# Lunar Escape-to-Orbit Systems Simulation (LESS) Using Simplified Manual Control

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**A fixed-base 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 of the manual guidance and control functions. Three types of attitude control—kinesthetic, all-jet, and double-gimbaled main thruster—were used successfully over a vehicle (including men and pressure suits) moment-of-inertia range of 340 to 16,200 kg-m² (250 to 12,000 slug-ft²). Five pilots made approximately 350 simulated escape-to-orbit flights, including 10 flights with a pilot wearing a full pressure suit. The pilots also had to cope with typical amounts of misalined thrust, uneven propellant drain, and thrust deficiency. Approximately 96% of the simulated flights resulted in the establishment of lunar orbits having pericynthions greater than 15 km (≈50,000 ft). Special attention is given to the analysis of the kinesthetic control results.**

## Nomenclature

| | |
|---|---|
| $b_{33}$ | = direction cosine of thrust vector with respect to local vertical |
| $g_m$ | = value of lunar-gravity acceleration, at lunar surface |
| $I_{xx}, I_{yy}$ | = moments of inertia of LES (including astronauts) about the body roll and pitch axes, respectively |
| $m$ | = instantaneous mass of LES (including astronauts) |
| $p,q,r$ | = angular velocity components about the body roll, pitch, and yaw axes, respectively |
| $T$ | = main thrust of the LES |
| $V_Z$ | = "indicated-velocity-along-thrust-axis" signal, assumed derived from output of integrating accelerometer alined with the thrust axis of the LES |
| $W$ | = Earth weight of the LES |
| $W_0$ | = Earth weight of the LES at takeoff |
| $w$ | = component of total linear velocity in the direction of $Z$ body axis of the LES |
| $\Delta Z$ | = $Z$ body-axis component of LES c.g. shift |
| $\theta$ | = pitch angle (zero when thrust axis pointed upward along local vertical) |
| $\theta_1, \theta_2$ | = reference pitch angles used in primary guidance plans for the LES |
| $\lambda$ | = kinesthetic torquing gain (see Fig. 5) |
| $\sigma$ | = standard deviation |
| $\phi$ | = roll angle |

## Introduction

A GENERAL safety goal throughout the Apollo program has been to provide redundancy in all lunar vehicle systems except where the reliability of particular components is judged to be sufficiently high (and suitable redundancy is not considered feasible). The single-engined lunar module (LM) takeoff system which performed flawlessly during the Apollo 11, Apollo 12, Apollo 14, and Apollo 15 flights is one of these exceptions. But for future lunar flights an alternate means of lunar takeoff (i.e., escape to orbit) would certainly enhance the probability of mission success and safe return of the two LM astronauts.

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A number of approaches to an emergency lunar escape system (LES) have been considered by both NASA and industry—including multimission shuttlecraft and long-range lunar flyers (surface-to-surface) which also have the capability to escape to orbit.[1–4] For the past several years another concept has been considered which involves a very lightweight, minimum-complexity LES which possibly could be packaged on the LM for transport to the moon; this concept was initially studied during a parametric investigation[3,4] of simplified lunar flying systems. A recent contractual study[5] was concurrent to and actively associated with the LES simulation (LESS) studies at Langley; the primary objective of the joint 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 a variety of inertia and propulsion system configurations, and the rendezvous capabilities of the orbiting command-service module (CSM). In the analytical study[5] it was also determined that cannibalization of guidance and control components from the LM is not feasible due to difficult access and inappropriate modularization; thus, except for propellants, it appears that a near-preassembled LES would have to be transported to the moon.

Concepts for minimum-complexity LES vehicles necessarily involve simplified 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 indicated that a simple constant-thrust flying platform should be a satisfactory vehicle concept, and that kinesthetic attitude control and a constant-angle-pitch guidance scheme were feasible (and compatible with the vehicle concept). These features were incorporated into the LESS program where the approach has been to look first at the most basic concepts and evaluate their adequacy in terms of orbit achievement and demands on the LESS pilot. Then, where necessary or desirable, additional features and alternate control systems were added and the system reevaluated.

