, and a maximum range of 250 miles for the unaided eye. Maximum brightness was not specified; however, the intent was to make the minimum-range target as bright as possible. The spot of light should be small enough that it does not stand out against the background stars unrealistically.

In all simulators with rendezvous capability, the window simulation was produced by electronic techniques on a CRT. This technique met the requirements. The major problem was in positional stability of the display. In the early simulations, frequent alinements were required; however, over the span of the Gemini and Apollo Programs, improved electronic circuit design has reduced this problem to a minimum.

In the Apollo CM, the unity-power telescope and a 28-power sextant were used during rendezvous. The simulation requirements for these instruments are similar to that of the basic window except for positional accuracy. The telescope was used to point the sextant to a specified accuracy of 0.5° relative to the sextant line of sight. For compatibility with navigational requirements, the sextant accuracy was specified as 30 arc seconds.

The telescope simulation for distant bodies was a later addition to the original simulator. Because of space constraints and the stability problem discussed previously, a CRT display was not practical. Instead, the point of light representing the target vehicle was produced by a simple light bulb. Displacements in the FOV and size were produced by mechanical means.

The CM sextant simulation also was added to the original simulator design. The requirement of the distant target was satisfied by using the sextant navigation star simulation (described in the paragraphs on celestial simulation) to represent the target-vehicle position. The resultant positional accuracy was much better than 30 arc seconds. There were two limitations with this sextant simulation. First, with 28-power magnification, the size, shape, and attitude of the target vehicle were apparent for relatively long ranges. Second, the omission behind the LM of a lunar background made spotting the LM much easier in the simulator than in flight. Of the two limitations, the lack of a lunar background was considered more critical. To fully simulate the actual situation, a moving scene beneath the CM and behind the LM would be required. However, a full simulation is not mandatory. A static scene of the lunar disk, or of the lunar limb and terminator, fulfills the minimum requirements.

Target Vehicle for Stationkeeping and Docking

At ranges up to 2 miles or when the target vehicle subtends an angle greater than 0.2°, simulation of the target-vehicle attitude, shape, size, and external features is mandatory. The target vehicle should be in proper orientation relative to the active spacecraft and should be illuminated in accordance with the relative position of the sun, earth, moon, and any lighting source on the active spacecraft. The angular accuracy of these vehicle features should be ±2° at ranges beyond 40 feet and ±1° at ranges within 40 feet. Linear parameters such as size should be accurate to within ±4 percent. Tolerances on lighting functions are large, approximately ±30 percent. All dynamic motions should be smooth, with no obvious stepping actions. Additional specifications are a proper background behind the target vehicle, with no apparent bleedthrough of stars, earth, or moon terrain.

Two general techniques have been used for target-vehicle simulation: a direct analog system of closed-circuit TV and models, and an electronically generated (drawn) image. In both systems, the input to the display system was through a CRT in the infinity optics systems. The electronic image generator (EIG) was used successfully in one of the Gemini mission simulators, in the Gemini part-task trainer, and in the LMPS. In the EIG system, the target vehicle was drawn on the face of the CRT. The outline or envelope of the target was drawn at a 60-hertz rate; however, the surface was filled in at a 15.75-kilohertz rate. The image generation contained nine degrees of freedom and produced such phenomena as line-of-sight blanking, illumination shadowing, and perspective distortion. Simple target shapes (cylinders, cones, and others) as well as combinations of these shapes were readily simulated with simple surface markings and details.

In the more conventional system such as that used on the Apollo mission simulators, a scale model of the target was viewed by means of a closed-circuit TV system. The model was mounted in a three-gimbal system to reproduce target-vehicle rotations. Generally, the innermost gimbals are in the model. The gimbal system should be offset relative to the camera optical axis to avoid gimbal lock at docking attitude. The TV cameras or lens systems attached to the TV cameras also are gimbaled in this case to represent the active-vehicle rotations. In the CMS, however, rather than camera rotation, active-vehicle motion was introduced by displacement of the video raster on the display CRT.

The relative range was introduced through a combination of techniques. In all TV systems, a track and carriage assembly was used to move the camera away from the model. Camera motion produced an apparent model-size reduction. For the Apollo CMS and the Gemini mission simulators, this size reduction was supplemented by a raster-shrink technique to provide total changes in range. Raster shrink of 67 to 1 was successfully used in the CMS. The LMS used two models, a one-eightieth and a one-twentieth scale. The total required range or apparent size change was obtained by moving away from one model, then switching to the other and moving from it. An example of the type of model used is shown in figure 11. This model, which is from the LMS, contains the lighted docking target in one of the CM docking windows. The docking probe and the CM conical portion were made of rubber to protect the probe and cameras in the event of inadvertent collision.

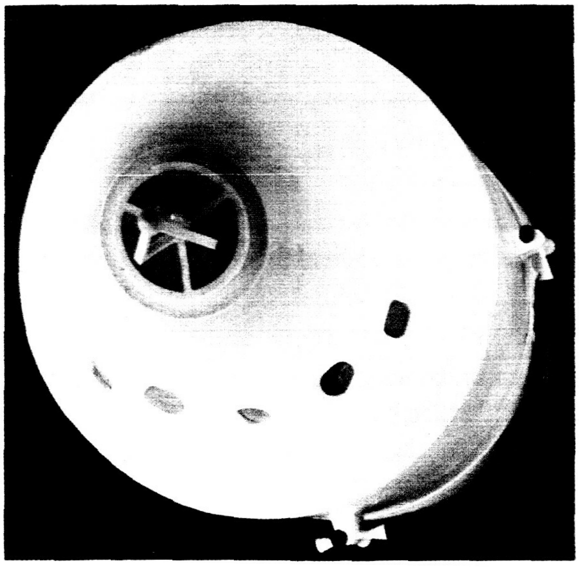

Figure 11. - Docking model of CSM in lunar docking simulator.

All TV systems are black-and-white, high-resolution (greater than 1000 TV lines) systems. Each system represented the best state of the art at the time of procurement. Since that time, however, these systems have been undergoing almost continuous rework to improve basic performance and reliability.

Sun, earth, moon, spotlight, and other lighting effects were introduced in the TV/model systems by high-intensity lamps surrounding the models. Both mechanically controlled lamps and switched banks of lamps were used with reasonable success.

Both the TV/model and electronic-image techniques have produced satisfactory displays for stationkeeping and docking. In the EIG technique, complex shapes cannot be drawn; therefore, realism is significantly less. Conversely, the EIG is a much simpler system to maintain and operate.

With the TV/model technique, external features such as windows, antennas, and docking aids can be portrayed very accurately. These features are extremely important, especially at the close-in docking distances. The picture fidelity obtainable with the TV/model system must be weighed against the complexity of the electromechanical devices required by this system. The TV/model technique has been animated so successfully in the mission simulators that full-scale-vehicle simulation for docking is no longer considered necessary, as it was in early Apollo training.

Near-Body Scenes

Scenes of the near body while in orbital flight cover the altitude range above the earth or the moon from 8 to approximately 1000 nautical miles. At these altitudes, the surface was assumed to be reasonably smooth, and terrain that appeared three dimensional (3-D) was not required. Near-body scenes were necessary for two purposes. The first was as a general reference from which the pilot could evaluate his attitude and estimate his position over the terrain. To meet these needs, horizon position, groundtrack movement, and general continental features were required. The second purpose was for landmark identification and tracking. To meet these requirements, a more detailed terrain scene was necessary, and the spacecraft position relative to the scene had to be more exact. For the earth, color was a highly desirable feature in terrain identification. For either function, several additional features were desirable, such as a day-night terminator and the highlight brightness that would approximate the out-the-window scene. Regarding the accuracies, the following parameters are noted:

Scene	Attitude function	Landmark function
Position of the horizon nadir, or other reference in the field of view, deg . . .	2	0.5
Groundtrack movement (azimuth angle), deg	2	.5
Size of landmasses, percent	10	10
Horizon curvature, percent	10	5
Resolution — general, deg	0.5	.5
Landmark areas,[a] deg	--	.1

[a] Landmark area was defined generally as a 10-mile-radius circle about the specific landmark. The transition from the accuracy of the landmark area to the general scene should occur over a 100-mile radius.

For the attitude function, the allowable distortion should permit identification of gross continental features. For the landmark function, the allowable distortion should permit easy identification of landmass features, capes, bays, peninsulas, river basins, major craters on the moon, and so forth.

In Project Mercury, the view through the periscope and through the window was simulated in what might be termed "moving-base devices." The periscope was simulated in the air-lubricated free-attitude (ALFA) trainer (fig. 12) by viewing a 12-foot-diameter rear-projection screen. The nadir scene was projected on the screen from a hand-painted strip film. Considering the large distortion of the spacecraft and trainer periscopes, the basic requirements of attitude reference and recognition of gross continental features were met. The requirement for window simulation in Project Mercury was uniquely tied to yaw-angle identification while in retrofire attitude. This need arose from an inflight problem during one of the early Mercury flights. Before the following flight, a yaw recognition device had been conceived and fabricated. The simulation consisted of a 32-foot-diameter screen curved to represent a portion of a globe 63 feet in radius. The shape was obtained by inflating an airtight envelope consisting of one translucent and one transparent Mylar sheet. A filmstrip depicting moving cloud cover was projected onto the translucent screen. The crewmember standing at the center and approximately 2 feet from the dome was at the proper scaled altitude. A simple, hand-held box outlined his window. Using this simulation, the crewmember could observe any yaw angle and readily learn to identify the yaw angles of interest while looking toward the horizon.

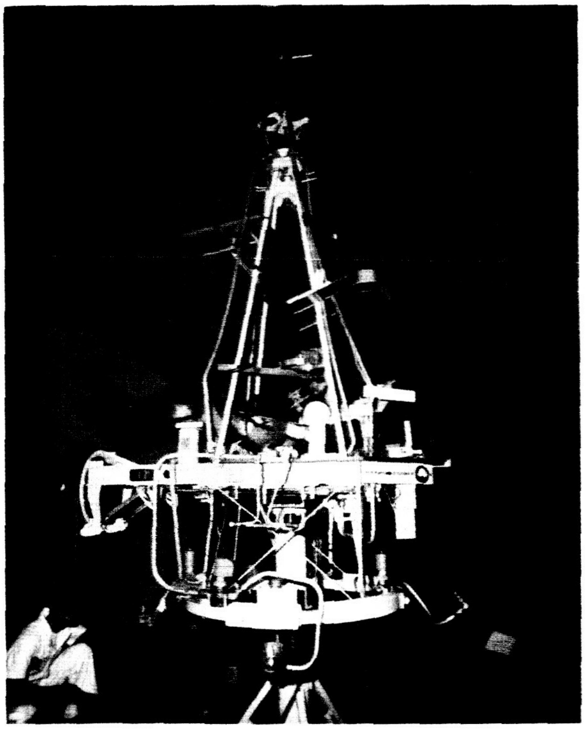

Figure 12. - Air-lubricated free-attitude trainer.

