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FIXED-BASE SIMULATOR INVESTIGATION OF LIGHTWEIGHT VEHICLES FOR LUNAR ESCAPE TO ORBIT WITH KINESTHETIC ATTITUDE CONTROL AND SIMPLIFIED MANUAL GUIDANCE

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16. Abstract

A piloted simulator investigation of the feasibility of using a class of very simplified and lightweight vehicles for emergency escape from the lunar surface has been made. The escape-to-orbit vehicles accommodate two men, but one man performs all the manual guidance and control functions. Kinesthetic control of pitch and roll was used successfully over a moment-of-inertia range of 340 to 1750 kg-m^2 (250 to 1290 slug-ft^2) for the vehicle (including men). The pilots were also able to cope with such off-nominal conditions as misalined thrust, uneven propellant drain, and thrust deficiency. About 5 percent of the runs were made with the pilot wearing a full pressure suit.

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SUMMARY

A piloted simulator investigation of the feasibility of using a class of very simplified and lightweight vehicles for emergency escape from the lunar surface has been made. Each assumed escape-to-orbit vehicle consists essentially of a platform mounted above a single rocket engine which is surrounded by four propellant tanks. The propulsion system has only two levels of constant thrust and uses lunar module (LM) propellants. The propulsion system and platform are sized to accommodate both LM astronauts, but one man performs all the guidance and control functions. The pilot's basic information display consists of a three-axis prototype LM 8-ball for attitude reference and a digital voltmeter for display of either time or velocity along the thrust axis.

During the investigation, five pilots flew approximately 200 simulated escape-to-orbit missions, controlling the vehicle pitch and roll kinesthetically. Trajectory guidance was based on two constant pitch angles with an approximately 19-second pitch-transition maneuver. A vehicle moment-of-inertia range of approximately 340 to 1750 kg-m^2 (250 to 1290 slug-ft^2) was used in the study. The pilots preferred the handling qualities of vehicle configurations having roll inertia I_{XX} greater than pitch inertia I_{YY}. In particular, they preferred that I_{XX} be greater than about 1200 kg-m^2 (885 slug-ft^2) and that I_{YY} be between 600 and 1000 kg-m^2 (443 to 738 slug-ft^2). The higher values of I_{XX} were preferred for roll-axis stability, while the somewhat lower preferred values of I_{YY} were a compromise between pitch-axis stability and the desired responsiveness for the performance of pitch-guidance tasks, particularly the pitch-transition maneuver.

The pilots were consistently able to establish "safe" lunar orbits (pericynthion altitude greater than 15 km or 50 000 ft) even when such off-nominal conditions as misalined thrust (up to 0.5°), uneven propellant drain (up to 1 percent), and thrust deficiencies (from 1 to 14 percent in take-off thrust) were present. It was concluded, on the basis of simulated trajectory results and the rated handling qualities of the vehicle, that an emergency lunar escape mission could be accomplished by using the combination of (1) a very simplified, lightweight escape vehicle, (2) kinesthetic control of vehicle pitch and roll, and (3) constant-pitch-angle manual guidance.

INTRODUCTION

A general safety goal throughout the Apollo program has been to provide redundancy in all systems except where component reliability is judged to be sufficiently high and redundancy is not considered feasible. The single engine of the lunar module (LM) take-off system is one of these exceptions, and it performed flawlessly during the Apollo 11, 12, and 14 flights. But for future lunar flights an alternate means of lunar take-off (i.e., escape to orbit) would certainly enhance the probability of mission success and safe return of the two LM astronauts.

Both NASA and industry have considered a number of approaches to an emergency lunar escape system (LES), including multimission shuttlecraft and long-range lunar flyers (surface-to-surface) which also have the capability of escaping to orbit (see refs. 1 to 4). For the past several years at the Langley Research Center, a third approach has been considered which involves a very lightweight LES of minimum complexity that possibly could be packaged on the LM for transport to the moon. This concept has been studied analytically (refs. 3, 4, and 5) under two separate Langley contracts. The study of reference 5 was concurrent with and contractually associated with the piloted LES simulator (LESS) study considered herein. The primary objective of the joint analytical-simulation effort was to establish the technical feasibility of particular escape-system concepts by evaluation of lunar visibility data, simplified guidance schemes, manual control techniques, the handling qualities of configurations with various moments of inertia and propulsion systems, and the rendezvous capabilities of the orbiting command-service module (CSM).

Concepts for very simplified LES vehicles necessarily involve manual guidance, control, and stabilization techniques and the use of LM ascent propellants (which become available in an emergency escape situation). Preliminary analyses at Langley have indicated that a simple constant-thrust flying platform could serve as a satisfactory vehicle and that kinesthetic attitude control may be feasible. Kinesthetic control in its various forms has been studied for a number of years (e.g., refs. 6 to 8) and has been found to be possible but not generally satisfactory for flight applications, primarily because of vehicle landing requirements. A LES vehicle, however, would not have any landing requirement.

A basic design rule for the LESS investigation was to limit the maximum dry mass of the LES to approximately 135 kg, corresponding to an earth dry weight of approximately 300 lb. The mass of a suitable hypergolic propulsion system (tanks, engine, plumbing, etc.) will probably exceed half of this allotment, thus dictating a very simple platform structure and a minimum of guidance and control equipment. Analyses (e.g., ref. 5) have indicated that cannibalization of guidance and control components from the LM is not feasible because of difficulty of access and inappropriate modularization; thus, except for propellants, it appears that a near-preassembled LES must be transported to the moon.

The approach in the LESS studies has been to look first at very simple LES vehicles and manual guidance, control, and stabilization schemes and evaluate their adequacy in terms of orbit achievement and demands on the pilot. Then, if necessary or desirable, additional features such as sensors and instrumentation can be added and the system reevaluated.

The results of the LESS study are primarily the pilot ratings of the handling qualities of the LES vehicle and the average characteristics of LES orbits established under a variety of simulated nominal and off-nominal conditions. Even though the orbit results are statistical, they are intended to give only a qualitative indication of how well the escape trajectory was flown under the various sets of conditions. An analysis-of-variance approach has not been used because the purpose of the study was to determine if and under what conditions simplified LES vehicles could be flown, rather than to determine the exact effect of a particular variable on the pilot's performance or on the characteristics of the established orbit.

Additional LESS studies involving (1) main-engine gimbaling, (2) a complete array of on-off jets for attitude control, and (3) slightly more sophisticated instrumentation have been conducted. A brief summary of the results of all the LESS studies is given in reference 9.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

a semimajor axis of LES orbit

b_{13},b_{23},b_{33} direction cosines used in transforming the acceleration due to gravity from the local-vertical system to the body-axis system (see eqs. (A1) and (A10))

D_1,D_2,D_3 auxiliary variables used in the moment equations (see eq. (A4))

g_e acceleration due to earth gravity, 9.81 m/sec^2 (32.2 ft/sec^2)

g_m acceleration due to lunar gravity, 1.62 m/sec^2 (5.32 ft/sec^2)

h_a altitude of apocynthion

h_p altitude of pericynthion

I_1,I_2,I_3 collections of inertia terms (see eq. (A3))

I_{xx},I_{yy},I_{zz} moments of inertia of LES about X_B, Y_B, and Z_B axes, respectively

I_{xz} product of inertia of LES with respect to X_B and Z_B axes

$K_1,\ldots,K_5$ constants in the torque equations (see eqs. (A5) to (A9))

M_θ,M_φ electrical signals from the load-cell pairs corresponding to kinesthetically induced pitch and roll torques, respectively

m instantaneous mass of LES vehicle

p,q,r components of angular velocity measured about X_B, Y_B, and Z_B axes, respectively

Q_{J,z_B} torque about Z_B axis due to yaw jets

Q_{x_B},Q_{y_B},Q_{z_B} total torques about X_B, Y_B, and Z_B axes, respectively

$\overline{R}$ position vector with respect to center of moon

r_m radius of moon

r_p radius of pericynthion

$\overline{T}$ force due to main thruster of LES

T_{x_B},T_{y_B},T_{z_B} body-axis components of $\overline{T}$

t time

u,v,w body-axis components of the linear velocity of the LES with respect to the launch site

V_h magnitude of LES horizontal velocity

V_t magnitude of LES total velocity

V_{z_B} simulated output of thrust-axis integrating accelerometer located at initial center of gravity of LES (see eq. (A10))

W earth weight of LES

W_o initial earth weight of LES

$W_{3,e}$ earth weight of LESS control pilot

X_B,Y_B,Z_B body axes with origin at instantaneous center of gravity of the LES (axes rotate with vehicle)

X_I,Y_I,Z_I inertial axes $\left(Z_I\right.$ lies along local vertical at lift-off site, and the X_IZ_I-plane coincides with plane of command-service-module orbit$\left.\right)$

X_{LV},Y_{LV},Z_{LV} local-vertical axes with origin at instantaneous center of gravity of the LES $\left(Z_{LV}\right.$ remains coincident with local vertical and Y_{LV} remains perpendicular to the instantaneous plane of the LES motion$\left.\right)$

z_h distance between main thruster nozzle and initial center of gravity of the LES

$\Delta x,\Delta y,\Delta z$ body-axis components of shift in LES center of gravity

$\delta_{x_B,3},\delta_{y_B,3}$ horizontal components of the distance the pilot moves his center of gravity from the balancing position

$\epsilon_{\theta_1},\epsilon_{\varphi_1}$ average pointing errors $\left(\theta - \theta_1\right)$ and $\left(\varphi - \varphi_1\right)$ before pitchover

$\epsilon_{\theta_2},\epsilon_{\varphi_2}$ average pointing errors $\left(\theta - \theta_2\right)$ and $\left(\varphi - \varphi_2\right)$ after pitchover

η downrange central angle (see fig. 1)

θ_1,θ_2 reference guidance pitch angles before and after pitchover, respectively

μ lunar gravitational constant, 4.9028×10^{12} m^3/sec^2 $\left(1.7314 \times 10^{14}\ \text{ft}^3/\text{sec}^2\right)$

ξ_{x_B}, ξ_{y_B} body-axis components of the thrust-misalinement angle

σ standard deviation

φ_1, φ_2 reference guidance roll angles before and after pitchover, respectively, $\varphi_1 = \varphi_2 = 0$

φ, ψ, θ Euler angles associated with roll, yaw, and pitch rotations relating the body axes to the local-vertical axes (φ, ψ, θ order required for the simulator 8-ball used)

Subscript:

BO at thrust burnout

A dot over a variable denotes differentiation with respect to time.

GENERAL CONSIDERATIONS

The single purpose of an emergency lunar escape system is to provide a backup means for the two lunar module astronauts to escape from the lunar surface to a "safe" lunar orbit. The primary specification for a safe orbit is that the pericynthion altitude be greater than 15 km (approximately 50 000 ft). This altitude is sufficient to assure clearance of lunar mountain peaks. Additional specifications involve LES orbit geometry and motion with respect to the established orbit of the CSM or target vehicle. That is, under the stipulation that the CSM will be the active vehicle during the rendezvous portion of an escape mission, combinations of the angle between the two orbits, nodal locations, phasing of the two vehicles, and orbital-energy relations must be such that the CSM can perform the rendezvous and docking within its characteristic velocity allotment (≈240 m/sec or 787 ft/sec) for rescue of the LM and the operating time limit (≈4 hr) of the portable life support systems worn by the astronauts. In the present study, satisfaction of only the primary specification was required.