This paper covers the basic concepts associated with minimum-complexity lunar escape systems and presents results of a piloted simulator investigation of some of the primary guidance and control problems. Two types of results are included—characteristics of the orbits established while using simplified manual guidance and control techniques, and pilot ratings of the handling qualities of particular vehicle configurations. In some cases analytical findings from the associated contract study[5] are presented to augment the simulation results.

## Basic Concepts

The basic design rule in developing the simplified LES concept was that the system need only to provide single-mission backup capability for 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). Additional specifications involve LES-orbit geometry and motion with respect to the established orbit of the CSM. That is, under the ground rule 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 ($\approx$240 m/sec) for rescue of the LM and the operating time limit ($\approx$4 hr) of the portable life support systems (PLSS) worn by the astronauts. In the LESS studies, however, satisfaction of only the primary specification was required.

Due to the assumed availability of large amounts of LM ascent-stage propellants it was not considered necessary for the LES to follow a propellant-optimized ascent trajectory. Accordingly, several guidance plans based on constant thrust and constant pitch angles were developed. Low dry weight of the LES vehicle was, however, deemed necessary. A dry mass of about 135 kg (corresponding to approximately 300 Earth lb) was estimated for the basic vehicle for which the use of kinesthetic control of pitch and roll was assumed. Subsequent estimates[5] indicated that if the attitude control concept were changed to a simple system of all jets or a double-gimbaled main thruster, the dry mass would rise to approximately 180 kg.

## Kinesthetic Control

The type of kinesthetic control considered for use with an actual LES involves the astronaut's ability to change and/or correct vehicle pitch angle $\theta$ and roll angle $\phi$ by intentionally shifting the c.g. of the man-vehicle system away from the vehicle's fixed thrust vector. This can be accomplished simply by the astronaut leaning or stepping in the direction of desired motion. To complete the attitude control system, a set of small jets can be used for yaw control.

Kinesthetic control was simulated in the LESS study as follows: in response to observed attitude errors on his three-axis eight-ball, the LESS pilot (standing) shifted his c.g. with respect to the vehicle's designated line of thrust by leaning his body in the appropriate direction. In most cases, the pilot locked his knees and pivoted about his angles while holding his body relatively rigid. The c.g. shift was detected by load cells installed under the floor of the LESS platform—one set on the pitch axis and another set on the roll axis. (The roll-axis set is shown in Fig. 1, which is a photograph of the LESS pilot control station. A block diagram of the full simulation system is presented in Fig. 2.)

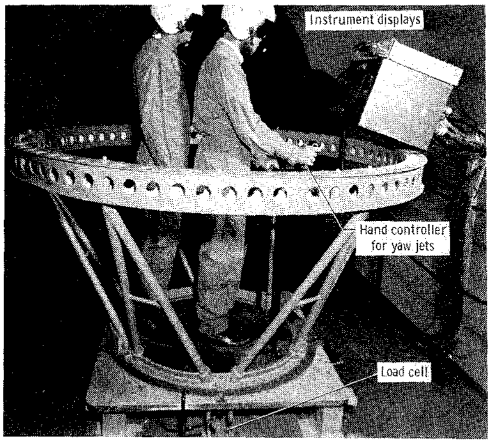


**Fig. 1 The simulator pilot-control station.**

The signals from the respective load-cell sets were scaled and transmitted over telephone lines to a real-time digital computing system where they were interpreted as pitching or rolling torques. In turn, the computer solved the equations of motion once every $\frac{1}{32}$ sec and returned attitude-angle signals to the LESS hardware where they were used to drive the three-axis eight-ball. A set of on-off jets was simulated for yaw control.