During the Gemini Program, the near-earth scenes were provided in the mission simulators. Two different techniques, both of which met the basic attitude-reference requirement, were used. At the completion of the Gemini Program, the equipment was updated and installed in the CMPS and the LMPS.

The CMPS system (from the MSC-based GMS) used a 6-foot-diameter globe, an articulated probe, and a closed-circuit TV system. Modifications from the GMS included a new earth globe and a new support system for the globe and probe. The probe exit pupil was positioned over the globe as a function of altitude and latitude. Rotation of the globe produced the proper longitude. Spacecraft rotations were introduced by motion of optical elements within the probe. The updated globe was built to accurate sphericity requirements and artistically rendered with high detail in selected landmark areas. The sphericity plus a stable probe mount provided good horizon positional accuracy and curvature up to an altitude of 4000 nautical miles. An artifact in the globe and probe system was the need to nutate the probe in azimuth as a function of latitude, an effect that complicated the probe drive equations.

The LMPS used a flying spot scanner system (from the KSC-based GMS) with film as the data-storage element. Latitude and longitude were produced by film translation, and spacecraft motions were introduced by electronic manipulation of the flying spot scanner output. The scanner pattern was spiral and centered at the nadir to produce a clean, sharp horizon. To provide equal element spacing as measured from the viewpoint in the spacecraft, the spiral scan spacing was nonlinear. The design resolution was equivalent to the best high-resolution TV raster systems. In the GMS, two parallel systems were used to produce a semblance of color. However, in the modification to adapt this system to the LMPS, this provision was eliminated. The modification also allowed simulation of an altitude range from 2500 feet to 100 miles by using zoom optics, zoom electronics, and a series of various film scales. The remainder of the LMPS modification was directed toward improving overall quality of the visual display by using a larger film format and improved electronics. Even with these improvements, the LMPS system has not proved as stable and as flexible as the more conventional mechanical and optical systems.

The LMS used a system similar in certain aspects to both of the previously described systems. In the LMS, an articulated probe and closed-circuit TV viewed a filmstrip of the near body. The LMS films and the LMPS films were actually the same image material printed at slightly different scales. The major difference in the systems was that, in the LMS, four windows were active and four probes were required, whereas, in the LMPS, the display was provided to one forward window and to the overhead window. Furthermore, the LMS scene requirements included landmark identification and tracking in addition to the vehicle attitude-reference task. In the LMS, a common filmstrip was projected through zoom optics onto four screens. The altitude range from near zero to orbit was simulated by a combination of optical zoom and film changes. The probes were mounted at a fixed distance above the screens and articulated with the ability to scan to any point on the screen. At the higher altitudes, spherical distortion was introduced by moving additional optical elements into the projection chain. The horizon was produced at the higher altitudes by illuminating an area smaller than full-screen size. At altitudes below 100 000 feet, a servomechanism-operated mirror system surrounding the screen produced the horizon. The lunar scene films used were, in chronological order, artistic rendition of the front side coupled with artistic imagination for rendition of the back, artistic rendition updated with Lunar Orbiter data, Lunar Orbiter photographs photomosaicked into a filmstrip, and Lunar Orbiter photographs photomosaicked with lunar photographs from Apollo flights. Final configuration of the film consisted of Lunar Orbiter strips for the high-altitude, full-orbit scenes and Lunar Orbiter strips mosaicked with Apollo photographs for the low-altitude scenes in the vicinity of the lunar landing site.

Several problems were associated with the system that materially reduced the usefulness of the LMS. A problem resulted from the splitting of the film image to four screens. The illumination on each vidicon was one-third to one-half of the desired minimum. Another difficulty involved the zoom optics. The design required no movement of the optical axis with zoom. The dynamic wander of the original hardware was such that the usable zoom ratio was restricted to 3 from the design ratio of 10. The wander also made registration difficult to maintain when switching from one to a second film scale. A problem was also associated with the film graphics. It was not practical to obtain continuous filmstrips with the information content desired. The Lunar Orbiter strips with Apollo photographs were available only for small areas of the moon. Also, framelet lines in the Lunar Orbiter strips were reproduced just as vividly as the craters and rilles. Furthermore, in the Lunar Orbiter films, it was not possible to simulate the effect of the sun elevation angle. Hand-painted films could have alleviated certain of these problems; however, the cost in manpower and time was prohibitive.

The overall effect of these problems was a degradation in the LMS fidelity, which necessitated use of other techniques and facilities to complement the LMS. For instance, for the landmark identification and tracking task, detailed briefings and lunar map reviews were held with the crew. The accuracy of the spacecraft navigation system also helped, because the crew rarely had to search for a landmark during flight. The desired target was usually where mission planning said it should be.

The CMS near-body simulation, from the outset, was mainly for the purpose of landmark tracking. The system consisted of direct view of color film projections of near-body imagery. Only such a direct-view system could provide the resolution specified. This system, known as the mission effects projector (MEP), was used in the four cabin windows and in the unity-power telescope. In the MEP, the image was projected through a series of optical devices onto a spherical screen. This screen served as the input of the infinity image system. The optics were driven by servomechanisms to simulate spacecraft rotations, limited altitude effects, day-night terminator, and so forth. Nadir position was introduced by driving the film, and large altitude changes were provided by dissolving to films with different scale factors. The MEP represented an extremely complex electronic, mechanical, and optical device. For instance, each MEP had over 30 computer-controlled servomotors and over 40 other computer-generated signals. Some compromises were required in the final operating configuration: the maximum detail scenic area, as measured from the spacecraft, was limited to a 90° cone centered about the nadir; the minimum altitude simulated was 100 nautical miles; and the film centerline was placed approximately along the groundtrack. The first of these was the greatest limitation, but it was partially alleviated by using a cloud cover that moved with the earth to fill the scene to the horizon.

The films covered relatively narrow strips centered on the groundtrack; and, because of retrogression of the orbit (westerly movement of the ascending node), 17 continuous strips were required to cover the Apollo earth-orbit mission. To resolve the round-to-flat mapping problem and the orbit-to-orbit scene repeatability, an extremely accurate globe, used as the data source, was photographed by a special modified-slit camera. The preparation of the filmstrip from this globe is described in reference 1.

The altitude variation for near-body orbits was specified as 100 to 1000 nautical miles and was obtained by a combination of three film scales with a 2.15:1 zoom capability. Over 250 feet of film stored in four film cassettes were required for each MEP system.

The CMS MEP system, like the LMS, did not meet all the initial design objectives. The complexity of the mechanical-optical device caused problems, and the number of MEP systems required to fill the windows of the three mission simulators made improvements extremely costly. The first of the difficulties concerned the illumination system, in terms of both the level of light and the uniformity of illumination across the full FOV. The relatively low level of illumination manifested itself in many other problem areas. The system design required an extremely high luminous flux on the surface of the film. Even with this flux, the final brightness as measured from the window was approximately one-fourth of the originally specified 4.5 ft-L and approximately one-eighth of the desired illumination to simulate a highlight brightness representative of a true out-the-window scene. With the high light flux, the film would be destroyed almost immediately by infrared and ultraviolet radiation. To limit this damage, heat absorption and rejection filters were used between the arc lamp and the film. Additional film cooling was achieved by a very high, continuous airflow. This high airflow, in turn, caused flutter and eventual destruction of the film. In the final mode of operation, a compromise was selected that accepted some film deterioration caused by the heating and flutter and a scene illumination that required a relatively dark crew station. In the simulator, the crew made use of the panel lighting and the small floodlights, whereas in the spacecraft the sun illumination through the windows was generally sufficient.

For other deficiencies in the system, practical solutions were never found, and, as a result, procedural workarounds were developed to alleviate the impact on training. One such deficiency involved the resolution of the imagery that was presented to the crewmember in the crew station. Although the inherent resolution of the direct-view film system satisfied the specified requirements, copies of the film could not be produced consistently with the same high image quality. The processing of 100-foot lengths of film does not produce results of the quality that can be achieved by copying individual photographs. A 30-percent degradation was not uncommon. Another problem involved the impossibility of maintaining the proper film positioning accuracy over the 80 feet of film in each of the cassettes. Minor film stretching and warpage introduced errors of significant magnitude. In addition, the drive system of the film did not have nearly as tight a tolerance as required. Finally, a problem existed with the colors in the film. While the films themselves contain very saturated colors, the projector tended to mute and mutilate the colors as displayed in windows — for instance, the blue oceans appeared almost black in the windows.

In both the CMS and the LMS, a defect existed in that the star simulation would bleed through the near-body scenes. The equipment, as originally designed, contained hardware to occult the stars in a circular pattern of the same diameter as the near body would subtend. This hardware proved difficult to maintain, was nonlinear with position and shape of the body in the FOV, and, as a result, did not successfully occult all the stars. Finally, a shortcoming of all near-body simulations was the low scene brightness. This condition required the crewmen to dark adapt to discern the necessary detail out the window.

Significant funds have been spent in developing the near-body simulations for the various space-flight vehicles. It is recommended that, in the future, the requirements for out-the-window scenes be very carefully analyzed and that extreme care be taken to limit the simulator requirements to those obtainable with reasonably simple hardware. For example, in the CMS, only the unity-power telescope in reality required stringent tracking accuracies. The other four active windows could have been animated with much less sophisticated hardware. Experience has also shown that window-scene generators should be more integrated as in the LMS and the CMPS than the system-per-window such as in the CMS. Such design considerations in future applications should both reduce initial costs and result in lower maintenance effort and costs.

Landing Scenes

Landing scene simulation was required only in the LMS for training in the lunar approach and landing phases. The altitude range desired was from a high-gate or breakout altitude down to and including touchdown. The scene was required to provide the crewmember with attitude and altitude information plus pertinent surface-feature details. In all other programs (for instance, during earth entry and landing), there was a minimum of crew activity relative to the window displays; therefore, little or no external scene simulation was supplied. In the LMS, the requirement was defined as a continuous scene from an altitude of approximately 15 000 feet to touchdown. The original requirement at the time of simulator procurement was for a generalized lunar surface containing representative features of the moon. This requirement was expanded subsequently to include modeling of the actual landing sites. Three-dimensional surface detail was required when surface irregularities became visible to the crewman. For the lunar landing simulation, the attitude at which surface features became important was defined as 2000 feet. An additional requirement was the casting of shadows such as would be caused by local surface irregularities when illuminated with collimated sunlight.