The following sections cover LESS study assumptions, description of the take-off trajectory and the two simplified guidance schemes investigated, and a brief description of the type of kinesthetic control used in the LESS studies. For convenience of discussion, the terms "pitch angle," "roll angle," and "yaw angle" are used interchangeably with the Euler angles θ, φ, and ψ, respectively (because φ and ψ remain near zero throughout the escape trajectory).

Assumptions

In addition to the 135 kg (300 lb) dry-mass limitation and the stipulation that the LES will not take an active part in rendezvous and docking, the following LESS study assumptions were made:

(a) The moon has an inverse-square gravity field.

(b) The moon does not rotate significantly during a LES flight.

(c) Some form of communications with either the CSM or Mission Control is available. Thus, the whereabouts of the CSM and the characteristics of its orbit are known prior to LES takeoff.

(d) Both astronauts must ride the same LES, but it is controlled by only one of them.

(e) Only a single burn of the rigidly mounted LES engine is allowed; however, a constant maximum thrust level ("thrust level one") and a constant intermediate level ("thrust level two") are available.

(f) Pitch and roll are controlled kinesthetically; small on-off jets (connected directly to a hand controller) are used for yaw control.

(g) Rate gyros for all three axes are installed on the LES; thus, both rate and attitude information can be displayed to the pilot.

(h) A simple integrating accelerometer is affixed to the LES vehicle to acquire velocity-along-the-thrust-axis information.

Reference Trajectory

Figure 1 is a sketch showing a profile of the LES trajectory, LES force and position vectors, pertinent angular measures, and relationships among the following reference coordinate systems:

(a) Body system X_B,Y_B,Z_B with origin at instantaneous center of gravity of the LES (system rotates with vehicle)

(b) Local-vertical system X_{LV},Y_{LV},Z_{LV} with origin at instantaneous center of gravity of the LES and axes fixed with respect to local vertical

(c) Inertial system X_I,Y_I,Z_I (shown at center of moon in fig. 1)

During preliminary investigations, digital-computer solutions were obtained for several reference escape trajectories based on very simplified guidance schemes. Characteristics of one of these trajectories (used as the primary reference trajectory for this study) are given in figure 2. The first part of this figure shows time histories of altitude,

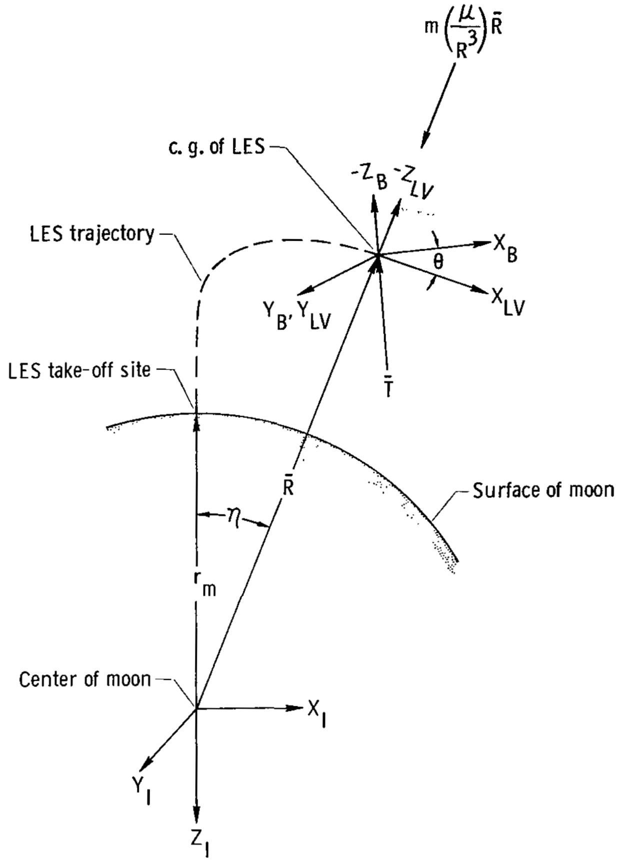

Figure 1.- Sketch showing LES force and position vectors, axis systems, pitch angle, and downrange central angle.

local pitch angle θ, downrange central angle η, and ratio of thrust T to earth weight W. This reference trajectory is vertical for the first 247.5 seconds, during which time the thrust level T remains constant at its maximum (thrust level one). At 247.5 seconds the thrust level is stepped down to 86.4 percent of maximum thrust and remains constant (thrust level two) throughout the remainder of the run. The pitch maneuver also begins at 247.5 seconds and is accomplished in approximately 19 seconds; it is based on a pitch acceleration of -1 deg/sec^2 for one-half of the interval followed by a counteracceleration of 1 deg/sec^2 during the second half. Thrust cutoff occurs at 653.39 seconds, resulting in a near-circular orbit at approximately 111 km or 364 000 ft (see "Ref. trajectory" in table III). The second part of figure 2 (page 10) gives the velocity time histories for the reference trajectory, where velocity along the thrust axis is the simulated output of a simple integrating accelerometer mounted on the thrust axis at the initial center of gravity of the vehicle.

Certainly a set of guidance pitch angles more efficient (in terms of propellants) than $\theta_1 = 0^{\circ}$ and $\theta_2 = -90^{\circ}$ could have been selected, but the emphasis in this initial LESS

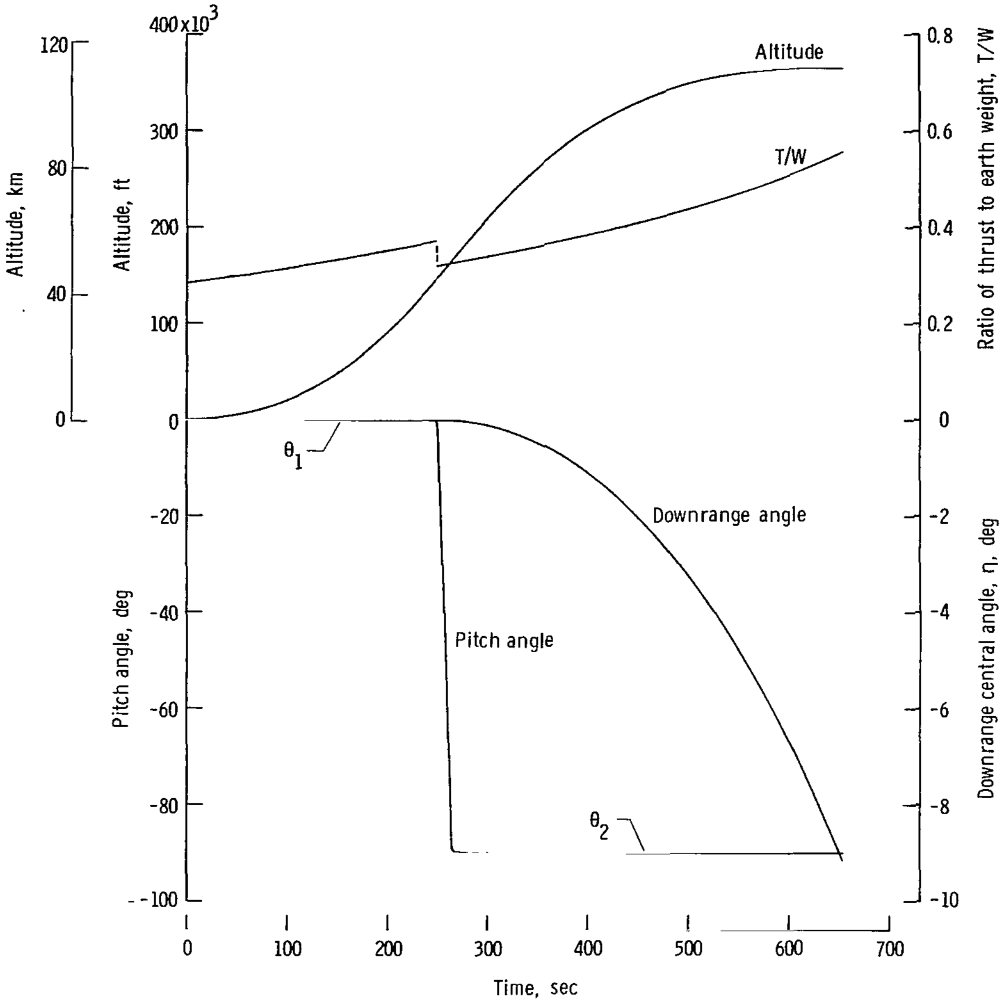

Figure 2.- Reference-trajectory characteristics.

study was on simplicity of guidance and control rather than propellant economy. (It is reported in ref. 5 that this particular set of guidance angles results in the use of approximately 15 percent more propellants than would be required for a propellant-optimized calculus-of-variations pitch profile.)

Simplified Guidance Schemes

For the piloted LESS runs, two similar guidance schemes were used in attempts to achieve the reference trajectory of figure 2. One scheme is based on "time-cue" initiation of events such as the "pitchover" (90^o pitch-transition maneuver) and thrust changes, and the second scheme is based on "velocity-cue" $\left(V_{z_B}\right)$ initiation of these same events. That is, the pitchover and/or thrust changes are initiated when either time or V_{z_B}

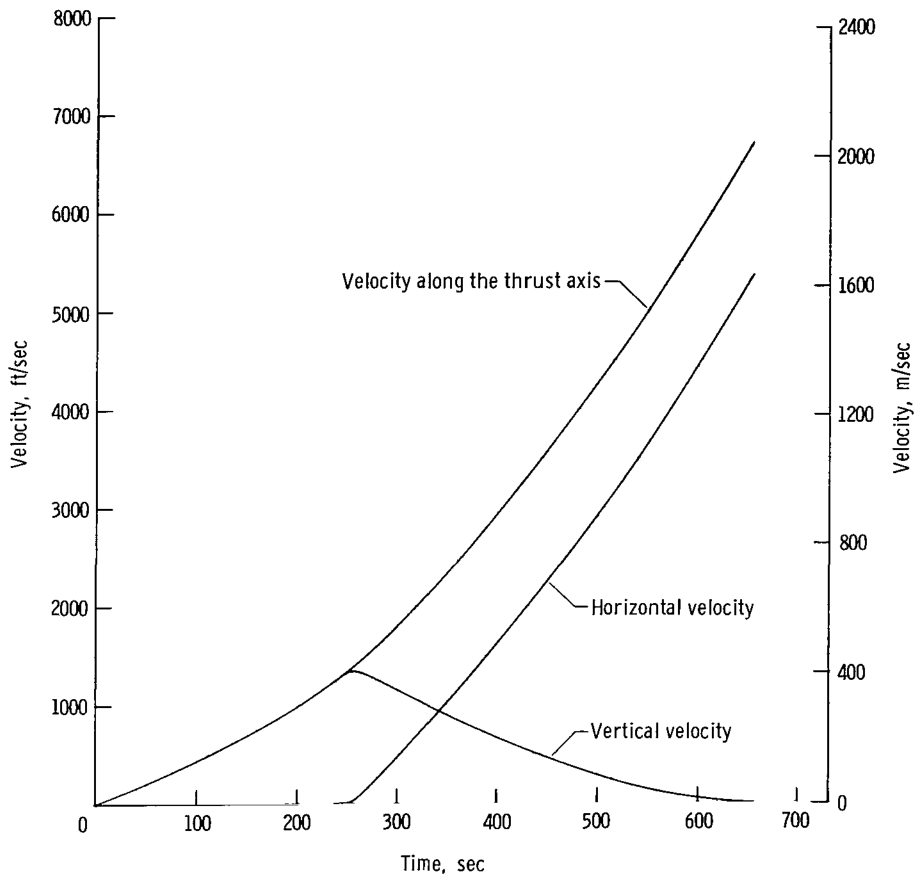

Figure 2.- Concluded.