During simulated flights in which a passenger stood behind the pilot on the LESS platform, the pilot had to locate himself forward of the line of thrust to balance the mass of this passenger. The basic technique of kinesthetic control was, however, not altered. The passenger was instructed to stand still and not attempt to assist the pilot in his control tasks; but as indicated in Fig. 2, if the passenger were to make any inadvertent moves, they would be detected by the load cells and summed with the kinesthetic control inputs of the pilot. (The load cells are strictly part of the stimulation equipment; they would not be included on the actual escape vehicle.)

Kinesthetic control was used to some degree to augment the all-jet and TVC control modes, particularly when off-nominal conditions (such as uneven propellant drain) were present.

## Thrust Vector Control (TVC)

TVC is herein applied to the technique of manually tilting the main thruster to achieve pitch and roll control. Several methods of implementing this technique are available, including double-gimbaling the main thruster. During the simulation, a three-axis hand controller was used to generate electrical signals proportional to pitch and roll controller displacements; the yaw axis was set up to deliver plus or minus step voltages whenever a 20% travel deadband was exceeded. The step voltages were used to fire a simulated set of yaw sets (separate from the main thruster). This is the same setup as used for yaw control during the kinesthetic-control runs.

## All-Jet Control

The all-jet control mode is essentially an expansion of the technique used to fire just the yaw jets. That is, plus and minus step voltages were delivered from any of or all three of the LESS controller axes. The same controller was used for the all-jet and TVC control modes. (The basic control logic for each of the control modes was located in the computer.)

## Simplified Trajectory Guidance Schemes

Four similar guidance schemes were used. The basis of each was a series of constant pitch reference angles and either one or two levels of constant thrust. Two of these schemes

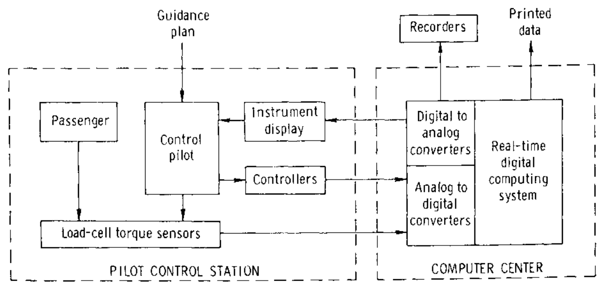


**Fig. 2 Block diagram of Lunar Escape System Simulator (LESS).**

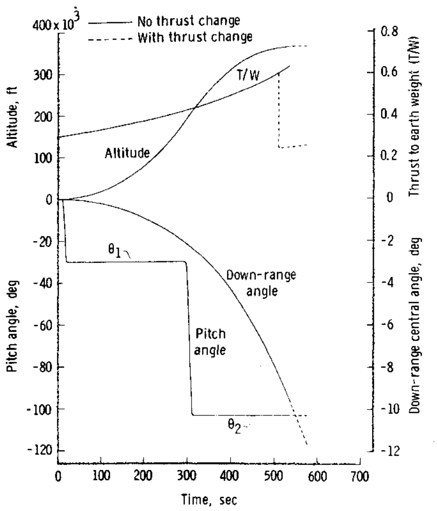


**Fig. 3 Characteristics of two simplified LESS guidance schemes.**

are characterized in Fig. 3. Both schemes involve a 10-sec vertical rise ($\theta = 0°$) followed by a pitch-transition maneuver to $\theta = -30°$; this $\theta_1$ attitude is maintained until approximately 296.5 sec when a second pitch-transition maneuver is executed; the second pitch maneuver is terminated when $\theta$ reaches $-103°$, and this $\theta_2$ attitude is maintained until orbit insertion. The primary difference in the two schemes is that thrust is reduced to approximately 40% of the initial level at about 510 sec. Even though this modification extends total flight time from 537 to 576 sec, vehicle handling qualities are improved during the interval after the thrust change. Thus the pilots should be able to better control their attitude and achieve lower angular rates at burnout.