The visual acuity requirement was to identify objects subtending approximately 0.5° at the pilot's eye. This angle represents an object the size of a 175-foot-diameter crater observed from 45° at an altitude of 10 000 feet, or a rock approximately 1 foot in diameter observed from 100 feet. The positional accuracy of the information in the window was specified as 0.5° measured at the eye. In addition, the simulated spacecraft should be capable of landing; that is, the eyepoint should approach its scaled height above the model surface at touchdown. The lunar-surface terrain should represent the broad features to an accuracy of approximately 50 feet. In the landing area (approximately 2 miles in diameter), this accuracy is increased to approximately 10 feet. The surface should be enhanced with rocks and small craters. The size, number, and distribution of these rocks and small craters are based upon statistical lunar-surface data. The size of rocks and craters should approach the lowest modeling limit of 0.02 inch.

As initially delivered, the LMS was designed to meet the specified 15 000-foot-altitude range capability with a combination of the closed-circuit TV/film technique described previously for near-body scenes, and a relatively conventional closed-circuit TV/3-D model system. This model system, known as the landing and ascent (L&A) system, was used below 1200 feet. The model was 1:1000 scale with three typical terrain types arranged in 120° pie sections; one each for hummocks and small fissures, boulders and large fissures, and craters. The distribution of these features was such that approximately 35 percent of the surface could be used for landing. Shadows were simulated by painting the model. The solar elevation angle was assumed to be 45°. Overall, this system was determined to be inadequate for training. The major shortcoming was the lack of continuity from breakout to touchdown caused by the film system problems mentioned in the discussion of near-body scenes. An additional shortcoming was the lack of realism in the landing area model. An upgraded system, which used a 3-D model from breakout altitude to touchdown, was developed for training of the first lunar landing mission crews. Maximum altitude of the model simulation was increased to approximately 12 000 feet, and the model scale was established at 1:2000. Two significant features were added — an accurate model of the targeted landing area and a collimated light source to illuminate the surface and produce lunar-terrain shadows. Figure 13 is a photograph of the upgraded system. The model was viewed by an

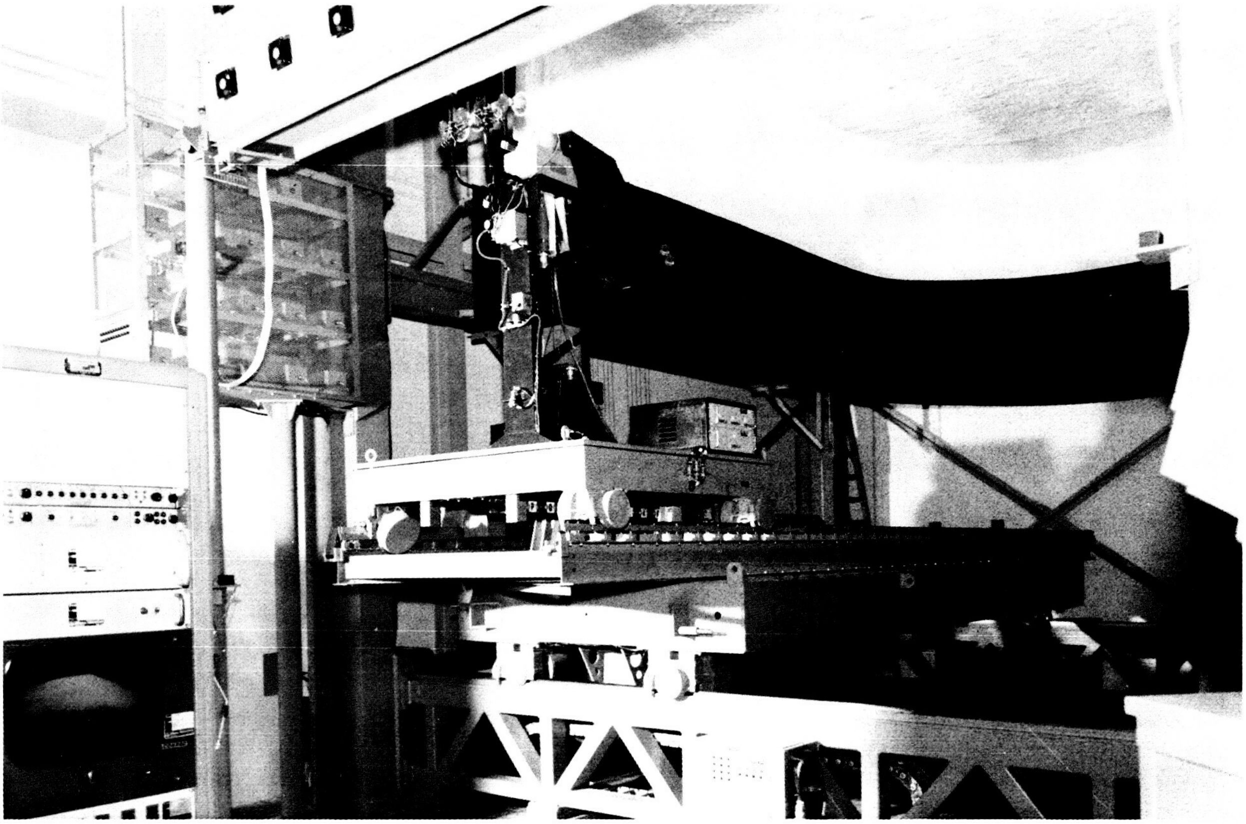

Figure 13. - Lunar-surface model (scale 1:2000) of lunar module simulator.

articulated probe with a 110° FOV. To produce the large depth of field required for viewing the surface obliquely, the probe had remote focus capabilities and tilt correction. The rotations in yaw and roll were unlimited, but pitch rotation was limited to -10° to +110°. The probe was driven horizontally across the surface in latitude and longitude, while the surface moved vertically to simulate altitude. The landing area simulated was approximately 5 by 8 nautical miles. The image was relayed from the probe to one window of the LM display system by the high-resolution closed-circuit TV. Switching was available to supply the image to either of the two LM front windows.

Several undesirable characteristics still existed with the upgraded L&A system. The closed-circuit TV performed according to expectations only with continuous maintenance. The horizon simulation, which was generated by mechanical rings around the model, exhibited errors of 3° to 5° for off-nominal trajectories. Duplication of the reflectivity of the lunar environment required continuous testing with each new surface installed. As the desired sun elevation angle increased above 12°, the probe shadow became very prominent and the actual touchdown area was in the shadow at angles above 18°. Various means of floodlighting this area alleviated the shadow but compromised the sun collimation.

Landing simulators used throughout the aircraft and airline industries for training pilots are in some ways similar to the L&A but are much less massive and, therefore, have lower demands upon servosystems. New designs for spacecraft landing simulators should take advantage of the design of these commercial systems. The use of collimated light to illuminate model surfaces should be carefully analyzed. Continued efforts should be expended toward producing a brighter image on the TV screen. Tests have been made with some degree of success on the use of black phosphors mixed with bright phosphors to provide a greater contrast ratio from less scattering of the light. Other techniques should be studied. Although simulation of the lunar landing did not require color (since the black-and-white system was very suitable), earth landing systems will probably require color; and the development of a tricolor high-resolution TV system is desirable, particularly for night approach simulation.

Concluding Remarks

Beginning with a simple simulation requirement to provide an out-the-window scene as a backup spacecraft-attitude reference in the Mercury flights, visual display simulation systems for the lunar landing mission have grown to become a major but necessary element of the Apollo mission simulators. For each visual task of the lunar landing mission, a visual scene was simulated through an infinity optics system in the mission simulator. Although the complexity and cost of these devices were significant, their use in mission training was mandatory.

MOVING-BASE SIMULATIONS

Various moving-base simulators have been used throughout manned space-flight programs for crew training. The primary objective has been to familiarize flight crews with the dynamic environment and to present them with visual realism of the operational task. The use of moving-base simulators and the experience gained while developing and operating such systems are described in this section.

A moving-base simulator is a device in which the major components have physical motion. The crew station or the crewmembers (or both) are subjected to the physical motion. The space-flight environments of earth launch, earth orbit, cislunar flight, lunar orbit, lunar landing, lunar-surface activities, lunar launch, atmospheric entry, and earth landing all contain elements of sight, sound, and touch that are not in man's normal experience. In these new environmental conditions, man has been asked to perform certain tasks, such as entry, docking, launch abort, and lunar landing. In preparation for these tasks, moving-base simulators have been used successfully to familiarize the crewmember with the anticipated environment and to confront him with the operations he would be expected to perform. New environments have consisted of launch acceleration profiles, reentry deceleration profiles, weightlessness, and the lunar gravity. Human centrifuges have been used to simulate the acceleration and deceleration profiles. The dynamic crew procedures simulator has been used to simulate the launch profile, including noise and vibration. Weightlessness has been simulated by aircraft zero-g flights and by water-immersion facility sessions. (These two facilities are not included in the category of moving-base simulators.) Training for the lunar-gravity environment has been accomplished through the use of the partial-gravity simulator (fig. 14), the mobile partial-gravity simulator (fig. 15), the lunar landing research facility (fig. 16), and the LLTV (fig. 5).

Although training for tasks such as reentry, docking, launch abort, and lunar landing has been accomplished on fixed-base simulators, crew proficiency for each of these tasks has been improved with moving-base simulators. The moving-base devices were used to add realism to the simulation by presenting realistic cues inherent in body acceleration and binocular vision.

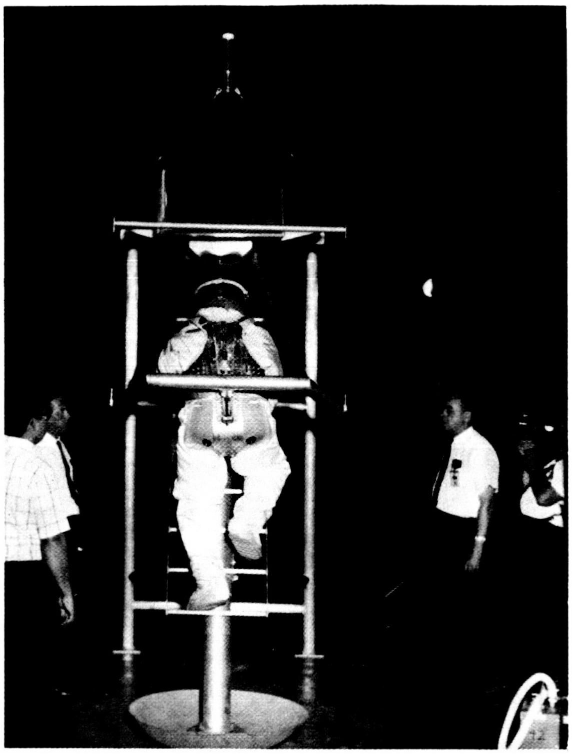

Figure 14. - Partial-gravity simulator.