(displayed to the pilot on a digital voltmeter) reaches certain target values. In the LESS study the same prototype LM three-axis attitude indicator (8-ball) was used for both schemes. Except in a few cases, no other guidance and control information was given to the LESS pilots, although the actual LES astronaut could probably derive useful visual cues from the lateral lunar horizons.

Kinesthetic Control

The type of kinesthetic control used in the LESS studies involved the pilot's ability to change and/or correct the vehicle pitch angle θ and roll angle φ by shifting his center of gravity with respect to the line of thrust of the LES. The usual procedure was for the pilot (standing) to plant his feet, lock his knees, and lean his body in the appropriate directions (pivoting about his ankles). Strain-gage load cells were installed under the floor of the LESS to sense the center-of-gravity shifts in terms of force (weight) changes at the cell locations. The electrical outputs of the load cells were shaped into appropriate pitch and roll command signals and transmitted to a real-time digital computer. At the computer the command signals were converted into simulated pitching and rolling moments according to the assigned thrust level and the calculated displacement of the total center of gravity from the designated line of thrust.

Kinesthetic control is discussed further in the sections that follow and in reference 10.

SIMULATION SYSTEM

Reference 10 deals with the development of the LESS system. This system is designed to accommodate a broad spectrum of studies of lunar escape using simplified guidance and control. In particular, the LESS is specially outfitted for studies of kinesthetic control or kinesthetic augmentation of other modes of simplified attitude control.

A block diagram of the LESS system, including hardware and the associated real-time digital computer program, is given in figure 3. The pilot control station is representative of a two-man vehicle which is outfitted for one-man control. It is assumed that the role of the second man is strictly that of a passenger who must stand (or sit) relatively still, or else his motions will be sensed by the load-cells and superimposed upon the kinesthetic-control inputs of the pilot.

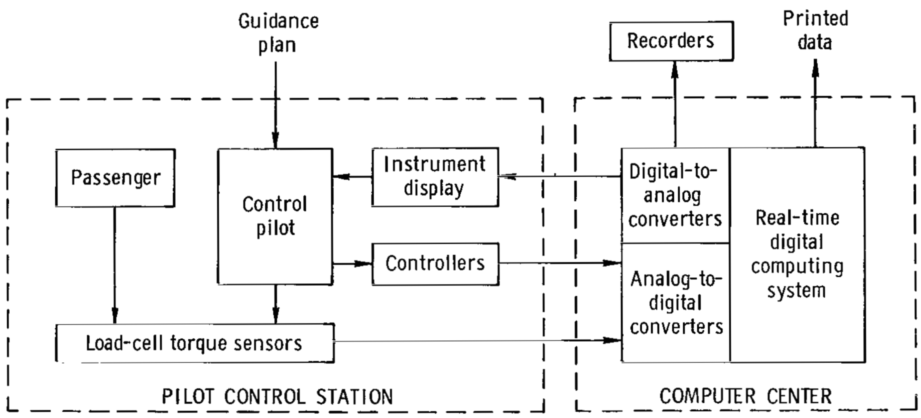

Figure 3.- Block diagram of lunar escape system simulator (LESS).

Figure 4 is a photograph of the two-man LESS pilot control station which features simplified hand controls, a limited-information pilot's display, and two pairs of load cells mounted under the outside edges of the simulator platform. The control pilot (front) has a three-position toggle switch at his left hand for commanding thrust level one, thrust level two, and thrust off. One axis of a three-axis CSM right-hand controller is being used by the pilot in figure 4 to command a set of simulated on-off yaw jets. This controller was replaced by a simple left-right, spring-centered lever (with microswitches) during part of the study.

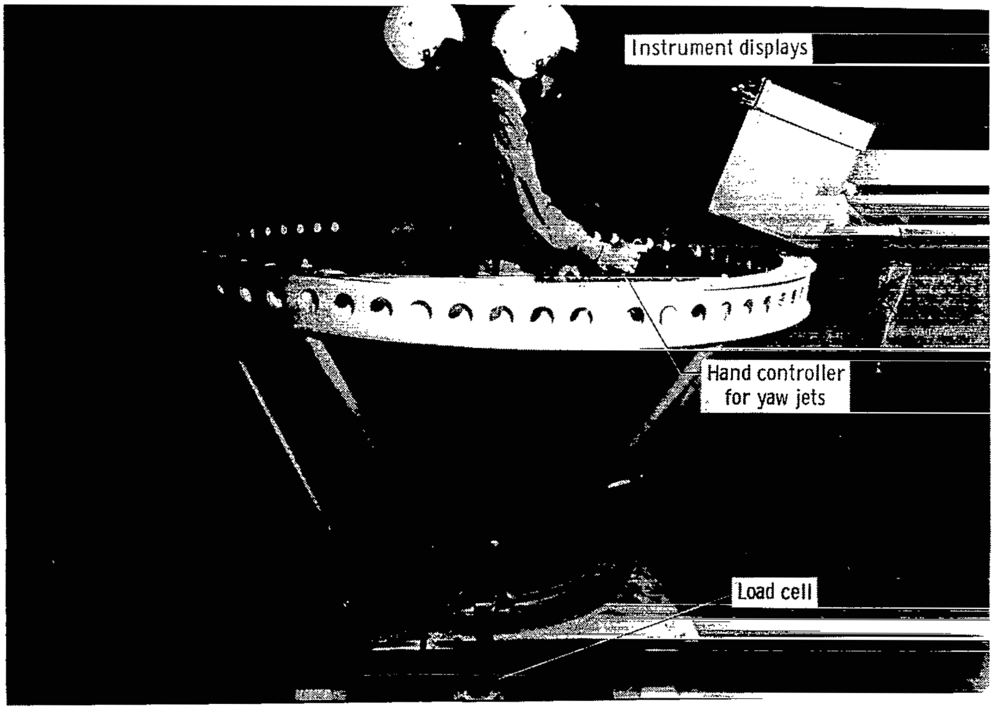

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Figure 4.- The pilot control station of the simulator.

Figure 5 is a photograph of the pilot's instrument display, featuring a prototype LM 8-ball and a large primary digital voltmeter. To improve the location of the digital voltmeter information in the pilot's field of view, a pair of planar mirrors was used to transfer the digital voltmeter image to just below the 8-ball (as shown). This digital voltmeter could display time in seconds or be switched to display other variables. Thus, time could be used on one run and V_{z_B} (velocity along the thrust axis) on the next run, without delay. During the velocity-cue runs, time was displayed as additional information on the small digital voltmeter to the left of the 8-ball. In general, however, the pilots tended to ignore this secondary digital voltmeter because of the necessity for intense concentration on the 8-ball and primary digital voltmeter.

All the LESS input signals were sent over telephone lines from the vicinity of the pilot control station to analog-to-digital converters at a central computing complex some distance away. The converted input signals were sampled 32 times each second by the real-time digital computer (1/32 second was the selected iteration-time increment for the trajectory calculations). The computer returned selected analog output signals to the pilot control station by means of digital-to-analog converters. The primary output signals were the Euler angles φ, ψ, and θ, which were used to drive the three-axis 8-ball, and either time or V_{z_B}.

A summary of the LESS computer equations is given in the appendix.

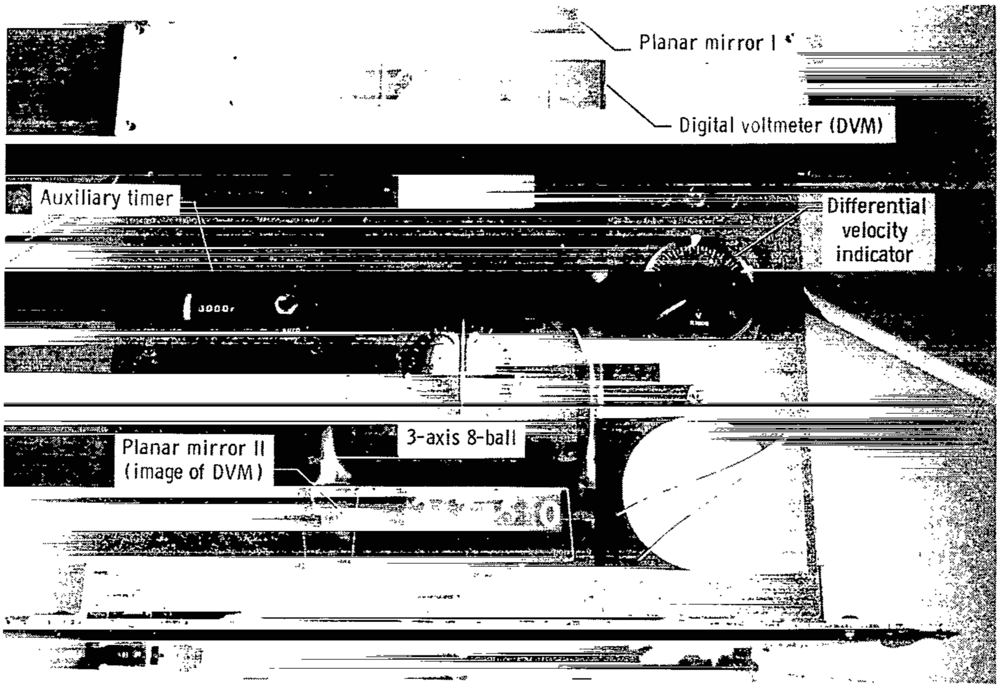

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Figure 5.- A pilot's view of the instrument display panel.

STUDY CONDITIONS AND PRELIMINARY RESULTS

Five test subjects were used as pilots for the LESS flights; four were experienced pilots who also had simulator experience and the fifth was a student with no piloting or simulator experience. Pertinent information about the LESS pilots is given in table I.

Six different inertia configurations, two initial thrust-weight ratios T/W_O, two simplified guidance schemes (time-cue and velocity-cue), and combinations of several off-nominal conditions (main-thruster misalinement, uneven propellant drain, and thrust

TABLE I.- PILOT RESUME

Pilot	Number of LESS runs	Present position	Previous piloting experience	
			Simulator	Flight
A	51	Engineer	Yes	Former Air Force instrument-flight instructor
B	57	Engineer	Yes	Light-aircraft pilot
C	43	Pilot	Yes	NASA test pilot
D	30	Engineer	Yes	Former Navy aircraft-carrier pilot
E	13	Student	No	None

deficiencies) were investigated during the simulated escape-to-orbit flights. With few exceptions, the pilots were informed of the selected inertia configuration and T/W_o prior to a run, but they were not informed when an off-nominal condition was scheduled. When the same type of off-nominal condition (e.g., thrust misalinement) was included in consecutive runs, the magnitude and/or direction was usually varied.

Most of the flights were made with only a single pilot on the simulator platform, but during several runs a passenger stood behind the control pilot. Also, ten runs were made by one pilot while wearing a full pressure suit and simulated portable life support system. The purpose of the runs with two men and with the pressure suit was to determine whether the kinesthetic control situation was altered significantly. If not, the study results should be valid for the actual two-man lunar escape situation.