Integrated acceleration along the spatially varying $Z$ axi, of the LES was used as a cue variable for execution of the pitch maneuvers and thrust changes. A simple integrating accelerometer alined with this axis was assumed for sensing the acceleration and providing the "indicated-velocity" cue. The fixed main thruster of the LES was also assumed to be alined with this axis, so the cue variable is referred to as "indicated velocity along the thrust axis" and designated $V_Z$. The equation for $V_Z$ is given by

$$V_Z = \int_0^t \left[\frac{T}{m} - b_{33}g_m + \Delta Z(p^2 + q^2)\right] dt \qquad (1)$$

where $b_{33}$ is a direction cosine with respect to the local verticals $\Delta Z$ is the vertical c.g. shift of the LES due to propellant burnoff, and $p$ and $q$ are the roll and pitch rates, respectively. The middle term "$b_{33}g_m$" indicates that the accelerometer has been biased for lunar gravity ($g_m$ = const). This simple bias (i.e., no variation of $g_m$ with altitude) was considered satisfactory because it was also used during the reference trajectory flights while determining the target values of $V_Z$ for initiation of the pitch maneuvers and thrust changes.

The variable $V_Z$ differs from the $Z$ body-axis component of total linear velocity (usually designated "$w$") in that $V_Z$ is not sensitive to large pitch and roll-angle changes. For example, if after a period of vertical flight the LES were to pitch 90°, the value of $V_Z$ would be affected very little but the value of $w$ would drop quickly to about zero (and begin to build up again as thrusting continued).

In a third guidance scheme, a thrust reduction to 86% of the initial level was made at the second pitch-transition maneuver (and maintained until burnout). This reduction of thrust earlier in the flight improved vehicle handling qualities a lesser amount than the reduction to 40% and reduces the propellant requirement about 6%.

The fourth scheme is a modification of the third scheme in that time is substituted for $V_Z$ as the cue variable and the

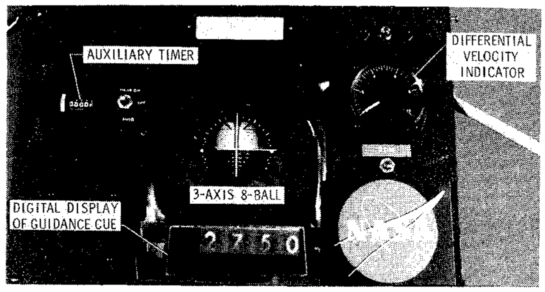


**Fig. 4 A pilot's view of the instrument display panel.**

first pitch angle is selected as vertical and the second as horizontal. This scheme is of primary interest because a clock is such a simple, lightweight, and reliable instrument. Also, with this selection of guidance pitch angles, the pilot may be able to use the lunar side horizons as a valuable cue. It is recognized, however, that if a thrust deficiency or weight uncertainty exists, serious trajectory errors can result from the use of time-cue guidance.

## Lunar Escape System Simulator

The fixed-base LES simulation (LESS) system depicted in Fig. 2 consists essentially of a LES pilot control station which was tied into a real-time digital computer through appropriate interface equipment. This type of system was selected because a high degree of resolution was required in computing the escape trajectories and the resulting orbital characteristics.

The two-man pilot control station pictured in Fig. 1 features simplified hand controls, a limited-information pilot's display, and the two sets of load cells already described. The control pilot (front) has a three-position toggle switch at his left hand (occluded) for commanding 1) the initial thrust level, 2) a second thrust level, and 3) thrust off. The controller at the pilot's right hand is a prototype CSM three-axis attitude controller. This controller was used for pitch, roll, and yaw commands during the TVC and all-jet control-mode studies and for yaw commands only during kinesthetic control studies.