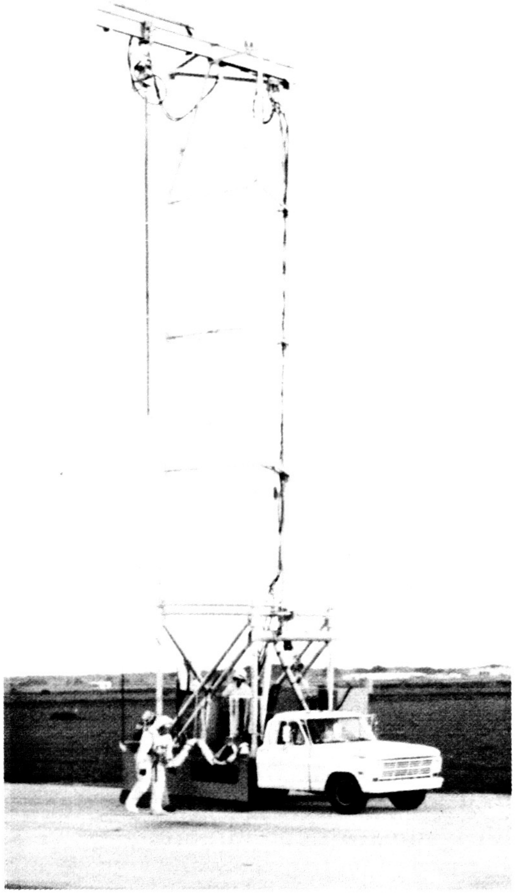

Figure 15. - Mobile partial-gravity simulator.

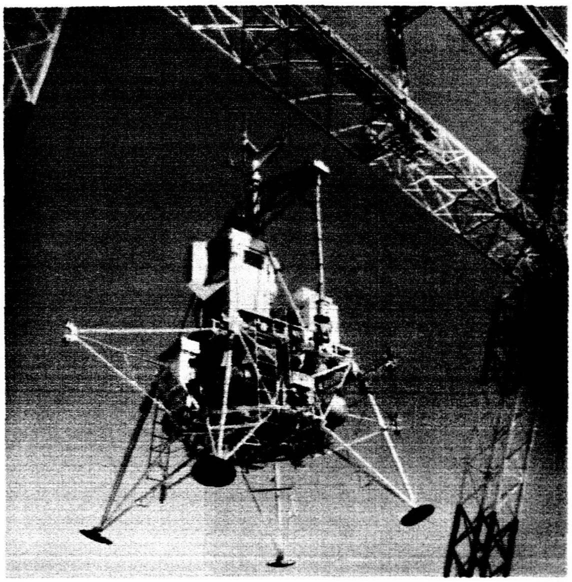

Figure 16.- Lunar landing research facility (Langley Research Center).

Application of Moving-Base Simulators

Several moving-base simulators have been used for crew training in environmental familiarization and development of task perfection. In preparation for the early space flights of Project Mercury, when little or no experience existed in the new environments, several devices were used to familiarize the crewmembers with anticipated or possible dynamic situations. The multiple-axis spin test inertial facility (fig. 17), which was a simulator built by the NASA Lewis Research Center, consisted of three gimbals individually powered by compressed-gas thrusters. Angular rates from near zero to more than 60 rpm could be generated. The crewmembers were whirled to rotational speeds at which disorientation occurred to familiarize them with this disorientation and to enable them to practice stopping the motions by use of the Mercury spacecraft hand controller and angular rate instrument displays. The tests served mainly to build confidence that, in the event of a gross automatic control system failure, the crewmembers could regain control of the vehicle and stop all tumbling.

The human centrifuge (fig. 18) at the Naval Air Development Center, Johnsville, Pennsylvania, was used for crew training in acceleration profiles and for engineering evaluation of crew-station equipment. The gondola of the centrifuge was equipped with the vehicle hardware required to support the astronaut in launch and reentry phases

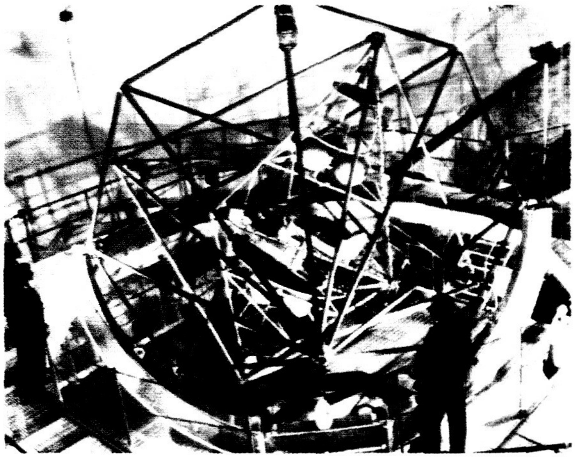

Figure 17. - Multiple-axis spin test inertial facility (Lewis Research Center).

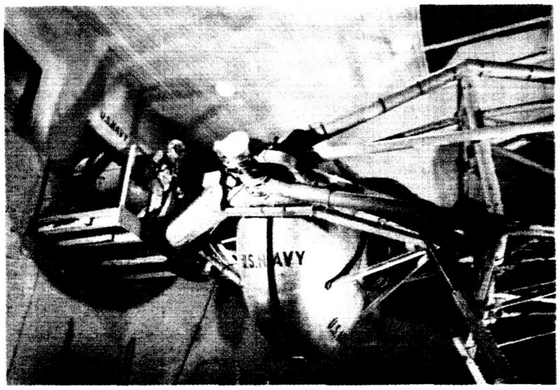

Figure 18. - Centrifuge (Naval Air Development Center, Johnsville, Pennsylvania).

of the mission. To further duplicate flight conditions, the gondola was evacuated to the reduced cabin pressure of actual flight. Six-degree-of-freedom equations of motion were used to animate the display panel and to generate the acceleration profiles. In the final training sessions for Project Mercury (August to September 1961), the crews, equipment, and procedures were evaluated by simulation of the complete three-orbit mission from preflight physical examination through countdown, launch, three orbits, reentry, recovery, and postflight debriefings and physical examinations. Baseline medical data for comparison with the flight data were derived from these sessions. The ALFA trainer (fig. 12) was basically a pseudo-Mercury spacecraft mounted on a spherical air bearing. This near frictionless support, coupled with a combined astronaut-plus-trainer center of gravity at the center of the ball, produced an accurate simulation of spacecraft motion as far as attitude control was concerned. The structural support systems and the effects of the one-g field on the trainer limited the yaw and pitch motions to ±35°. Roll was unlimited. All three attitude-reference systems (periscope, panel instruments, and window) were available to the crewmember. For the periscope display, a 10-foot-diameter screen was viewed through optics simulating the wide-angle view of the vehicle periscope. A moving earth scene of the orbital track was back projected onto the screen. This display was relatively accurate for deviation angles up to 25°. For the panel displays, actual vehicle hardware was used to measure the attitudes and rates and to display these values to the crewmember. For the view through the window, a lighted horizon and a generalized star field were provided. Motion of the trainer was controlled by the crewmembers' use of compressed-air jets. Mercury spacecraft control systems were simulated. Disturbances that could be produced by misalinement of the retrorockets also were simulated by compressed-air jets.

As the manned space-flight program progressed and experience was gained in space flight, crewmembers and engineers became more familiar with the dynamic environment. Crew performance in space was demonstrated, and many of the previous unknowns were no longer areas for concern. The performance of new tasks was necessary to achieve the goal of placing a man on the moon. Thus, the emphasis previously placed on dynamic environment familiarization became secondary to training for performance of special tasks. The tasks of docking, lunar landing, and traversing the lunar surface were approaching, and crew experience was needed. To meet this requirement, a new generation of moving-base simulators was developed for crew training. The Langley rendezvous and docking simulator (fig. 19) used a crew station supported in a gimbal that was suspended from a bridge crane. The crew station had six degrees of freedom and operated in conjunction with a stationary target vehicle. Primary attention was given to crewman position, control assembly, control modes, viewing window configuration, docking aids, and target-vehicle geometry. Development work on docking procedures was accomplished as well as crew training and evaluation of docking aids. This simulator was used for Gemini docking and for both Apollo docking configurations (CM and LM).

The MSC translation and docking simulator (figs. 20 and 8) was a six-degree-of-freedom simulator used primarily for crew training. The hardware consisted of a crew station mounted in a three-axis gimbal. The gimbal was supported by an air-bearing carriage to permit lateral motion. The two remaining translations, longitudinal and vertical, were simulated by target motion. These two motions were reversed to give the proper directional illusion of crew-station motion. Primary emphasis was placed on vehicle configuration and visual environment. Various control system modes were

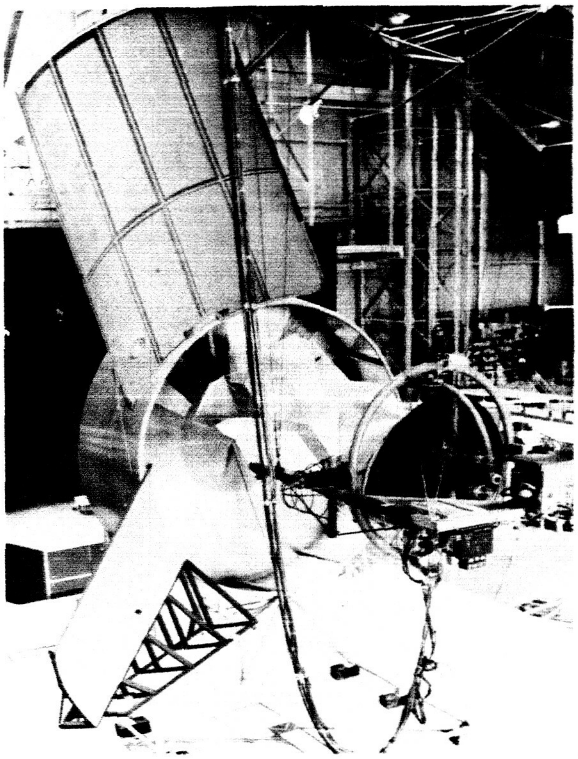

Figure 19. - Rendezvous and docking simulator (Langley Research Center).