Each of the five LESS pilots used slight variations in stance and definite variations in control pattern (i.e., input frequency and amplitude) while holding the attitude excursions of the vehicle within approximately the same tolerances (usually $\pm 2^{\circ}$ in θ and $\pm 3^{\circ}$ in φ). Figures 6 and 7 present 2-minute time histories of typical kinesthetic-control input-output relationships for pitch and roll immediately after lift-off. Pilot B (fig. 6) tended to use high-frequency, high-amplitude body motions (indicated by the M_{θ} and

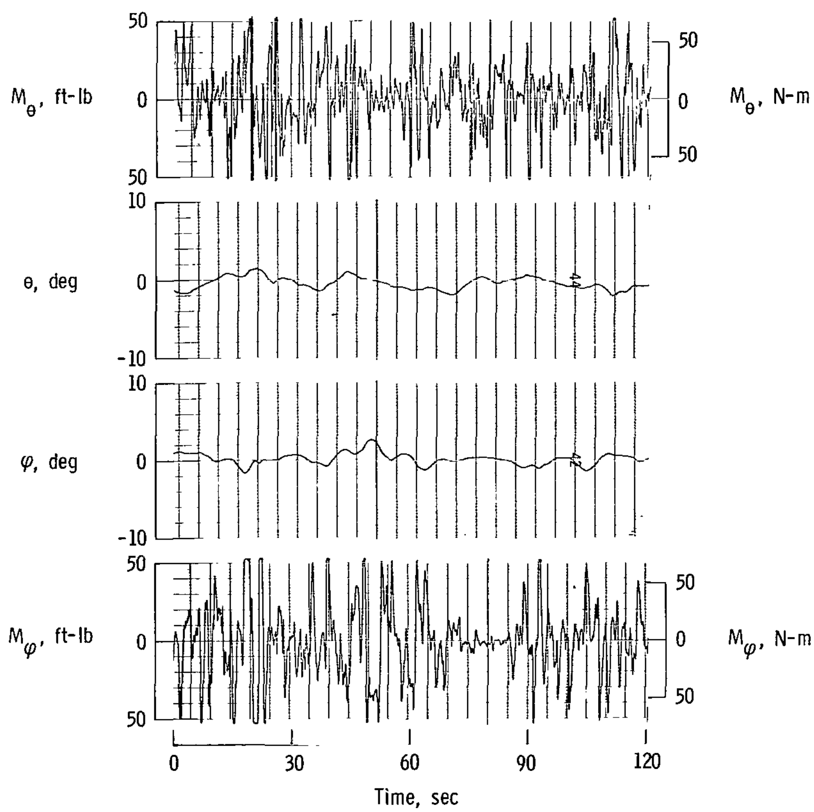

Figure 6.- Time histories of kinesthetic-control input-output relationships for pilot B.

M_φ traces). Pilot C (fig. 7) used fewer and more-deliberate corrective inputs as he attempted to control θ and φ excursions to within approximately $\pm 2^\circ$. During the course of the study, pilot B maintained somewhat smaller maximum excursions in θ and φ and established slightly less eccentric orbits than pilot C, but as the M_θ and M_φ input traces suggest, he worked much harder physically (kinesthetic body motions) to achieve such results.

In figures 6 and 7, lift-off (time zero) was preceded by a kinesthetic prebalance period of approximately 30 seconds. The simulated LES vehicle was assumed to be pivoted on its launch rack to allow free θ and φ motions, and to have a leveling indicator. However, in order to achieve favorable phasing with the orbiting CSM, the LES was required to lift off at time zero regardless of the existing attitude of the vehicle; this explains why the θ and φ traces were not exactly zero at lift-off. During the prebalance period, the kinesthetic handling characteristics of the vehicle were somewhat different from those after lift-off because kinesthetically induced torques were related to lunar gravity rather than the thrust level. However, during the prebalance period the pilots were usually able to establish foot positions which did not have to be changed again during the flight, except when off-nominal conditions were introduced.

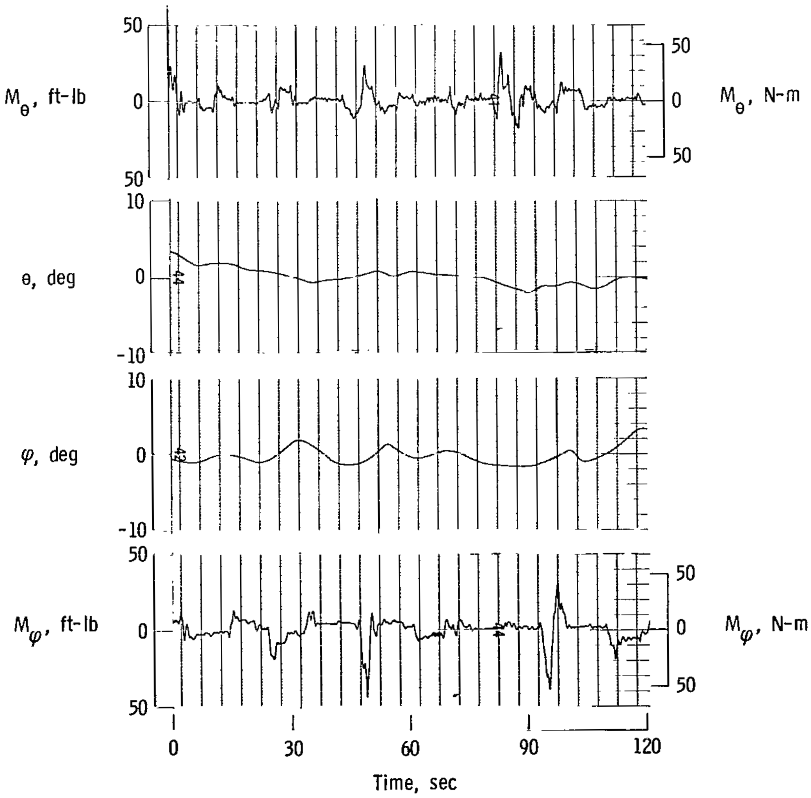

Figure 7.- Time histories of kinesthetic-control input-output relationships for pilot C.

For the range of vehicle configurations and thrust levels simulated, all five of the LESS pilots considered kinesthetic control to be a difficult task, primarily because of the intense concentration required. However, the control technique itself was not difficult to learn. Previous piloting experience did not seem to be a significant advantage, although previous use of a three-axis 8-ball appeared to be quite helpful. During preliminary checkout runs several nonpilot engineers adapted quickly to the system as soon as they learned to interpret the motions of the 8-ball. Pilot E in the LESS study had no previous piloting experience or familiarity with an 8-ball; after less than 1 hour (in several practice segments) of initial training, he was ready to begin his data runs. As a further example, pilot D, who had previous piloting and 8-ball experience, made his first data run after about 1 minute of practice and established a safe orbit. The other LESS pilots were ready to begin their data runs after 5 to 30 minutes of initial practice. Even though all the LESS pilots learned quickly, their performance continued to improve during their first 20 to 30 flights and then became fairly constant.

During the velocity-cue runs, the digital voltmeter integers advanced as fast as 18 per second (corresponding to an acceleration of 18 ft/sec^2, or 5.5 m/sec^2), which made it difficult for the pilot to read V_{Z_B} closer than about 10 ft/sec (3 m/sec). Because the velocity information was presented in terms of integers indicating ft/sec to the LESS pilots, these units are used in the following discussion (with SI units in parentheses). To alleviate the difficulty of monitoring the digital voltmeter, the dial to the right of the 8-ball was programed as a differential-velocity indicator during intervals of 100 ft/sec (30 m/sec) surrounding important control events. For example, the V_{Z_B} target value for initiation of the 90° pitch maneuver (and simultaneous reduction of the thrust level) was 1292 ft/sec (394 m/sec). The differential-velocity indicator was programed to begin its sweep when the digital voltmeter reading reached 1242 and to reach full scale (and reset) at 1342. Thus, when the sweep hand reached the triangular tape marker positioned at approximately half-scale (see fig. 5), the pilot initiated the pitchover and changed the thrust. Similarly, the sweep hand was again activated when the digital voltmeter reading reached 6652, or 50 ft/sec (15 m/sec) before the thrust-cutoff target value of 6702 ft/sec (2043 m/sec). Because the pointer moved much faster on this second sweep (higher acceleration due to loss of vehicle mass), some of the early runs were made with a thrust-cutoff tape marker at about three-fourths scale (see fig. 5) to allow the pilot more time to stabilize his attitude precisely just before thrust cutoff. (After thrust cutoff the pilot can no longer control θ and φ kinesthetically.) This extra time proved to be of no particular benefit, as it also extended the time during which the pilot had to divide his attention between the differential-velocity indicator and the 8-ball.

This scheme of using the differential-velocity indicator allowed the control events to be initiated within a few feet per second of target values, most of the error being attributed to the pilot's reaction time. The motion of the sweep hand in his peripheral vision was a noticeable cue which alerted the pilot for initiation of a control event and precluded the need for auxiliary cues such as flashing lights or auditory signals.

An indication of the sensitivity of some of the more critical LES guidance and control parameters is given in table II. In this table several error values that lower the percynthion altitude of the LES orbit from the nominal 111 kilometers (60 n. mi.) to about 18.5 kilometers (10 n. mi.), which is near the lower limit for a safe orbit, are given for both time-cue and velocity-cue guidance schemes. The critical thrust-cutoff errors were determined during the LESS study and the critical T/W_o and θ errors were approximated from curves in reference 5. One reason for the breakdown in this table according to guidance cue is to show that a thrust deficiency (error in T/W_o) is not nearly as critical for velocity-cue guidance as for time-cue guidance. A detailed error analysis covering several guidance profiles and a range of T/W_o is given in reference 5.

In general, the indicated V_{z_B} values in the LESS studies were 1 to 3 m/sec (3 to 10 ft/sec) greater than vehicle velocity at the pitchover maneuver and 3 to 9 m/sec (10 to 30 ft/sec) greater than the intended velocity at thrust cutoff. The average error at thrust cutoff might have been improved somewhat by shifting the V_{z_B} target value, although the pilots generally tended to cut off about 1.5 to 3 m/sec (5 to 10 ft/sec) late, mostly because of reaction time. In some cases the pilots deliberately delayed thrust cutoff by 6 to 9 m/sec (20 to 30 ft/sec) while they attempted to stabilize their attitudes more precisely; this late cutoff was not an option in the simulation flight plan, but rather an independent action by the pilots to improve their chances of establishing a safe orbit and of avoiding high vehicle tumbling rates.

TABLE II.- TYPICAL PARAMETER-ERROR VALUES THAT REDUCE PERICYNTHION ALTITUDE FROM 111 KILOMETERS OR 60 N. MI. (CIRCULAR) TO APPROXIMATELY 18.5 KILOMETERS OR 10 N. MI.

Parameter	Time-cue guidance	Velocity-cue guidance
Thrust cutoff time	3.8 sec early	-------------
Thrust cutoff velocity	------------	21 m/sec low (70 ft/sec low)
T/W_o	1 percent low	9 percent low
ϵ_{θ_1} and ϵ_{θ_2}	1.5° high[a] or 5° low	

[a]1.5° behind vertical for ϵ_{θ_1} and 1.5° above local horizontal for ϵ_{θ_2}.