Figure 4 is a closeup of the LESS instrument panel which included a prototype-LM three-axis eight-ball and a digital display of the guidance-cue variable. Time in seconds or $V_Z$ in fps was displayed depending on the guidance plan being used. To improve the location of the digital display in the pilot's field of view, a pair of planar mirrors was used to transfer an image of the display to just below the eight-ball (see Fig. 4). During $V_Z$-cue flights an auxiliary timer and a differential velocity dial were included as additional displays. The pilots tended to ignore the timer but found the sweep of the hand on the velocity dial to be a valuable cue. The dial hand was activated as a direct function of $V_Z$ during the short intervals starting just before the second pitch transition maneuver and again near orbit insertion. The initial motion of the hand alerted the pilot to prepare for execution of the pitch maneuver or thrust change. The pilot could track the motion of the hand with his peripheral vision until just before it reached the triangular tape marker (shown in Fig. 4 at $\frac{3}{4}$ travel), then he could quickly glance at the sweep hand and execute the control event as the hand passed the marker. Thus the pilot only had to switch his attention away from the eight-ball once, and then for a very short time. The differential velocity indicator was particularly useful because extreme concentration on the eight-ball was required and the rapidly changing numerals on the digital display of $V_Z$ were difficult to monitor without focusing directly on the display image.

The digital computer was programed for six-degree-of-freedom motion and real-time calculation of the orbital parameters. Basic motion equations were modified by the addition of terms containing time rates of change of mass and inertia and c.g. shifts. Control system logic equations were included in the computer program.

## Assumptions and Study Conditions

In addition to the CSM-active rendezvous ground rule, the following LESS study assumptions were made: 1) the moon has an inverse-square gravity field, 2) the moon does not rotate significantly during an LES flight, 3) some form of communications is available, either with the CSM or Mission Control in Houston; thus the whereabouts of the CSM and the characteristics of its orbit are known prior to LES takeoff, 4) both astronauts must ride the same LES, but there is a single pilot control, 5) rate gyros (for all three axes) are installed in the LES; thus both rate and attitude information are available for display to the pilot (e.g., a three-axis eightball can be used), 6) a simplified integrating accelerometer is affixed to the LES to provide velocity-type ($V_Z$) information [see Eq. (1)], and 7) only a single burn of the LES engine is allowed; however, a constant maximum thrust level and a constant intermediate level are available.

Thirteen different moment-of-inertia configurations, three basic attitude control modes, four simplified manual guidance schemes, and combinations of the following off-nominal conditions were included in the investigation: a) main thruster misalinement—up to 0.5° in any direction; b) uneven propellant drain—up to 1% on any side; c) thrust deficiency—up to 1%.

Ten flights were made by one pilot while wearing a full pressure suit and a simulated portable life support pack. With few exceptions, the pilots were aware of the selected inertia configuration and ($T/W_0$) ratio prior to a flight but they were not informed when an off-nominal condition was scheduled. When the same type off-nominal condition was included on consecutive flights, the magnitude and/or direction was usually varied.

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. During the LESS study series these pilots made a total of over 350 escape-to-orbit flights. Most of the flights were made with only one pilot on the simulator platform, but eight flights were made with a second man onboard in order to verify that his presence did not significantly affect the control situation.

## Results and Discussion

The over-all results of the LESS investigations were that all five pilots consistently achieved "safe" lunar orbits with very basic LES vehicles while using kinesthetic attitude control and any of several simplified manually executed guidance schemes. Two other types of simplified attitude control were also used with comparable results. It was demonstrated that the pilots could cope with control situations which included the effects of the off-nominal conditions listed in the preceding section. The effects of a full pressure suit (and PLSS) were investigated and it was found that successful escape flights could be made, but that kinesthetic control tasks were much more difficult to perform. These results are expanded in the following paragraphs into specific trajectory results and pilot ratings of the handling qualities of particular control-system, thrust, and moment-of-inertia configurations. In keeping with the study approach, the results obtained with the most basic systems and concepts are discussed first, and then additional features are introduced as they appear appropriate.