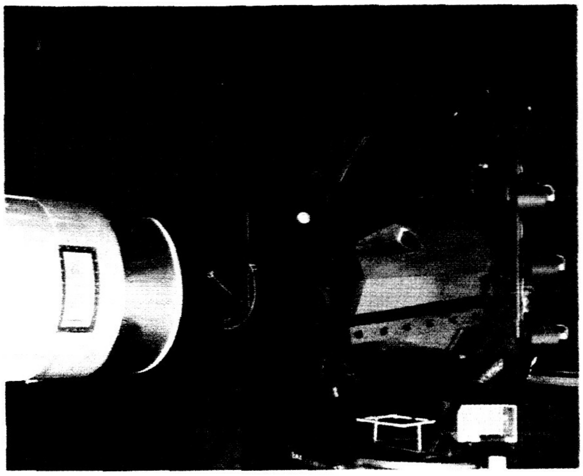

Figure 20. - Translation and docking simulator (Gemini).

simulated, and flight-type docking aids were used. Simulator configuration included Gemini docking, Apollo LM-active docking, and a modified CSM-active docking, in which CSM mass properties were programed into the simulator with control from the LM crew station.

The dynamic crew procedures simulator (fig. 21) consisted of a crew-station gondola supported in a gimbal that was cantilevered into a spherical dome. The design of this simulator was based on the idea of presenting the rotational acceleration to the crewmember while separating the velocity cues into a visual presentation. The interior of the dome was used as a screen on which an earth image or star field could be displayed. One of the primary features of the simulator was that it could present the dynamic environment (noise and vibration) of launch and reentry for crew familiarization. Procedure development and practice on the simulator have included launch, launch abort, reentry, and rendezvous. The simulator, which originally was designed and built in Gemini configuration, also has an Apollo CSM configuration (fig. 9).

The lunar landing research facility (fig. 16) was used for research and for crew training associated with the piloting of a vehicle in simulated lunar gravity. This outside facility consisted of a gimbal-mounted vehicle suspended from a traveling bridge crane. The piloted vehicle, originally with the crewman seated and later modified to a standup configuration, had an operating envelope of 180 feet vertically, 360 feet longitudinally, and 42 feet laterally. Two operational modes were used. The first mode, used primarily for pilot indoctrination and system test, simulated the lunar-gravity environment and rocket-engine lift through the use of the translation drive systems. The second (simulation) mode used the main rockets and onboard fuel to develop lift while the translational drives supported five-sixths of the vehicle weight to simulate lunar

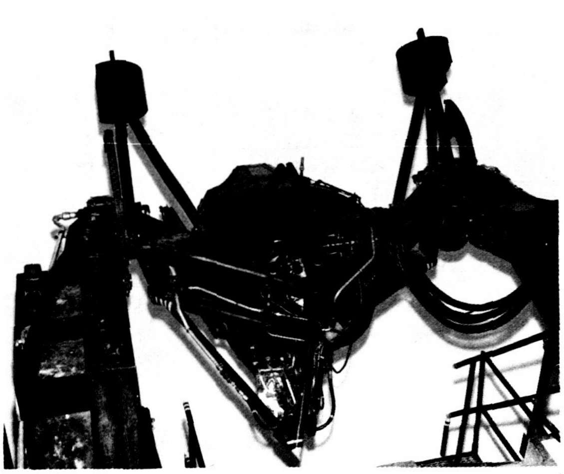

Figure 21. - Dynamic crew procedures simulator (Gemini).

gravity. The simulation mode allowed approximately 2 minutes of operation whereas the first mode afforded more than 20 minutes of continuous operation. Evaluations of control system parameters and piloting techniques associated with lunar landing touchdown were conducted. Operation with various landing models allowed evaluation in the area of obstacle avoidance and a limited look at surface dust effects.

The LLTV (fig. 5) is a free-flight vehicle consisting of a tubular frame on which a crew station, a jet engine, lift rockets, attitude control rockets, control electronics, and associated equipment are mounted. The jet engine, which was mounted vertically, provided main power for takeoff and supported five-sixths of the vehicle weight during simulation of the lunar environment. The vehicle was used to simulate the lunar landing from an altitude of 500 feet to touchdown. Operations were conducted over an airport runway and consisted of several familiarization flights prior to the lunar simulation flights. A fixed-base LLTV simulator (fig. 22) was used to familiarize the pilot with crew-compartment instruments and controls. Use of the simulator allowed the pilot to practice LLTV procedures and to become familiar with vehicle operations.

The partial-gravity simulator (fig. 14) consisted of a gimbal supported from a pneumatic cylinder. The pneumatic cylinder provided lift to support a proportional amount of a crewman's weight. The simulator was used to familiarize crewmembers with lunar-surface mobility. Use of lunar tools was practiced. A mobile partial-gravity simulator (fig. 15) also was used to familiarize the crewmembers with lunar-surface mobility. The two simulators were of the same basic design except that the mobile unit was suspended from a truck-mounted tower. This arrangement was used to extend the operating range and to allow investigation and familiarization with running under lunar-gravity conditions.

Figure 22. - Lunar landing training vehicle simulator.

Simulation Experience

In general, the design, operation, and modification requirements of moving-base simulators are similar to those of other simulation hardware. However, in addition to the greater emphasis on crew safety required, some unique features must be considered in the design and operation of moving-base simulators.

Moving-base simulators usually are designed for a special task or set of tasks.

The design must concentrate on the simulation of those tasks while minimizing the undesirable side effects that are inherent in moving hardware. To overcome undesirable side effects and to accomplish successful moving-base simulation, innovation and unique approaches are needed, such as the separation of simulated acceleration cues (seat of the pants) and velocity cues (visual), the use of airbearings to minimize other motion cues such as rumble, special servosystem design to keep undesirable dynamic cues outside the frequency and amplitude domain of sensory perception, rotation about the individual body center of gravity to equalize force on extremeties, painting, lighting to hide support or enclosure structure, and so on. The hardware design as well as the computer software must take into account the man-in-the-loop aspect. Convenient ingress and egress provisions are required and actual man-machine interface is necessary; however, only the pertinent interface should be included. Special programing, such as drive-system compensation, may be required for proper hardware performance. An overall systems analysis should be performed before design finalization to ensure that optimum simulation can be performed. Size and weight are basic considerations in the design. The simulator size is dictated by flight-vehicle configuration, and the design weight affects drive-system design and overall system complexity. Structural integrity must be consistent with the dynamic environment and the man-machine interface. Fidelity of the simulations is dependent on a satisfactory balance of these parameters. Controls and displays usually are limited to those necessary to accomplish the unique task or tasks. Cockpit displays other than those of the spacecraft are necessary in some moving-base simulators, such as the LLTV, because of their operating requirements. Special effects of lighting and sound have been used to add significant cues for the performance of a given task. Lighting also can be used to enhance the simulation. For example, in the MSC TDS, the target vehicle was illuminated to make it stand out against a subdued background. This technique is used to reduce the false cues given by supporting structures and surrounding walls. Foremost in the mind of the designer must be the characteristics of the spacecraft or the situation being simulated. If characteristics peculiar to the simulator overshadow the situation or spacecraft being simulated, the simulator will be of little value.

Moving-base simulator operations have requirements in addition to those of other simulators. These considerations exist because the crewman experiences the dynamic environment and because some physical limitations with moving hardware do not exist with electronic or optical simulations. The interface of the crewmember with the hardware is a prime consideration in the design and basic configuration. Crew restraints and hardware arresting gear are a part of the basic design. Computer program scaling and signal limiting should be compatible with the dynamic environment to be simulated. Operating procedures need careful consideration to allow successful simulation. These procedures include inspections and preventive maintenance; preflight checkout; and power-up, power-down, and backup procedures. The key to crew safety is a knowledgeable and alert operator with positive control over the motion systems. Velocity, acceleration, and position limits are a part of moving-base simulation. The task being simulated must be considered in the setting of these limits. In addition to these physical limits, equations-of-motion scaling limits and electrical limits are included to provide fidelity of simulation and safety of operation, respectively. These constraints are an inherent part of moving-base simulators and cannot be overlooked when considering operations.

As with any hardware, a development period is needed when producing a moving-base simulator to permit optimum engineering trade-offs. Simulator design in this area is unique because a limited number of simulators of a particular configuration are built, possibly only one. Therefore, a preliminary fabrication and checkout period, in which prototype hardware is developed and tested before production, could be used to develop better hardware and to eliminate operational problems. Another design consideration should be the use of off-the-shelf items to minimize special equipment, which is hard to replace and usually expensive. In addition, it should be remembered that simulation equipment has a high use rate and needs to be designed with a high degree of reliability. The computer program (analog or digital) will in some ways be unique because of the interface requirements with moving hardware. The nature of the hardware must be considered and special formatting or signal conditioning accomplished to perform a valid simulation. In addition, it is useful to be able to verify the computer program independent of the moving hardware. A computer self test, or program designed to close the loop on itself, can be a valuable tool in program verification and checkout.

Concluding Remarks

Various moving-base simulators have been used in manned space flight to add a degree of fidelity in certain flight regimes not available in fixed-based simulations. In spite of design complexities, additional operational procedures, and safety considerations (compared to fixed-base devices), moving-base simulators will continue to play a significant role in training and simulation for future programs.

SIMULATOR CONFIGURATION MANAGEMENT

The three manned-space-flight programs (Project Mercury, the Gemini Program, and, in particular, the Apollo Program) have emphasized progressively the requirement for a firm simulator-configuration-management program. The requirements for simulator-configuration management exist for the same reasons as those of spacecraft configuration management; that is, the need to know the vehicle configuration at any point in time and the need to know the vehicle future or desired design configuration. The converting of the vehicle, or in this case, simulator, from an actual configuration to a design configuration must be by means of an organized and systematic procedure — one that will provide the highest crew-training return with a reasonable manpower and dollar investment. The guidelines in this section describe how this balance, or goal, has been achieved closely in past programs and how it can be realized fully in future programs. The following discussion defines the necessary building blocks for simulator configuration identification: configuration tracking, configuration control, and configuration accountability — the total of which is synonymous with configuration management.

Configuration Tracking

The major crew-training (mission) simulators for Project Mercury and for the Gemini and Apollo Programs all were developed and constructed by industry contractors. Each simulator constituted a contract end item and was initially designed to a basic data package, largely supplied by the spacecraft prime contractor through NASA. This data package was serviced and updated in total until the simulator preliminary design review

(PDR) and formed the basic mathematical model and hardware design definition for each respective simulator. At the PDR, the simulator reached a contract definition stage (usually, although somewhat erroneously, referred to as a contractual "design freeze"), beyond which all simulator updates or changes to the spacecraft baseline data package constituted a design change and required a corresponding simulator contractual change. It is at this point that the terms "modification," "configuration control," "in-line modifications," and "modification kits" assume their full significance and the execution phase of modification activity begins. This modification activity usually commences prior to formal contract delivery of the basic simulator to NASA.