RESULTS AND DISCUSSION

Two types of results are presented in this section: trajectory results and pilot ratings of vehicle handling qualities for the various conditions. The trajectory results are based on a total of 194 simulation runs by all five LESS pilots, while the pilot ratings were given by only three of these pilots.

Six of the 194 runs were aborted for the following reasons: (1) pilot forgot to initiate a control event (e.g., change pitch angle) at the proper time (four runs), (2) pilot was not told that the study included any off-nominal conditions and he quit controlling during first off-nominal run, thinking the computer had malfunctioned, and (3) pilot read his 8-ball backwards and lost control on first run after a 27-day layoff. The abort for reason (3) was unusual because the same pilot and other pilots made some of their best runs on the first try after layoffs ranging from 15 to 69 days.

A summary of the trajectory results for the 188 completed runs is shown in table III. The entries are in terms of mean and standard deviation σ values of insertion conditions (at thrust cutoff) and characteristic altitudes of the resulting orbits.

TABLE III.- SUMMARY OF LESS TRAJECTORY RESULTS

(a) SI Units

Initial thrust-weight ratio	No. of runs	Orbit altitude, m, at –						Insertion velocity, m/sec					
		Insertion		Pericynthion		Apocynthion		Horizontal[a]		Vertical[b]		Side[c]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	111 118	----	110 758	------	111 510	------	1628.28	-----	0.14	-----	0	-----
$T/W_o = 0.286$	173	114 518	5381	87 308	31 703	139 458	27 275	1624.24	15.19	-3.04	17.28	20.62	39.09
$T/W_o = 0.964$	15	107 788	6944	85 530	21 512	153 331	36 717	1634.62	14.01	11.66	16.15	34.32	48.09

(b) U.S. Customary Units

Initial thrust-weight ratio	No. of runs	Orbit altitude, ft, at –						Insertion velocity, ft/sec					
		Insertion		Pericynthion		Apocynthion		Horizontal[a]		Vertical[b]		Side[c]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	364 561	------	363 379	-------	365 847	-------	5342.12	-----	0.47	-----	0	------
$T/W_o = 0.286$	173	375 716	17 653	286 442	104 012	457 540	89 486	5328.87	49.85	-9.96	56.70	67.64	128.25
$T/W_o = 0.964$	15	353 634	22 783	280 610	70 577	503 053	120 461	5362.93	45.95	38.25	52.97	112.59	157.78

[a]Includes side velocity and forward velocity (component parallel to CSM orbit plane).

[b]Positive values indicate downward velocities.

[c]Velocity normal to CSM orbit plane, positive to the right.

All but four of the 188 runs resulted in safe orbits; two of the unsatisfactory orbits intersected the moon and the other two had pericynthion altitudes of approximately 6 and 11 km (19 000 and 37 000 ft) respectively. Three of these unsatisfactory runs occurred during the first 4 days of running and the orbit with the 11-km pericynthion occurred about halfway through the study.

Effect of High Thrust-Weight Ratio

As indicated in table III, most of the runs (173) were based on an initial ratio of thrust to earth weight T/W_O of 0.286, which was determined to be near optimum with respect to boost energy for the reference trajectory to 111 km (364 000 ft). (See ref. 5.) Then in an extreme departure, 15 exploratory runs were made with $T/W_O = 0.964$ to determine whether the vehicle was kinesthetically controllable at this higher thrust level (W_O was not changed for these runs). The high-thrust conditions lasted only about 55 seconds, after which the thrust was changed to approximately 23 percent of maximum. The pilots liked the reduction in total flight time from 654 to 544 seconds, but declared strongly that vehicle handling qualities during the first 55 seconds were unacceptable (although none of the pilots actually lost control, and all 15 runs resulted in safe orbits). Handling qualities after the thrust change were judged acceptable and were similar to those which occurred during the second half of the primary runs ($T/W_O = 0.286$). All 15 of the high-thrust runs were made with time-cue guidance.

A comparison of the two sets of simulation values in table III indicates that the high-thrust runs resulted in slightly more eccentric orbits, primarily because of greater horizontal velocity at orbit insertion. An examination of the data printouts for these runs revealed that thrust cutoff averaged less than 1/2 second late, but a pointing bias in pitch during the vertical step of the trajectory resulted in an average forward velocity at pitchover of approximately 8 m/sec (26 ft/sec). (In an actual LES flight this velocity would not be sensed, so it was not displayed to the LESS pilots.) Also, the thrust level was reduced about 1/2 second early (just prior to pitchover) which contributed somewhat to the lower altitude and downward velocity at orbit insertion. This downward velocity also contributed to the greater orbit eccentricity. However, it should be noted that for all data the mean pericynthion altitude is less than 26 km (84 000 ft) below the 111 km (364 000 ft) CSM orbit.

Effect of Variation of Moments of Inertia

The six LESS vehicle configurations covered a moment-of-inertia range of approximately 340 to 1750 kg-m^2 (250 to 1290 slug-ft^2). Time histories of I_{XX} and I_{YY} for four of these configurations are shown in figure 8. Also shown in this figure are three approximate time intervals (I, II, and III) during which three of the pilots rated the vehicle handling qualities, using the rating scale shown in table IV. (This scale was developed in ref. 11.)

The results of the pilot ratings are given in table V. The pilots were permitted to resolve their ratings to half-points on the index scale of table IV (for example, A4.5) whenever they felt the rating lay between two adjacent categories. As shown, the pilots preferred the handling qualities with inertia E and rated inertia A the poorest, particularly

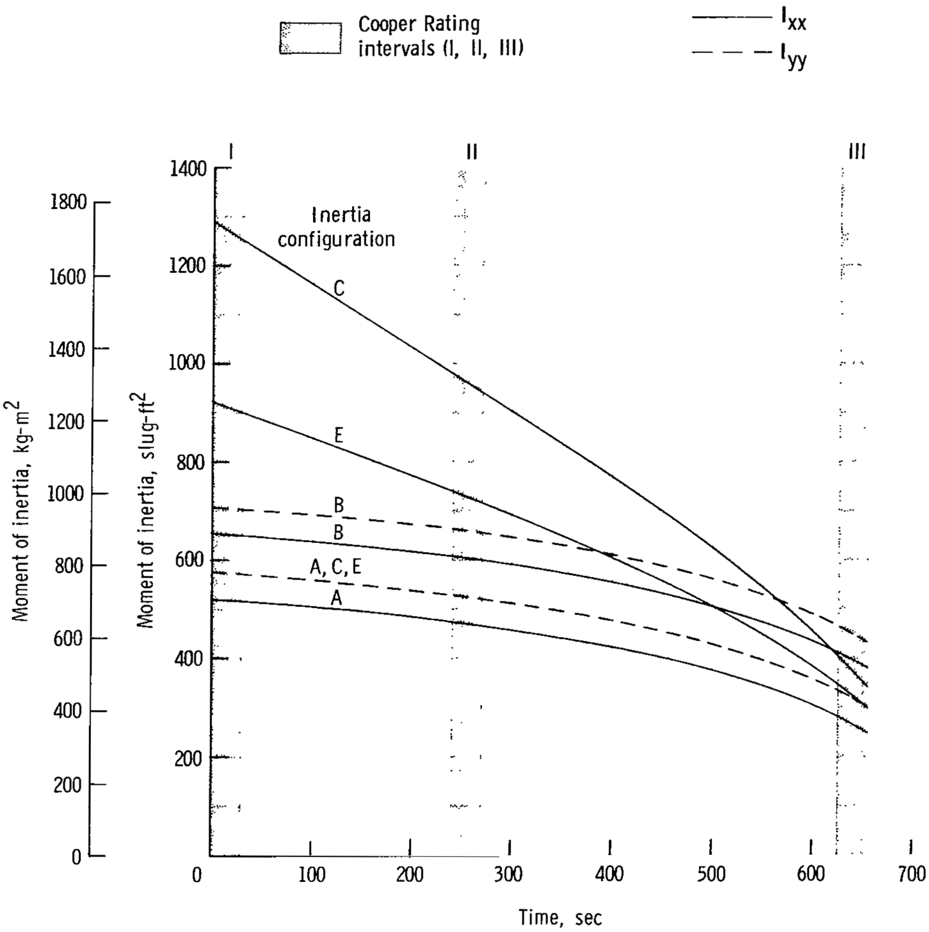

Figure 8.- Time variation of LES moments of inertia about roll axis (I_{xx}) and pitch axis (I_{yy}).

during rating interval III where inertia A was rated only marginally acceptable. Two of the three pilots preferred inertia C to the balanced inertia condition ($I_{xx} \approx I_{yy}$) of inertia B; the third pilot, however, downrated inertia C enough to rank it third. The two pilots who did not give formal ratings also strongly preferred the handling qualities associated

TABLE IV.- REVISED COOPER SCALE FOR EVALUATING VEHICLE HANDLING QUALITIES

[From ref. 11]

A1	Excellent, highly desirable	SATISFACTORY Meets all requirements and expectations, good enough without improvement. Clearly adequate for mission.	ACCEPTABLE May have deficiencies which warrant improvement, but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.	CONTROLLABLE Capable of being controlled or managed in context of mission, with available pilot attention.
A2	Good, pleasant, well behaved			
A3	Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.			
A4	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.	UNSATISFACTORY Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.		
A5	Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.			
A6	Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.			
U7	Major deficiencies which require mandatory improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.		UNACCEPTABLE Deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation.	
U8	Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.			
U9	Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.			
10	Uncontrollable in mission.	UNCONTROLLABLE Control will be lost during some portion of mission.		

TABLE V.- HANDLING-QUALITIES RATINGS OF FOUR LESS INERTIA CONFIGURATIONS

Inertia designation[a]	Average rating during interval[b] –		
	I	II	III
A	A4.6	A5.4	A6.5
B	A3.8	A4.5	A5.6
C	A4.0	A4.8	A5.8
E	A3.4	A4.3	A5.0

[a]Defined by figure 8.

[b]Rating intervals are shown in figure 8.

with inertias C and E. Thus, on the basis of the pilot ratings and other pilot opinions, the following inertia conditions were generally preferred for kinesthetic control of an LES:

(a) I_{xx} greater than about 1200 kg-m^2 (885 slug-ft^2)

(b) I_{yy} between 600 and 1000 kg-m^2 (443 and 738 slug-ft^2)

The rationale for this preference was that relatively high I_{xx} provided better roll-axis stability, while the somewhat lower values of I_{yy} were a compromise between pitch-axis stability and the desired responsiveness for the performance of pitch-guidance tasks, such as the pitch transition maneuver.