**Table 1 Effect of time-cue and velocity-cue guidance on trajectory**

| Parameters | 93 Time-cue flights | | 67 Velocity-cue flights | |
|---|---|---|---|---|
| Orbit altitudes, | m | ft | m | ft |
| Insertion, avg. | 114,475 | 375,574 | 113,563 | 372,521 |
| Std. deviation | 5,126 | 16,819 | 5,003 | 16,413 |
| Pericynthion, avg. | 81,847 | 268,523 | 93,573 | 72,962 |
| Std. deviation | 37,464 | 122,913 | 22,239 | 306,998 |
| Apocynthion, avg. | 141,187 | 463,211 | 134,368 | 440,839 |
| Std. deviation | 30,635 | 100,510 | 21,202 | 69,559 |
| Insertion velocity, | m/sec | fps | m/sec | fps |
| Horizontal, avg. | 1625.42 | 5332.75 | 1627.41 | 5339.28 |
| Std. deviation | 13.70 | 44.94 | 8.61 | 28.24 |
| Vertical[a], avg. | −5.03 | −16.50 | 1.66 | 5.43 |
| Std. deviation | 19.36 | 63.53 | 12.27 | 40.27 |

[a] Positive values denote downward velocity.

### Effects of Type of Guidance Cue

To ascertain the suitability of using only time-cue execution of one simplified LES guidance plan, 93 simulated escape-to-orbit flights were made using kinesthetic control and a variety of nominal and off-nominal conditions. Pertinent characteristics of the orbits resulting from these flights are tabulated in the first two columns of Table 1. The average pericynthion altitude of approximately 82 km is well above the "safe-orbit" limit of 15 km, although three unsafe orbits were established early in the study while the pilots were still improving their kinesthetic control skills. None of the time-cue flights were made with thrust-deficiency conditions because it was determined analytically[5] that unsafe orbits result if the thrust deficiency is greater than about 1.5% and the LES pitch maneuvers and thrust changes are made on the basis of a time cue.

Sixty-seven velocity-cue ($V_Z$) flights with essentially the same variety of nominal and off-nominal conditions were made for comparison to the time-cue runs. The results of the $V_Z$-cue runs are entered in the last two columns of Table 1. An improvement in both the average pericynthion altitude and orbit eccentricity can be noted for the $V_Z$-cue runs. Also, only one trajectory resulted in an unsafe orbit. Part of the improvement can be explained by the fact that a large percentage of the $V_Z$-cue flights were made after the time-cue flights, and thus the pilots were better trained. Also, because the $V_Z$ signal is derived from an integrating accelerometer (aligned with the thrust axis), $V_Z$ is adaptive to the effects of certain off-nominal conditions. For example, it was also determined in the analytical study[5] that thrust deficiencies as large as 9% could be tolerated if the thrust and pitch events were executed on the basis of a velocity cue.

### Comparison of Attitude Control Modes

After completion of the 160 flights just discussed, a series of $V_Z$-cue flights was made with each of the three attitude control modes—kinesthetic, TVC, and all-jet. Comparable trajectory results were obtained for each mode; these results are shown in Table 2. In fact, the all-jet control flights were terminated after 12 runs because the data were so similar to those obtained with the other control modes. Note that in Table 2, the kinesthetic control results are better than those in the velocity-cue columns of Table 1. That is, the average pericynthion altitude was comparable, but the $\sigma$-value was smaller and the orbits were less eccentric. This improvement indicates that useful training was obtained during the Table 1 flights.

Three pilots evaluated LES vehicle handling qualities during this phase of the study and indicated a definite preference for the TVC and all-jet modes over the kinesthetic mode.