In its simplest terms, a spacecraft modification is a class I or class II change to the flight vehicle that requires duplication in the simulator to prevent a serious degradation in crew training or simulator configuration. A class I change is an out-of-scope modification to the flight vehicle and is initiated by a contract change authorization (CCA) from NASA to the spacecraft prime contractor. A class II change is an in-scope modification that the spacecraft prime contractor finds necessary to implement, and does so without a change or amendment to the contract. All spacecraft modifications in either class are reviewed and considered for implementation into the simulator. A routine, thorough review of all these changes is hardly acceptable in terms of man-hours (at one point in the Apollo Program, the change activity was running at 75 to 100 changes per week), and timesaving shortcuts can be identified quickly. Examples of shortcuts that are used on the Apollo Program will be given later. First it is necessary to define the methodology and technique used in identifying spacecraft changes from a simulation point of view. Through January of 1970 in the Apollo Program, 1050 changes were approved for incorporation into the CMS alone, and approximately 700 of these resulted from counterpart spacecraft changes. The following procedures can be adapted and used to identify simulator changes (resulting from actual or proposed spacecraft changes) for any given program. No attention will be given here to the simulation-fidelity requirements relative to a spacecraft change, as that subject is covered in other portions of this report.

1. Monitor and review regularly the agenda and minutes of the spacecraft Configuration Control Panels (CCP's). This activity will normally cover all proposed and approved requests for engineering change proposals (RECP's) from NASA and all engineering change proposals (ECP's) from the contractor of less than a certain dollar value or with less than a certain schedule impact.

2. Monitor and review regularly the spacecraft Configuration Control Board (CCB) agenda and minutes. This activity will identify high-impact approved or disapproved spacecraft changes and items referred by the spacecraft CCP.

3. Obtain copies of, and review, the prime contractors' internal change authorization paperwork. In the Apollo Program, these authorization documents were the manufacturing change request (MCR) and the lunar module change request (LCR) from the prime contractors for the CSM and the LM, respectively. These documents are normally released to initiate a design study and frequently are weeks ahead of RECP, ECP, or CCA action. Consequently, the use of this monitoring tool allows routine identification of proposed changes much earlier than the activities described previously (items 1 and 2); however, care must be exercised in cross-checking these releases against the NASA CCP and CCB activity for approval authorization. An alternative to this procedure is to obtain the contractor's MCR release-to-manufacturing milestone,

which signifies that the MCR is approved for implementation. It should be noted that there is no obligation for the contractor always to release an MCR (or a similar type paper) for a change, and frequently the contractor does not do so for class II changes.

4. Routinely review basic system schematics on a per-spacecraft basis as a cross-check against items 1 to 3.

5. Obtain routine distribution of all mission-definition documents and updates of these documents within NASA.

6. Obtain routine distribution of all guidance and navigation onboard computer program documentation and pertinent engineering reports.

7. Establish channels with all NASA associate contractors for applicable spacecraft data on an as-required basis.

As mentioned earlier, certain shortcuts can be taken to decrease the NASA man-hours required to review and control the rather large bulk of information and documentation identified previously. Examples of the shortcuts that have been used on the Apollo Program and that should be considered on future programs are as follows:

1. Have the spacecraft contractor categorize MCR's and filter out those clearly not applicable to simulator design. Examples are ground-support equipment MCR's that are not transmitted to NASA simulation personnel.

2. Do not submit any simulator change for approval unless the spacecraft counterpart is released to manufacturing or the item is considered to be a long-lead-time type change. In the past, the released-to-manufacturing milestone has been identified on the MCR document; if it is not, a tabulation of this information is required from the contractor.

3. Review CCB directives. This procedure will provide a summary of NASA-approved CCP and spacecraft changes and will reduce review of agenda and minutes to a cursory level to identify only those proposed changes placed in a deferred status.

4. Establish a procedure for the spacecraft contractor to audit, screen, and identify all class II changes that could be applicable to the simulator configuration.

5. Initiate parallel shipment of spacecraft-modification data to the simulator design contractor or support contractor (or both) as well as to NASA. This procedure will enable parallel review and impact analyses of modifications.

Whereas the previously mentioned simulator modifications may result from a spacecraft subsystem change, subsystem improvement, elimination of crew safety hazard, elimination of potential single-point failure, change in trajectory or landing site, and so forth, there is also a category of simulator improvement modifications not contingent upon spacecraft changes. This category is for the improvement of operational, maintenance, or training capabilities of the simulator in terms that are evident to NASA operations personnel or NASA support contractor modification and maintenance personnel. This type of modification has no parallel in the true spacecraft. Either NASA or simulator contractor personnel initiate this type of change, although this procedure is not mandatory. However, these persons usually possess the firsthand experience and knowledge needed to recognize candidate simulator improvements. When simulator history is traced from the first Mercury procedures trainer to the CMS and the LMS, a dramatic increase in simulator improvement modifications is apparent. This increase can be attributed, in large part, to the justifiable increase in complexity in the man-machine interface. For example, whereas the Mercury procedures trainer was a rather simple procedural analog training device designed to simulate a somewhat repetitive series of missions, the CMS and LMS, each with a powerful computing complex and complicated MCC interface, were designed to simulate a much larger repertoire of missions.

In addition to the configuration change identification data discussed earlier, spacecraft change implementation data must be defined and obtained. These data fall into the following areas:

1. Internal MSC data such as mission planning and trajectory data

2. Internal NASA data such as NASA George C. Marshall Space Flight Center booster and launch trajectory data

3. NASA associate contractor data such as the Massachusetts Institute of Technology onboard computer programs and necessary supporting documentation for the Apollo Program

4. NASA spacecraft prime contractor and subcontractor vehicle subsystems data

The process of identifying and obtaining the data listed in items 1 to 3 is simple, but a difficulty inherent in item 4 is the undesirability of receiving updates to 500 000 spacecraft drawings. The method that works well on the Apollo Program is correlation of the spacecraft prime contractor MCR or LCR to newly defined spacecraft drawings or engineering order (EO) to existing drawings, and transmittal to NASA of the drawings or EO's on microfilm aperture cards. Furthermore, NASA reviews MCR and LCR documents immediately after they are released and informs the contractor which potential changes will have impact on the simulator; consequently, particular data are identified long before the data are released, which is a desirable condition. Also, this procedure eliminates transmittal of data for MCR's that do not have impact on a simulator. The document that relates MCR's to drawings and EO-type data is called a data submittal letter and is a cross-tabulation of MCR number to drawing or EO number. After an MCR or LCR is defined as applicable to a simulator, all spacecraft data released against it will be supplied to NASA.

All proposed modifications for the simulator submitted to the Simulator Control Panel (SCP) require preparation of a standard form known as a modification request (MR). The MR is required to contain the following information:

1. The change to the actual spacecraft and its effect on vehicle operation or crewmember interface (or both) (not required for simulator improvement modification)

2. Definition of the counterpart simulator change required to update the simulator to reflect the spacecraft

3. The effect on crew training if the change is not implemented

4. Spacecraft and simulator effectivity

5. How, and to what extent, the hardware or software (or both) is to be modified

6. An estimate of parts cost and source, and the man-hours and computer-hours required to implement the modification from preliminary design to final NASA acceptance

7. A schedule of all pertinent milestones including final installation acceptance

The author of the MR supplies information for items 1 to 4. The NASA simulator contractor, who will implement the modification, supplies information for items 5 to 7. All MR packages are reviewed and screened for accuracy and relevance before submittal to the SCP — which is the next subject and the first step in configuration control.

Configuration Control

All MR's require SCP approval before implementation. The functions and responsibilities of the SCP are defined as follows:

1. Evaluate spacecraft changes that have impact on the simulator.

2. Evaluate all other proposed changes, such as launch vehicle, mission trajectory (reset), and simulator improvement, that have impact on the simulator.

3. Review the availability of spacecraft data for each spacecraft modification presented for approval.

4. Confirm simulator effectivity for a modification.

5. Assign responsibility for implementation of each modification.

6. Approve a schedule for each modification based on consideration of the following items:

   a. Mission effectivity and schedule

   b. Crew-training requirements

   c. Simulator availability

   d. Flight controller (integrated mission) training requirements

   e. Difficulty and extent of modification

   f. Cost

7. Review the total operational and modification status of the simulator.

8. Act as the overall configuration management control point by defining any additional procedures required for a specific modification, assigning action items, and ensuring that the overall modification cycle is operating in a smooth and timely manner.

Immediately before a scheduled SCP meeting, a pre-SCP meeting is held between NASA and simulator support contractor personnel. The purpose of this meeting is to review all modifications on the SCP agenda for technical accuracy, format, and completeness. In the pre-SCP meeting, the disposition of all new and open MCR's that are not ready for presentation to the SCP also is determined. The functional placement of the pre-SCP and SCP activities are shown in figure 23. The following categories are used in the pre-SCP meeting to classify all MR's:

1. Recommend SCP disapproval of the MR or determine that the MR is not applicable to the simulator.

2. Determine that the MR is not yet impacted and that impact is required for consideration at the next SCP meeting.

3. Determine that the MR is not impacted because of lack of data and that action is required to obtain data.

4. Recommend approval of the MR to the SCP.

5. Place the MR in abeyance to be reevaluated at a future NASA-specified date.

6. Place the MR in a hold status pending more detailed NASA review.

7. Determine that the MR revision has no effect, and, thus, that the previous revision level remains in effect.

8. Determine that the MR affects telemetry measurements and should be grouped into one master, collective MR.

9. Determine that the MR is approved for implementation, but that new impact on GFE or CFE hardware is required for the the next SCP meeting.

The SCP consists of representatives from the appropriate MSC directorate, from the NASA simulator support contractor project management office, and of attendees from other MSC organizations concerned with the simulator interface areas to be discussed. The SCP receives and reviews those modifications recommended for approval or disapproval at the pre-SCP meeting. Presentations are made routinely on these modifications.

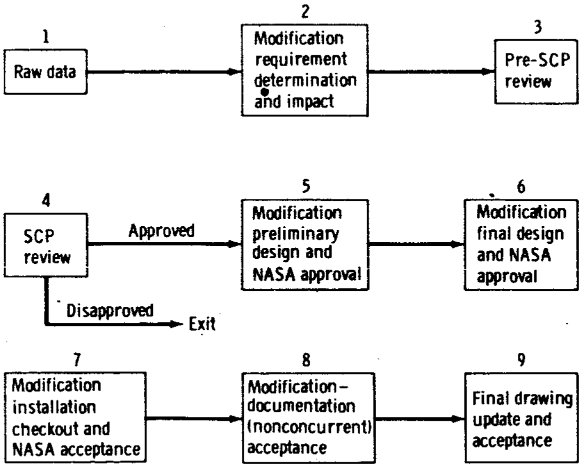

Figure 23. - Simulator modification flow.