TABLE VI.- COMPARISON OF LESS TRAJECTORY RESULTS[a] FOR SEVERAL INERTIA CONFIGURATIONS

(a) SI Units

Inertia configuration	No. of runs	Orbit altitude, m, at –						Insertion velocity, m/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal[b]		Vertical[c]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	111 118	----	110 758	------	111 510	------	1628.28	-----	0.14	-----
A	48	114 758	4886	75 177	46 097	135 843	34 748	1622.36	14.60	-6.43	17.35
B	26	114 679	5155	88 432	26 358	138 100	30 073	1625.84	10.08	-3.00	13.34
C	36	112 590	4378	96 167	17 501	139 220	23 499	1629.78	9.38	2.73	12.24
E	33	112 963	4670	93 954	20 647	141 560	23 573	1629.73	9.85	1.91	14.80
Other	17	116 697	6125	82 991	26 812	137 564	13 432	1623.68	9.82	-7.30	23.87

(b) U.S. Customary Units

Inertia configuration	No. of runs	Orbit altitude, ft, at –						Insertion velocity, ft/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal[b]		Vertical[c]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	364 561	------	363 379	-------	365 847	-------	5342.12	-----	0.47	-----
A	48	376 503	16 031	246 644	151 236	445 678	114 003	5322.71	47.91	-21.08	56.93
B	26	376 242	16 914	290 132	86 478	453 085	98 665	5334.12	33.06	-9.84	43.77
C	36	369 390	14 363	315 508	57 418	456 757	77 096	5347.04	30.76	8.97	40.15
E	33	370 612	15 320	308 249	67 740	464 435	77 340	5346.88	32.30	6.28	48.55
Other	17	382 865	20 095	272 279	87 966	451 324	44 067	5327.02	32.23	-23.95	78.31

[a]Not included are runs with pressure suit, high T/W_o, or very low thrust.

[b]Combination of side velocity and forward velocity.

[c]Positive values indicate downward velocities.

Trajectory results associated with the various inertia configurations are given in table VI. The results for inertias B, C, and E are somewhat better than those for inertia A. However, a large number of the runs with inertia A were made early in the study while the pilots were still improving their kinesthetic-control skills, so this inertia configuration should not necessarily be rejected because of the somewhat poorer handling-qualities ratings and trajectory results. (Inertia A, for example, can be associated with more compact and lighter weight vehicles than the other three inertia configurations.) An inertia F configuration was rejected after two runs. This configuration had the I_{XX} and I_{YY} values of inertia C reversed (that is, I_{YY} was greater than I_{XX}), which produced very poor kinesthetic-control handling qualities and considerable anxiety for the two pilots. Pitch response was judged to be too sluggish, while roll was too sensitive.

Comparison of Time-Cue and Velocity-Cue Guidance

The LESS trajectory results were also compared on the basis of the guidance scheme used. (See table VII.) The statistics give a slight edge to the velocity-cue scheme; but because most of the time-cue runs were made first, while the pilots were still improving their skills, the difference is not considered significant. It is difficult, however, to compare the two schemes directly because they are not sensitive to the same anomalies. For example, a timer is very accurate as an instrument, but it remains invariant when thrust errors or weight uncertainties exist. A simple integrating accelerometer, on the other hand, can detect a thrust deficiency, but its reading will differ somewhat from actual velocity when there is poor attitude control and a significant shift in center of gravity. Thus it may be advisable to use a velocity meter for the primary guidance cue, with a timer as a backup to preclude premature cutoff of thrust.

Effect of Off-Nominal Conditions

The two rows of nominal-condition results in table VII were combined statistically and entered in the second row of table VIII as reference values for comparison with results from runs in which thrust misalinement, uneven propellant drain, thrust deficiencies, and combinations of these off-nominal conditions were present. Main-thruster misalinement angles of $\pm 0.10^{\circ}$, $\pm 0.25^{\circ}$, and $\pm 0.50^{\circ}$ were used to produce a variety of fixed-torque disturbances during 21 runs (third row of table VIII). To simulate uneven propellant drain, error functions (which increased with time) were programed to simulate combinations of up to 1-percent error in the drainage of both oxidizer and fuel.

Pilot ratings of vehicle handling qualities were also made during several runs involving main-thrust misalinement and uneven propellant drain. These ratings and pilot opinion during debriefing sessions indicated that small thrust misalinements did not significantly degrade the handling qualities, but uneven propellant drain (1 percent) tended to degrade the handling qualities by approximately one-half a Cooper number during rating interval III and somewhat less during interval II. Thus, none of the off-nominal conditions seemed to increase excessively the difficulty of the pilot's control tasks, although runs with both thrust misalinement and uneven propellant drain caused the pilots some initial confusion. There was no loss of control, however, and usually by the end of his second

TABLE VII.- COMPARISON OF LESS TRAJECTORY RESULTS FOR TIME-CUE AND VELOCITY-CUE SIMPLIFIED GUIDANCE SCHEMES

(a) SI Units

Guidance scheme	No. of runs	Orbit altitude, m, at –						Insertion velocity, m/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal[a]		Vertical[b]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	111 118	----	110 758	------	111 510	------	1628.28	-----	0.14	-----
Nominal conditions											
Time cue	82	114 845	5262	78 654	36 937	140 240	30 854	1624.23	14.29	-6.89	19.40
Velocity cue	36	113 997	5327	97 344	23 512	140 536	21 947	1628.99	9.05	-1.43	10.84
All conditions[c]											
Time cue	93	114 475	5126	81 846	37 464	141 187	30 635	1625.42	13.70	-5.03	19.36
Velocity cue	67	113 563	5003	93 573	22 239	134 368	21 202	1627.41	8.61	1.66	12.27

(b) U.S. Customary Units

Guidance scheme	No. of runs	Orbit altitude, ft, at –						Insertion velocity, ft/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal[a]		Vertical[b]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	364 561	------	363 379	-------	365 847	-------	5342.12	-----	0.47	-----
Nominal conditions											
Time cue	82	376 788	17 263	258 050	121 186	460 104	101 227	5328.85	46.89	-22.60	63.65
Velocity cue	36	374 006	17 476	319 369	77 139	461 076	72 006	5344.47	29.69	-4.68	35.57
All conditions[c]											
Time cue	93	375 574	16 819	268 523	122 913	463 211	100 510	5332.75	44.94	-16.50	63.53
Velocity cue	67	372 521	16 413	306 998	72 962	440 839	69 559	5339.28	28.24	5.43	40.27

[a]Combination of side velocity and forward velocity.

[b]Positive values indicate downward velocities.

[c]Not included are runs with pressure suit, high T/W_o, or very low thrust.

run each pilot had modified his kinesthetic control technique to handle the situation adequately. In the debriefing sessions the pilots agreed that thrust misalinement alone was quickly recognized and easily compensated for by shifting their foot placements on the simulator platform. This problem was usually solved completely within 15 seconds after detection, and control from the new standing position was then normal for the rest of the flight. The uneven propellant drain conditions required more attention by the pilot because as the magnitude of the torque increased, the pilot had to repeatedly seek new

TABLE VIII.- COMPARISON OF LESS TRAJECTORY RESULTS FOR OFF-NOMINAL CONDITIONS

(a) SI Units

Condition	No. of runs	Orbit altitude, m, at –						Insertion velocity, m/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal[a]		Vertical[b]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	111 118	----	110 758	------	111 510	------	1628.28	-----	0.14	-----
Nominal conditions	118	114 586	5296	84 356	34 509	140 330	28 434	1625.69	13.10	-5.22	17.43
Misalined main thrust	21	110 901	2217	96 344	19 065	139 653	28 314	1631.32	8.99	9.67	8.30
Uneven propellant drain	7	112 894	2284	93 217	15 636	121 054	3 868	1624.88	2.84	6.36	10.26
Multiple off-nominal conditions	8	117 283	4905	88 298	19 041	136 667	12 372	1623.41	9.68	-10.42	11.25
1-percent thrust deficiency	6	113 217	5066	90 829	18 896	116 775	6 226	1625.17	3.44	-3.63	10.29
Very low take-off thrust[c]	3	126 643	3494	80 464	19 898	144 798	22 112	1611.77	4.89	-21.10	12.94

(b) U.S. Customary Units

Condition	No. of runs	Orbit altitude, ft, at –						Insertion velocity, ft/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal[a]		Vertical[b]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	364 561	------	363 379	-------	365 847	------	5342.12	-----	0.47	-----
Nominal conditions	118	375 939	17 376	276 757	113 217	460 400	93 289	5333.62	42.99	-17.13	57.18
Misalined main thrust	21	363 848	7 273	316 090	62 548	458 179	92 893	5352.11	29.49	31.71	27.24
Uneven propellant drain	7	370 388	7 492	305 831	51 297	397 160	12 690	5330.97	9.31	20.85	33.65
Multiple off-nominal conditions	8	384 788	16 093	289 693	62 470	448 373	40 592	5326.14	31.75	-34.20	36.90
1-percent thrust deficiency	6	371 446	16 622	297 994	61 996	383 121	20 425	5331.92	11.30	-11.90	33.75
Very low take-off thrust[c]	3	415 497	11 462	263 988	65 581	475 060	72 547	5287.95	16.05	-69.23	42.46

[a]Combination of side velocity and forward velocity.

[b]Positive values indicate downward velocities.

[c]Take-off thrust approximately 14 percent lower than nominal.

standing positions (or continuously lean his body farther away from the vertical, which became tiresome).

All nine of the thrust-deficiency runs of table VIII were made with the velocity-cue guidance scheme. During the six runs with a deficiency of about 1 percent, the pilots were not aware of the situation until the pitchover maneuver, when they noticed that on the auxiliary timer the time for pitchover arrived somewhat before the velocity target value was reached. They followed their velocity-cue plan, however, and all trajectories resulted in safe orbits, with characteristics roughly comparable to those of the runs with regular thrust.

Analytically, the main effect of this lower thrust is the attainment of a higher altitude before the target velocity is reached. That is, if $v^2 = 2as = \text{Constant}$, the effect of lower acceleration a is higher altitude s. In the LESS study this effect is illustrated by the mean value of insertion altitude in the last row of table VIII. For these three runs it was assumed that maximum thrust (thrust level one) was not attainable and the LES took off with thrust level two, the level normally used after pitchover, which was approximately 86 percent of maximum. The two pilots who flew these runs were at once aware of an abnormal situation because of slightly changed vehicle handling qualities and slower buildup of velocity values on the digital voltmeter. Both pilots, guessing that a large thrust deficiency existed, flew the missions with strict adherence to the velocity display and established safe orbits.

At the time of the pitchover maneuver, neither pilot realized that he had already gained a significantly higher altitude because of the thrust deficiency, and both felt the need to attain extra altitude. Therefore they performed the pitchover more slowly than usual and then biased the pitch angle a fraction of a degree above the horizontal. As a result, the altitude rate averaged about 21 m/sec (70 ft/sec) upward at orbit insertion, and the slow pitchover caused a slightly premature thrust cutoff, so that the horizontal velocity averaged about 9 m/sec (30 ft/sec) less than circular velocity at the insertion altitude. Because of the higher altitudes at insertion, however, the pericynthion altitudes were comparable to those for the regular runs. The apocynthion altitudes were also comparable because of the velocity deficiency at orbit insertion.

A review of table VIII shows that the results for the runs at off-nominal conditions were at least as good as those for the runs at nominal conditions. Pilot opinion on this point was that they (the pilots) were probably more strongly motivated to perform the control functions carefully, even though they felt they were doing their best during the runs at nominal conditions. Also, the off-nominal conditions were introduced late in the simulation program, after the pilots had refined their kinesthetic control skills.

Effect of Pressure Suit

Pilot B, who had prior suit experience, made 10 kinesthetic control runs while wearing the B. F. Goodrich Mark V full pressure suit and simulated portable life support system shown in figure 9. One of these runs had uneven propellant drain. The results of these runs are given in table IX along with results of all of pilot B's nonsuit runs and also four special reference runs made on the day preceding the pressure-suit runs (the pressure-suit runs were made midway through the LESS study). A slight degradation in performance is noted in the pressure-suit runs. For example, the mean altitude at orbit insertion was more than 6 km (20 000 ft) above the CSM, as compared with less than 1.8 km (6000 ft) for the nonsuit runs. Also, the orbits were more eccentric for the suit runs. A large part of the degradation is attributed to poorer pitch-angle control.