The NASA simulator support contractor SCP responsibilities and participation are as follows:

1. As a routine activity, evaluate for technical impact and for simulator and spacecraft effectivity all MR's received from NASA, received from the prime spacecraft contractor, or self-originated (or any combination of these sources).

2. Assure that the necessary spacecraft data are collected and reviewed to the extent necessary for impact on the modification for the SCP. This impact entails the following activities:

a. Estimate the engineering effort and schedule for each individual modification submitted for approval. This estimate includes the engineering effort necessary to change or update (or both) the affected hardware drawings, software mathematical models, specifications, interface control documents, and so forth.

b. Estimate the programing effort and schedule for implementation of each software modification to the actual simulator program. The estimate will cover adding the modification either as a patch (octal correction) or as a basic change to the software load (assembly change).

c. Estimate the design and drafting effort necessary to originate or update (or both) drawings, wiring lists, and other affected documents for an electrical or mechanical modification. This activity usually is related to the supporting engineering activity in item a.

d. Estimate the on-line man-hours and machine-hours required for installation and checkout of each modification.

e. Estimate any required parts cost and indicate the parts sources.

f. Estimate a final date for each modification to be ready for NASA acceptance and subsequent shipment to other simulators, as required.

3. Provide logistics support and necessary SCP documentation (agenda, minutes, manpower curves, etc.) as a routine requirement.

4. Be prepared to participate at the project managerial level in any discussions and reviews of the overall modification activity as it affects crew training, schedules, manpower levels, areas of required additional technical emphasis, and future goals for all simulators.

5. Understand and implement the ECP decisions and assigned action items with proper NASA coordination.

Configuration Accountability

Configuration accountability involves the establishment, monitoring, and updating of simulator documentation to define a baseline and a modified current configuration of a simulator at any point in time in terms of hardware and software. This process requires the following:

1. A description and understanding of the types of documentation and the methodology in changing these documents

2. A centralized, organized, rapid-information-transfer system for implementing item 1 with proper interfacing approval points within configuration control management

3. A rigorous library and information system designed to handle listings and records of multiple simulator configurations that are in work

4. Standardization of items 1 to 3

All simulator hardware has required and will continue to require comprehensive documentation. This documentation ranges from the basic drawing tree definition to the specific drawings defining fabricated and purchased hardware as well as locating the hardware within the simulator complex. However, within this large mass of documentation, the basic requirements and procedures for updating, providing traceability, and, in general, accountability are the same for every hardware document in the system. Thus, for purposes of this paper, discussion will be provided for a single piece of hardware documentation entitled a drawing, with the realization that, although this drawing may have dozens of variations and specific uses, for purposes of configuration management it is one homogeneous entity.

The following facts have been proved true for hardware accountability:

1. A baseline set of drawings and drawing tree must be established to match simulator hardware.

2. One piece of paper must be generated for every simulator hardware change. (This paper has had and may use any one of a number of names, but it is most universally known as an EO.)

3. An EO must describe before and after conditions when the EO makes a hardware change in an existing drawing.

4. New drawings must be authorized by EO's. The EO's place the new drawings in their respective positions within the drawing tree by making proper references to the next higher and lower drawings in the tree.

5. An EO must be approved by configuration control management and may be issued only to correct an error or discrepancy or to implement an approved modification. The only exception to this rule is the temporary EO that is used to allow experimental or short-lived changes in hardware for a definite period of time. At the termination of this period, the hardware must be returned to the original configuration, or formal modification procedures must be exercised to produce a permanent EO.

6. The quality control section performs the final acceptance inspection of an EO by comparing it to the affected, parent, and updated drawings and to the hardware.

7. The EO's may be allowed to build up against a drawing but never to the extent that the usefulness of the drawing is destroyed.

8. Each time a drawing is called for by anyone, open EO's are automatically provided with the requested drawing.

9. When a drawing is modified by an EO, the modification is indicated by a revision letter on the drawing.

10. The exact hardware configuration of any simulator can be tracked and identified by tracking all EO's with the baseline drawings (item 1).

11. Maximum utilization is made of computerized monitoring (particularly in multiple simulator and multiple configuration situations) of the hardware drawings and EO definitions of each individual simulator configuration.

Although software accountability appears to be vastly different from hardware configuration activities at first sight, parallel procedures are used to focus upon the same goals. The Apollo Program provided the most complex simulator software control and accountability situation known to date and at its peak had three CM simulators and two LM simulators, each in different spacecraft configurations, concurrently undergoing some common and some unique spacecraft modifications. Coupled to this activity was the routine software housekeeping-discrepancy cleanup, which resulted in further impact on the situation. Fortunately, very early in the Apollo Program the master load concept was organized and executed, and it represents the present state of the art in simulator software accountability. The master load operation, the use of which has made the described situation workable, is summarized as follows:

1. As was the case in hardware accountability, the first order of business is the establishment of one software program that operates on all common simulators with defining mathematical model and program-listing documentation.

2. From item 2 forward, no change is made to the assembly, or master load, without a software change request (SCR) — the authorizing software configuration change document.

3. An SCR may be generated only to implement a modification or to correct a discrepancy in the software. The SCR's are reviewed and approved by one centralized group before being coded for use. A temporary SCR is used with the same ground rules and restrictions as the temporary EO.

4. Under normal circumstances, no newly added, revised, or corrected software is made directly in the assembly.

5. Routinely, all software changes or additions (modifications of discrepancy corrections) are approved first as a patch to the existing load by all parties concerned. Specifically, the new work is verified as a parallel piece of software by exiting and entering the existing load at appropriate points. Thus, the load software represents a

fail-safe capability that prevents the affected program or subroutine from degenerating to a state any less desirable than that prevailing before a modification.

6. Item 5 may be implemented by card patches or octal tape techniques, whichever is easier for the particular simulator or rate-of-change traffic.

7. All approved modification and discrepancy patches (SCR's) are recorded and approved for the next scheduled assembly. It is highly desirable to minimize this recording effort by automating (computerizing) the off-line capability to do so. (At the time of this writing, this activity is in work for the Apollo Program simulators.)

8. The frequency of new loads or assemblies is dictated by the quantity of approved patches and the associated core and timing penalties. During the Apollo Program, new assemblies were generated every 3 to 4 months.

9. Software mathematical models are updated and referenced to approved SCR's by using the same logic and requirements used for the hardware drawing and the associated EO. The SCR is the software change-defining document.

10. When a software mathematical model is called for, all open approved SCR's are provided automatically.

11. Traceability exists between SCR's, patch (listing), controlling paperwork (discrepancy report or modification), and, if approved, the SCR occupation in the next new load.

12. The octal training tape technique also should be examined for usefulness and application to a specific simulator program. This approach uses two octal tapes, one containing all newly created work and the other containing all newly approved work. Work is shifted (approved) from one tape to the other and, for crew training, the load and the octal tape with approved software are used. Naturally, the next new assembly adds to this approved software and the cycle repeats itself. The advantage of this operation is that new software work can be used almost immediately without waiting for a new assembly. At the same time, approved software is segregated from developmental or unapproved software and preserves the configuration and operational integrity of the simulator.

Concluding Remarks

Because of the continuing changes of both the spacecraft and mission, and the necessity for a correspondingly prompt and accurate method of updating the flight crew simulators, a systematic method of simulator configuration management is a confirmed requirement. The Apollo Program provided the most severe requirements and problems encountered to date in this area. These requirements and problems were satisfactorily met and resolved. The viable methods of simulator configuration management that were developed and refined during the Apollo Program should lend themselves directly to future programs.

CONCLUSIONS

Because of the total-commitment and economic aspects of manned space flight, the use of comprehensive, high-fidelity simulators for flight crew training will continue as a firm requirement in future programs. Through space-flight experience and the development of simulators to meet the training requirements, a number of factors have been established as basic in providing the required simulation fidelity.

1. A high degree of crew-station detail, particularly in the full-mission simulators, is necessary to simulate accurately the spacecraft performance and mission characteristics. In addition to a complete simulation of the spacecraft controls and displays, such items as stowage provisions, lighting, aural cues, and crew-station hardware are extremely important in providing this required fidelity.

2. Visual display systems providing out-the-window simulation of visual tasks are mandatory for accurate flight simulation.

3. Moving-base simulators add a necessary degree of realism in certain phases of spacecraft simulation that is important to the total training requirements.

4. A systematic method of simulator configuration management is a necessity. Acquiring and verifying the spacecraft and mission data, reviewing changes for applicability to the simulators, and identifying simulator configuration at any point in time by correlation with the spacecraft and mission are all necessary parts of this system. The viable methods of simulator configuration management that were developed and refined during the Apollo Program should lend themselves directly to future programs.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, July 14, 1972
076-00-00-00-72

REFERENCE

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APPENDIX

SIMULATOR DESCRIPTION

PROJECT MERCURY

Mercury Procedures Simulator

Two MPS's (fig. 1), one housed at Langley Field, Virginia, and the other in the Mercury Control Center at KSC, were the main crew simulators for Project Mercury. Both simulators used small, although somewhat different, analog computers to drive the equations-of-motion simulations. All spacecraft systems were simulated actively by hardwired electronic circuitry with the capability of introducing approximately 276 separate system failures. The simulator at Langley Field had an active periscope display consisting of a moving dot (on the face of a CRT), which was activated by a hand controller through the analog computer. Late in the program, an out-the-window display was added to this simulator.

Centrifuge

The centrifuge located at the Naval Air Development Center, Johnsville, Pennsylvania (fig. 18), was used to provide the Project Mercury crews with training for the launch, launch abort, and entry phases under simulated acceleration loads. The acceleration simulation was mechanized in both closed- and open-loop modes through the Aviation Computer Laboratory analog computers. Initial runs were made in the closed-loop mode, in which the resulting acceleration profile as well as the panel displays responded to inputs from the pilot's hand controller. Analyses of these first runs indicated that adequate training could be obtained by simply preprograming the acceleration profiles (open loop). In subsequent centrifuge training, only the displays were integrated with the computer to respond to the pilot's inputs. The cockpit equipment included individual crew couches, restraint systems, the spacecraft hand controller, and a portion of the spacecraft instrument panel with emphasis on the sequence telelights. Training was accomplished with both soft and hard pressure-suit operations. Manual control of the spacecraft, including manual retrofire maneuvers and simulated system failures during launch and entry, was covered in the training.

Air-Lubricated Free-Attitude Trainer

The ALFA simulator (fig. 12) was a moving-base device consisting of a Mercury-type couch supported by a 5-inch-diameter spherical air bearing to provide a close simulation of spacecraft rotational motions. No computer was used; rather, the simulator was a direct analog of the spacecraft using compressed air jets as the attitude reaction-control forces. For the cockpit displays, actual spacecraft hardware was used to measure the attitudes and rates and to display these values to the pilot. A simulated out-the-window display was provided. (A detailed description is provided in the section entitled "Moving-Base Simulations.")

Part-Task Simulators

Two part-task simulators (fig. 24) provided the first simulation of the astronaut's control tasks in Project Mercury. Both simulators used analog computers. The tasks simulated included changing spacecraft attitude in orbital flight (including orientation for retrofire), holding retrofire attitude in the presence of retrorocket misalinements, and damping pitch and yaw oscillations through the entry.

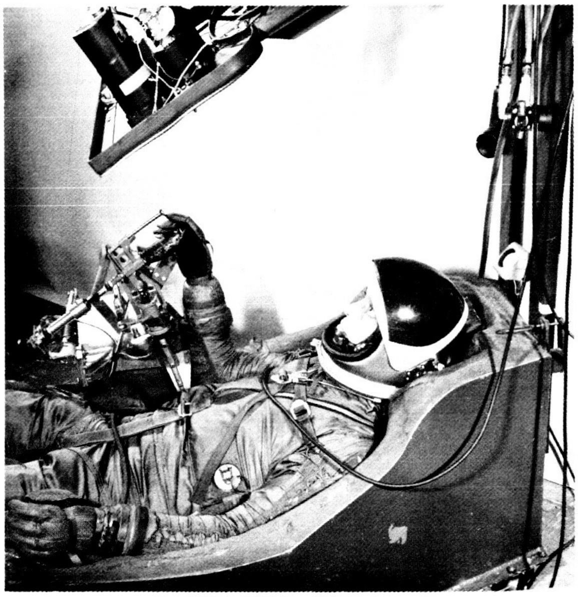

Figure 24. - Mercury part-task trainer.

GEMINI PROGRAM

Gemini Mission Simulators

Two GMS's (fig. 2) were the principal crew-training devices for the Gemini Program. One was located at MSC in Houston and the other at KSC. The GMS provided simulation of the Gemini spacecraft, the Gemini launch vehicle, the ground tracking sites, and the Agena target vehicle. The GMS could be operated as an independent crew simulator or integrated with the MCC for combined flight crew and flight controller training. The simulator included a high-fidelity representation of the interior of the spacecraft crew station, an instructor's console with a capability to insert more than 600 different system malfunctions, and a computer complex consisting of three digital computers. Infinity optical display systems were used to provide dynamic out-the-window scenes including the moving earth, stars, and Agena target vehicle.

Dynamic Crew Procedures Simulator

This moving-base simulator (fig. 21), located at MSC, provided Gemini mission training in the launch, launch abort, and entry phases. The gondola was supported in a set of gimbals that accommodated a Gemini crew station. The gimbals were driven in conjunction with a visual display to provide rotational cues and initial g-force onset typical of launch vehicle lift-off. In addition, the launch-phase environment was closely simulated by providing launch vehicle noise and vibrations. The DCPS was driven by a hybrid setup consisting of a digital computer and an analog computer.

Translation and Docking Simulator

The TDS (fig. 20) was designed to provide crew training for the last 100 feet of the orbital rendezvous — the final closure and docking. The simulator provided six degrees of freedom with the proper combination of motion of the crew station (spacecraft mockup) and the simulated Agena target vehicle. Both the spacecraft carriage and the target vehicle were supported on air bearings to provide the low friction required to simulate the small, precise motion of orbital flight. Various lighting conditions and control modes were provided in the training operation. In addition to the docking maneuver, the simulator provided a training capability for formation flying and target-vehicle inspection. The simulator was driven by analog computers.

Centrifuge

The Naval Air Development Center centrifuge (fig. 18) at Johnsville, Pennsylvania, was used to provide launch, launch abort, and entry acceleration training for the Gemini astronauts. The cockpit was configured to simulate the Gemini command pilot's station. The acceleration profiles were preprogramed; however, the entry dynamics as displayed to the pilot on his cockpit instruments were closed loop with the analog computer. Suited runs were made to include the effect on the control task of both soft and hard (pressurized) modes of suit operation.

APOLLO PROGRAM

Command Module Simulator

Three CMS's (fig. 3), one located at MSC and two at KSC, provided the major portion of the CSM crew training for the Apollo Program. The three simulators were designed and maintained to be identical for maximum modification and operation efficiency. The CMS was capable of accurately simulating all phases of the CSM operation. Each CMS consisted of a high-fidelity representation of the spacecraft interior, an accurate presentation of exterior visual scenes through an infinity optics display system, an operator console, and a computer complex. The computer complex consisted of four digital computers, one of which was assigned solely to simulation of the onboard guidance computer. The CMS could be operated independently, integrated with either the MCC or the LMS, or integrated with the MCC and the LMS in a complete mission simulation mode. Beginning with training for the Apollo 10 mission, a fifth computer was added to each CMS to provide a simulation of the Apollo/Saturn V launch vehicle.

Lunar Module Simulator

Two LMS's (fig. 4), one located at MSC and the other at KSC, provided the training for the LM portion of the Apollo missions. The two simulators were designed, built, and maintained to be identical. They consisted of an instructor and operator control console, an infinity optics display system for complete out-the-window scene simulation, a high-fidelity representation of the LM crew station, and a three-machine digital computer complex. The digital computers were the same as those used in the CMS. Also as in the CMS, one computer was assigned exclusively to simulation of the onboard guidance computer. A significant portion of the LMS, which provided training for final touchdown, was the L&A visual display system. This system included a lunar terrain model (scale 1:2000) of the specific landing site for each mission.

Command Module Procedures Simulator

The CMPS (fig. 6) was developed originally from the GMS and was used extensively for procedures development and verification in addition to providing crew training in the various flight modes. This simulator, along with the LMPS, was driven by a large second generation digital computer. The CMPS included the CSM guidance, navigation, and control system; the stabilization and control system; and the propulsion system, in addition to the guidance computer functions that were required to perform the rendezvous maneuvers and earth entry. An out-the-window scene, which included stars, the earth, and a target model, was provided through an infinity optics system.

Lunar Module Procedures Simulator

The LMPS (fig. 7) was operated in conjunction with the CMPS and was driven by the same computer system. Also like the CMPS, the LMPS was capable of simulating all the LM guidance and control systems, and all appropriate controls and displays. The visual display system used infinity optics to provide horizon and surface features, stars, and the CM target.

Dynamic Crew Procedures Simulator

The DCPS (fig. 9) for the Apollo Program training was modified by replacing the Gemini Program configured gondola with a CM crew station. In addition to providing launch, launch abort, and entry training, the simulation was expanded to cover the translunar injection maneuver, including the manual backup mode during this phase. The increased complexity of the Apollo Program required the addition of another digital computer to the existing hybrid setup used during the Gemini Program.

Translation and Docking Simulator

At the conclusion of the Gemini Program, the TDS (fig. 8) was modified to provide training for the Apollo LM-active docking. The LM-active mode (rather than CM-active) was simulated as it represented the more difficult task because of the range of control available, and docking was conducted with the view through the overhead window of the LM. An LM crew station was installed as the active vehicle, and a modified CSM mockup replaced the Gemini Agena as the passive target vehicle. For the initial Apollo flights, training for the CM-active mode was provided on the NASA Langley Research Center full-scale rendezvous docking simulator (RDS) (fig. 19). For later missions, the docking model system in the mission simulators was improved to a level that enabled discontinuation of training on both the TDS and the RDS.

Centrifuge

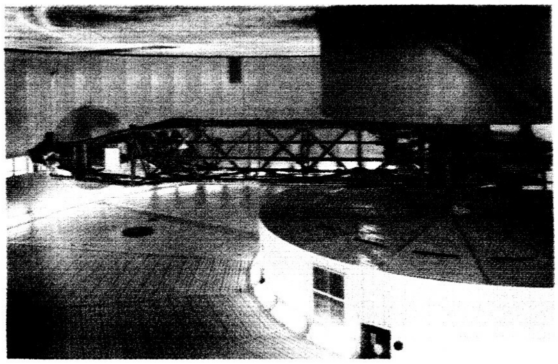

Figure 25. - Centrifuge (Manned Spacecraft Center).

The MSC centrifuge (fig. 25) was used to provide Apollo Program crew training in the use of the entry monitor system during simulated lunar-return entry and associated acceleration conditions. The simulated cockpit in the gondola included three crew couches, an entry monitor system, a flight director attitude indicator, a gravity meter, and the right-hand rotational hand controller. Five computers, three analog and two digital, were used to simulate the vehicle dynamics and to drive the centrifuge.

Lunar Landing Training Vehicle

The free-flight LLTV (fig. 5) was designed to provide Apollo Program crews experience in the handling characteristics of the LM during the final portion of the lunar descent and touchdown. The LLTV used a vertically mounted, gimbaled jet engine, automatically controlled to support five-sixths of the vehicle weight. The remaining one-sixth was lifted by two 500-pound maximum thrust, throttleable lift rockets to simulate the LM descent engine. The cockpit included an LM three-axis attitude control assembly, the throttle for the lift rockets, a horizontal velocity indicator, the altitude and altitude-rate tape indicators, and a thrust-to-weight indicator. Although the pilot of the LLTV was seated because of the necessity for a rocket-propelled ejection seat, the location of the flight instruments and controls relative to the pilot's hands and eyes was similar to that in the LM.

Lunar Landing Training Vehicle Simulator

The fixed-base LLTV simulator (fig. 22) was built and located at MSC to provide flight-crew familiarization with the LLTV systems, procedures, flight trajectories, and control system characteristics. The major systems that were simulated included jet engine, rocket propulsion, electrical, electronic control, and jet-engine attitude control. The equations of motion were programed on two analog computers. A visual system was used for display of a simulated runway scene.

Lunar Landing Research Facility

The lunar landing research facility (LLRF) (fig. 16) was a research device (located at Langley Research Center) that was used to provide initial training. The LLRF used a cable tether system to support five-sixths of the crew-station weight and a hydrogen peroxide system for attitude control.

Partial-Gravity Simulators

Two dynamic simulators were designed and operated to provide astronaut training for the 1/6-g lunar-surface operations. Both simulators incorporated a uniquely designed overhead support system, which provided lifting force equal to five-sixths of the astronaut's total weight (suit, backpack, etc.). The vertical servosystem of the partial-gravity simulator (fig. 14) was suspended from an overhead monorail. This concept was subsequently adapted to a truck body for the mobile partial-gravity simulator (fig. 15) and thereby provided essentially unlimited fore-and-aft mobility.

NASA-Langley, 1973 —— 31 S-346