A pointing-error analysis was made for five of the pressure-suit runs and for 29 nonsuit runs (same inertia conditions but several pilots) which were made subsequent to the suit runs. These results are shown in table X as mean and standard deviation σ values of the pitch and roll pointing errors during the time interval before and the time interval after the pitchover maneuver. The results show that both the θ and φ pointing errors were, in general, appreciably larger for the suit runs than for the nonsuit runs. One exception was $\epsilon_{\theta 2}$, the pitch-angle error after pitchover, for the four runs involving uneven propellant drain; this 0.91° error was about as high as the 0.96° error

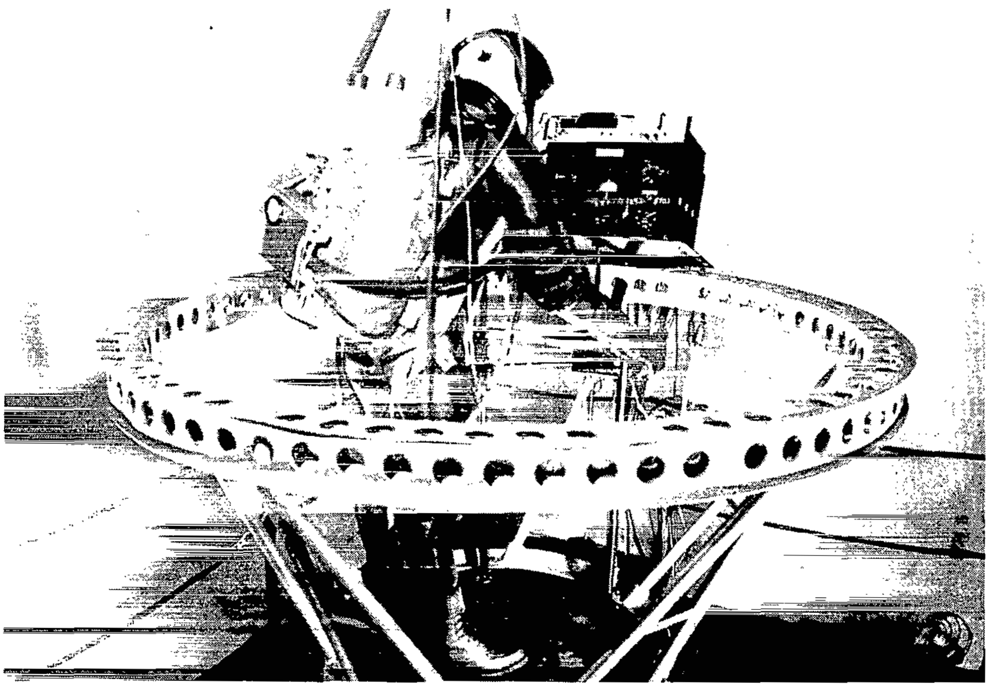

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Figure 9.- A view of the pilot during the tests that included a full pressure suit.

for the suit runs. As indicated in the discussion of table VIII, the pilots considered uneven propellant drain late in the flight as the most bothersome (to their control task) of the off-nominal conditions studied.

Another factor which may have caused some degradation of performance while wearing the pressure suit was that some of the LESS equipment was not suitably designed for pressure-suit operation. For example, the toggle-switch used to change the thrust could hardly be felt through the pressure glove and had to be enlarged after the first run. Even then, after each thrust change the pilot had to look down (awkward in a pressure suit)

TABLE IX.- COMPARISON OF RUNS MADE BY ONE PILOT WITH AND WITHOUT FULL PRESSURE SUIT

[All runs with velocity-cue guidance scheme]

(a) SI Units

Condition	No. of runs	Orbit altitude, m, at –						Insertion velocity, m/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal[a]		Vertical[b]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	111 118	----	110 758	------	111 510	------	1628.28	----	0.14	-----
Selective comparison											
Nonsuit reference runs	4	112 714	3904	108 620	2 427	134 661	13 190	1631.42	5.13	-0.72	7.22
Comparative suit runs	6	117 196	4167	102 733	9 349	165 172	18 793	1632.68	5.95	-16.48	15.77
Full comparison											
All nonsuit nominal-condition runs	14	112 791	4253	101 198	19 338	143 436	18 002	1631.59	9.45	-1.64	10.17
All suit runs	10	117 687	4984	98 175	15 129	155 886	22 440	1629.24	6.41	-10.52	16.77

(b) U.S. Customary Units

Condition	No. of runs	Orbit altitude, ft, at –						Insertion velocity, ft/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal[a]		Vertical[b]	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Ref. trajectory	---	364 561	------	363 379	------	365 847	------	5342.12	-----	0.47	-----
Selective comparison											
Nonsuit reference runs	4	369 795	12 808	356 364	7 961	441 802	43 273	5352.44	16.83	-2.36	23.68
Comparative suit runs	6	384 501	13 672	337 050	30 673	541 902	61 657	5356.56	19.51	-54.28	51.73
Full comparison											
All nonsuit nominal-condition runs	14	370 049	13 953	332 014	63 445	470 592	59 062	5352.98	31.00	-5.38	33.37
All suit runs	10	386 112	16 353	322 096	49 636	511 437	73 621	5345.28	21.04	-34.50	55.02

[a]Combination of side velocity and forward velocity.

[b]Positive values indicate downward velocities.

TABLE X.- RESULTS OF LESS POINTING-ERROR ANALYSIS

[The 8-ball was not flipped in any of these runs]

Condition	No. of runs	ϵ_{θ_1}, deg		ϵ_{θ_2}, deg		ϵ_{φ_1}, deg		ϵ_{φ_2}, deg	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ
Suit runs									
Nominal[a]	5	1.36	0.87	0.96	0.75	0.75	0.98	1.05	1.21
Nonsuit runs									
Nominal conditions	17	0.32	0.61	0.39	0.42	0.31	0.27	0.13	0.52
Misalined thrust	6	.30	.30	-.01	.63	-.18	.25	-.26	.16
Uneven propellant drain	4	.38	.08	.91	.36	.03	.17	.25	.46
Total[b]	29	.34	.49	.39	.52	.15	.33	.02	.50

[a]One of these runs involved uneven propellant drain.

[b]Includes the nonsuit runs of this table plus two nonsuit runs in which there were multiple off-nominal conditions.

to verify that he had positioned the switch correctly. The pressure suit also caused the pilot to crouch forward, and consequently his style of kinesthetic control was modified somewhat. A set of handlebars was installed (see fig. 9) so the pilot could use his arms to help straighten himself up and reach the thrust and yaw control switches more easily. The handlebars were retained during the last half of the LESS study as convenient steadying handholds, although very little force was applied to them except during the pressure-suit runs.

Miscellaneous Results

Three miscellaneous cue variations were investigated briefly: control-event warnings, a "flipped" 8-ball circuit, and inclusion of attitude rate $(\dot{\varphi},\dot{\psi},\dot{\theta})$ information on the 8-ball display. As indicated in the following three paragraphs, the effect of these cues was not always clearly determined.

To alert one pilot to monitor his digital voltmeter closely for a control-event target value, approximately five clicks (1 second apart) were produced over his intercom. (He preferred this auditory cue to blinking lights, which were used in some preliminary runs.) In all runs where the auditory cue was used, the pilot indicated that he was very much aware of an impending digital voltmeter target value before he heard the clicks, and the auditory cues were soon discontinued at his suggestion. In the LESS study, however, a total of five control events were missed (all by another pilot) and several other events were initiated several seconds late, resulting in four of the six runs aborted during the study. Thus, it appears that an auditory cue of some type might be helpful.

It was difficult for the pilots to interpret the 8-ball quickly during the time period after the pitchover to $\theta_2 = -90^\circ$ because they had to look into the pole of the black hemisphere where the longitude ψ and latitude θ lines converge. (See fig. 10.) The problem was particularly acute when multiple errors in angles and attitude rates existed simultaneously and the pilot also had to monitor his digital voltmeter closely for a guidance-cue. Consequently, a 90° pitch bias ("flip circuit") was installed which allowed the 8-ball to be flipped back to its zero position in pitch after the pitchover. The pilot could then use the interface of the black and white hemispheres (i.e., the equator) as the pitch-angle reference while he attempted to hold the pitch angle at -90°. Also, the longitude and latitude lines were farther apart here and thus easier to interpret. (See ref. 10 for further illustrations and discussion.) The flip circuit was activated with a toggle switch, usually when the pilot felt he had reached "steady" conditions after the pitchover maneuver. One pilot, however, preferred to flip the 8-ball when he was about two-thirds of the way through the pitch maneuver so he could view the flipped display as he stabilized the vehicle at the end of the pitch maneuver. The flip-circuit innovation was well received

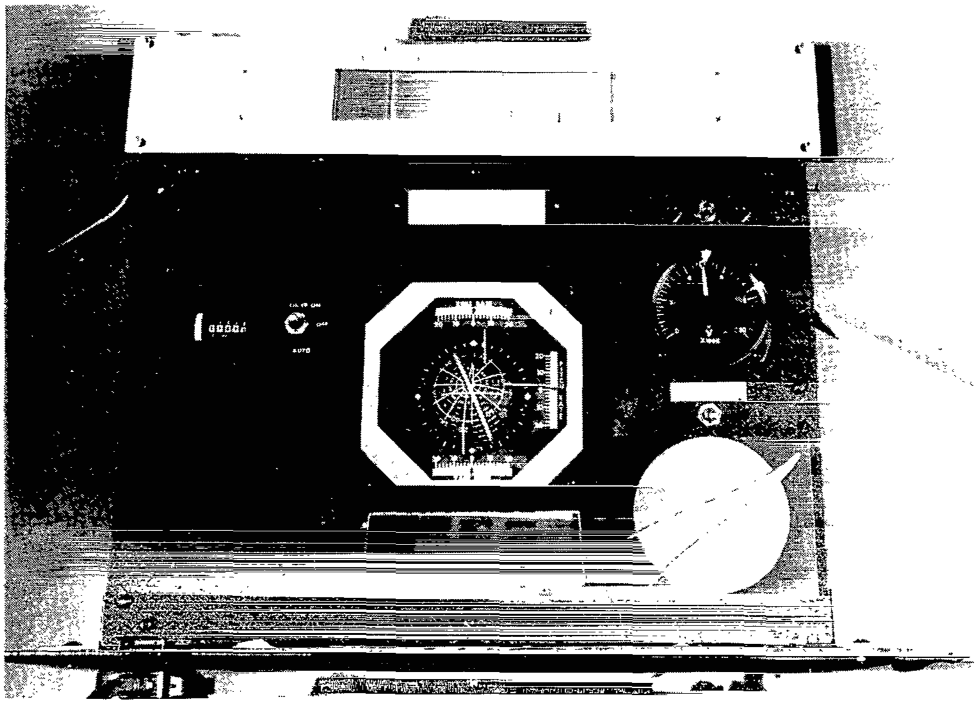

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Figure 10.- Pilot's view of the 8-ball after pitchover.

by all the pilots and it was used in more than 100 runs, or nearly all the runs after its introduction. Because of the diversity of study conditions and because the flip-circuit runs were made during the second half of the LESS study, the runs with and without the flip circuit were not compared statistically. However, a cursory examination of some runs made on the same day with and without the flip circuit indicated that the trajectory results were roughly equivalent.

During several of the early time-cue runs the attitude rates $\dot{\varphi}$, $\dot{\psi}$, and $\dot{\theta}$ were displayed along with φ, ψ, and θ on the LESS 8-ball. The experienced pilots liked having this familiar rate information available but agreed that they tended to concentrate too much on nulling the rates to the detriment of careful angle control. In particular, slightly larger average pitch-angle errors and, consequently, somewhat poorer orbits resulted, so the rate display was discontinued.

Most of the 194 simulation runs were made with only one pilot standing on the simulator platform. In the few runs made with a passenger standing behind him, the pilot did not appear to have any control difficulties that could be attributed to the passenger's inadvertent inputs. In one run the passenger was instructed to add some sizable disturbances discreetly; he did this by extending one arm sideward while holding a 2.27-kg (5-lb) lead weight. Although the pilot was able to maintain fairly good control, these disturbances initially caused him some anxiety, primarily because he did not know what was causing them. After the first few such disturbances during this run, however, the pilot became very alert for the onset of 8-ball motions and was quick to take corrective action. As a result, his established orbit was no worse than average.

CONCLUSIONS

On the basis of pilot opinion, observation of the pilot's control techniques, and the trajectory results of 194 simulated lunar escape runs, the following conclusions have been reached:

(1) A pilot can consistently establish safe lunar orbits with emergency escape vehicles using simplified manual guidance schemes and kinesthetic attitude control. In particular, kinesthetic control of vehicle pitch and roll is acceptable for an emergency lunar escape mission; if not selected as the primary control mode, it can be a very simple and reliable backup technique.

(2) Kinesthetic control tasks are easy to learn but require almost the full attention of the pilot for their execution.

(3) A pilot's kinesthetic-control skills are retained without degradation for at least 14 days.

(4) The presence of a second man (passenger) standing on the platform of the lunar escape system simulator (LESS) did not contribute disturbance torques which significantly increased the difficulty of the pilot's kinesthetic control tasks.

(5) The lunar escape mission can be performed by a pilot wearing a full pressure suit; execution of the control tasks is much more difficult and tiring, but satisfactory orbits can be established.

(6) Trajectory results for the time-cue and velocity-cue guidance schemes are generally comparable; however, velocity-cue guidance is more appropriate if a thrust deficiency exists.

(7) All inertia configurations used in the LESS study were kinesthetically controllable, although the handling qualities of one configuration were declared "unacceptable." In general, the following ranges of I_{xx} (moment of inertia about the roll axis) and I_{yy} (moment of inertia about the pitch axis) were determined to be most appropriate for kinesthetic control of an emergency LES:

(a) I_{xx} greater than 1200 kg-m^2 (885 slug-ft^2)

(b) I_{yy} between 600 and 1000 kg-m^2 (443 and 738 slug-ft^2)

(8) The LESS trajectory results were not adversely affected by such off-nominal conditions as small thrust misalinements, uneven propellant drain, or thrust deficiencies; such conditions only added slightly to the difficulty of performing the kinesthetic control tasks.

(9) All of the pilot's display information must be concentrated near the center of the pilot's look direction; extreme concentration on the 8-ball is required and it is undesirable for the pilot to glance away to observe other necessary information.

(10) The pilots considered an 8-ball flip circuit (for pitch angle) a welcome enhancement to the basic information display. Also, a differential velocity indicator with a prominent sweep hand is considered desirable to augment the velocity display on the digital voltmeter.

(11) An auditory cue to alert the LES control pilot for important control events seems desirable; the communications system, however, can probably be used to fulfill this need.

(12) Inclusion of attitude-rate information on the 8-ball does not appear to be necessary or particularly beneficial because it increases the number of variables among which the pilot must divide his attention.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., April 26, 1971.

APPENDIX A

DESCRIPTION OF AXIS SYSTEMS AND SUMMARY OF COMPUTER EQUATIONS

Axis Systems

The simplified guidance schemes used in the LESS studies are based primarily on measures which are related to the local vertical. However, it is convenient to sum the forces and moments acting on the LES in a body-axis system X_B,Y_B,Z_B with origin at the instantaneous center of gravity. Therefore, velocities determined in the body-axis system were transformed by means of direction cosines to a local-vertical system X_{LV},Y_{LV},Z_{LV} and to an inertial system X_I,Y_I,Z_I for the trajectory calculations and orbit determinations. The axis systems are shown in figure 1 and details concerning generation of the various direction cosines are given in reference 10.

Equations of Motion

A summary (from ref. 10) of the translational- and angular-acceleration equations of motion, expressed in the body-axis system, is given below. The three linear-acceleration components are:

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} \dfrac{T_{x_B}}{m} + b_{13}\dfrac{\mu}{R^2} - wq + vr \\ \dfrac{T_{y_B}}{m} + b_{23}\dfrac{\mu}{R^2} - ur + wp \\ \dfrac{T_{z_B}}{m} + b_{33}\dfrac{\mu}{R^2} - vp + uq \end{bmatrix} \tag{A1}$$

where b_{13}, b_{23}, and b_{33} are direction cosines appropriate to transforming the gravity acceleration from the local-vertical system into body coordinates; R is the distance from the origin of body coordinates to the center of the moon; and T_{x_B}, T_{y_B}, and T_{z_B} are body components of the main thrust. Except in cases where the main thrust is misalined, T_{x_B} and T_{y_B} are zero.

The associated angular accelerations are given by:

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} I_1\left(Q_{x_B} - D_1\right) + I_3\left(Q_{z_B} - D_3\right) \\ \frac{1}{I_{yy}}\left(Q_{y_B} - D_2\right) \\ I_2\left(Q_{z_B} - D_3\right) + I_3\left(Q_{x_B} - D_1\right) \end{bmatrix} \tag{A2}$$

where I_1, I_2, I_3, and I_{yy} are inertia terms; D_1, D_2, and D_3 are collections of miscellaneous terms from the moment-equation derivations; and Q_{x_B}, Q_{y_B}, and Q_{z_B} are body-axis torques.

The inertia terms are further defined by

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} I_{zz}\Big/\left(I_{xx}I_{zz} - I_{xz}^2\right) \\ I_{xx}\Big/\left(I_{xx}I_{xz} - I_{xz}^2\right) \\ I_{xz}\Big/\left(I_{xx}I_{xz} - I_{xz}^2\right) \end{bmatrix} \tag{A3}$$

Because of assumed symmetry in each of the LES vehicle configurations, the only non-zero product of inertia is I_{xz}. Examples of inertia variations during the escape flights are shown in figure 8 for several vehicle configurations.

The auxiliary variables D_1, D_2, and D_3 are given by

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} \dot{I}_{xx}p + \left(I_{zz} - I_{yy}\right)qr - I_{xz}pq \\ \dot{I}_{yy}q + \left(I_{xx} - I_{zz}\right)pr + I_{xz}\left(p^2 - r^2\right) \\ \dot{I}_{zz}r + \left(I_{yy} - I_{xx}\right)pq + I_{xz}qr \end{bmatrix} \tag{A4}$$

where the inertia rates are retained because such a large percentage of the total mass is propellant mass, which is expended during a flight.

Body Torques and Horizontal Center-of-Gravity Shifts

Because the kinesthetic-control torques are a function of the horizontal center-of-gravity shift (with components Δx and Δy) off of the line of thrust, it is necessary to sense or determine Δx and Δy continuously. The load cells under the LESS platform were used to generate the electrical signals M_θ and M_φ, which were proportional to the pitch and roll torques, respectively, that were created when the LESS pilot shifted his center of gravity with respect to the balance point of the control station. (See ref. 10.) In equation form,

$$M_\theta = K_1 W_{3,e} \delta_{x_B,3} \tag{A5}$$

$$M_\varphi = K_1 W_{3,e} \delta_{y_B,3} \tag{A6}$$

where K_1 is a gain factor (to boost signal strength), $W_{3,e}$ is the earth weight of the control pilot, and $\delta_{x_B,3}$ and $\delta_{y_B,3}$ are distances the pilot moves his own center of gravity from the balancing position. Then the body-axis components of the horizontal center-of-gravity shift of the vehicle system are

$$\Delta x = K_2 \frac{M_\theta}{mg_e} \tag{A7}$$

$$\Delta y = K_2 \frac{M_\varphi}{mg_e} \tag{A8}$$

where mg_e is the earth weight of the LES, and K_2 relates the load-cell signals to vehicle torques when the signals are converted at the digital computer.

With Δx and Δy thus continuously determined, the equations for the torques acting on a LES during an escape flight can be written as

$$\begin{bmatrix} Q_{x_B} \\ Q_{y_B} \\ Q_{z_B} \end{bmatrix} = \begin{bmatrix} T\left[\Delta y - \left(z_h - \Delta z\right)\xi_{y_B}\right] + K_3\,\Delta y\, m\,\frac{\mu}{R^2} + K_4 t \\ T\left[-\Delta x + \left(z_h - \Delta z\right)\xi_{x_B}\right] + K_3\,\Delta y\, m\,\frac{\mu}{R^2} + K_5 t \\ Q_{J,z_B} \end{bmatrix} \tag{A9}$$

where (T Δx) and (T Δy) are the inflight kinesthetic control torques; ξ_{x_B} and ξ_{y_B} are thrust misalinement angles; z_h is the distance from the initial center of gravity of the vehicle to the thruster nozzle; and $m\mu/R^2$ is the lunar weight of the LES. The terms containing K_3 permit kinesthetic control on the launch rack during the prebalance period; K_3 has a value of 1 prior to take-off and 0 when thrust is turned on. The terms K_4t and K_5t are used to simulate uneven propellant drain, and Q_{J,z_B} is the torque due to the yaw jets.

Velocity Along the Thrust Axis

The following equation was used to represent the output of the integrating accelerometer mounted on the thrust axis at the initial center of gravity of the vehicle:

$$V_{z_B} = \int_0^t \left[\frac{T}{m} - b_{33}g_m + \Delta z\left(p^2 + q^2\right)\right] dt \tag{A10}$$

where g_m is the acceleration due to lunar gravity (constant) and the term containing Δz has the form of the factor normally used to correct sensed acceleration to vehicle acceleration; however, in the present application this term is used with the opposite sign in order to generate the uncorrected or sensed acceleration (for display to the pilot) from the computed acceleration.

Orbital Parameters

The primary characteristics of the LES orbits are determined from the following equations based on "burnout" conditions (variables with subscript BO) in the escape trajectory.

The semimajor axis is determined from

$$a = \frac{R_{BO}}{2 - \dfrac{R_{BO}\left(V_t\right)_{BO}^2}{\mu}} \tag{A11}$$

where V_t is the total velocity of the LES and μ is a lunar gravitational constant. Next the radius of pericynthion is given by

$$r_p = a\left[1 - \sqrt{1 - \frac{R_{BO}^2\left(V_h\right)_{BO}^2}{a\mu}}\right] \tag{A12}$$

where V_h is the local horizontal component of V_t. From this the altitude of pericynthion is

$$h_p = r_p - r_m \tag{A13}$$

where r_m is the radius of the moon. The altitude of apocynthion is thus

$$h_a = 2a - r_p - r_m \tag{A14}$$

A number of other parameters (eccentricity, semilatus rectum, etc.) were also determined in the computer program but are not used directly in this report.

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