**Table 2 Trajector results while using each attitude control mode**

| Parameters | Pericynthion altitude m | Pericynthion altitude ft | Orbit eccentricity |
|---|---|---|---|
| Kinesthetic control | | | |
| 39 runs, avg. | 92,924 | 304,869 | 0.0099 |
| Standard deviation ($\sigma$) | 19,212 | 63,032 | 0.0052 |
| Thrust-vector control (TVC) | | | |
| 39 runs, avg. | 90,488 | 296,877 | 0.0115 |
| Standard deviation ($\sigma$) | 22,166 | 72,724 | 0.0062 |
| All jet control | | | |
| 12 runs, avg. | 88,304 | 289,712 | 0.0114 |
| Standard deviation ($\sigma$) | 12,825 | 42,076 | 0.0070 |

Using the Revised Pilot Rating Scale[6] of Table 3, the pilots rated the handling qualities for all-jet and TVC runs about even and rated kinesthetic control handling qualities (for otherwise comparable conditions) about one point higher (poorer). All average ratings fell within the "unsatisfactory but acceptable" region of Table 3, although ratings of "A3" were given to some configurations. The only off-nominal condition which affected the ratings was uneven propellant drain; the ratings were about one-half point poorer for this condition while using each of the three control modes. The reason for the degradation is that uneven propellant drain caused steadily increasing asymmetric torques about the pitch and/or roll axis which caused the pilot to continuously adjust his control inputs to the changing situation.

Based on the Table 2 results and the pilot ratings of vehicle handling qualities, it appears that any of the three manual-control modes are feasible for control of an emergency LES vehicle. An all-jet system may have a slight advantage in that the jets could be used to null tumbling rates after orbit insertion, a feature not available with the other two modes. If system weight were critical, then kinesthetic control might be favored because it would involve essentially no additional weight. In any event, kinesthetic control is inherently available as a backup technique.

### Effects of Pressure Suit

The results of 10 flights made by one pilot while wearing a full pressure suit (and simulated PLSS backpack) are given in Table 4. All 10 flights resulted in safe orbits, but the pilot reported that kinesthetic control was much more difficult to perform in a pressure suit. For comparison, the results of this pilot's nonsuit runs made with the same guidance scheme are also shown in Table 4. The orbits resulting from the pressure suit runs are only slightly more eccentric than for the nonsuit runs. The average insertion altitude for the suit runs is, however, about $6\frac{1}{2}$ km above the intended insertion value of 111 km, and there is a significant upward (vertical) component of the insertion velocity. These two factors indicate that poorer pitch-angle control during the suit runs may have been the cause of the more eccentric orbits. An examination of the attitude angle records for the Table 4 runs confirmed this. A pointing-error analysis revealed: a) for the suit runs, the average pitch error $(\theta - \theta_1)$ before the pitch-transition maneuver was 1.36° [the error $(\theta - \theta_2)$ after pitchover was 0.96°]; b) for the nonsuit runs, the average-error values were $(\theta - \theta_1) = 0.32°$ and $(\theta - \theta_2) = 0.39°$; c) A similar degradation was noted for corresponding roll errors, but they had little effect on the pericynthion altitudes and orbit eccentricities.

The pitch errors for the suit runs are, however, within the acceptable limits determined during the associated contractor study.[5] Thus, even though attitude control was not precise and the kinesthetic control task was more difficult, it is concluded that an LES pilot wearing a full pressure suit could make a successful escape-to-orbit flight using kinesthetic attitude control.

### Effects of Reduced Thrust Just Prior to Burnout

No determination of acceptable tumbling rates $(p,q,r)$ after orbit insertion has been made because the LES-CSM docking technique has not been completely defined. It is apparent, however, that the best docking situation is one in which the LES tumbling rates are very low. Twenty-six flights were made in which main thrust was reduced (to 40% of the take-off value) near burnout in order to produce improved vehicle handling qualities and, hopefully, lower angular rates at burnout. The pilots were not told specifically to concentrate on achieving low rates at burnout during these runs, although they had been instructed at the beginning of the LESS studies to try to achieve low angular rates at burnout. The average $p,q,r$ values at burnout for these 26 runs are compared in Table 5 to 26 runs in which thrust was not reduced. Both

**Table 3 Revised pilot rating scale for evaluating handling qualities**

<table>
<tr><td>$A_1$</td><td>Excellent</td><td rowspan="3">Satisfactory: meets all requirements and expectations, good enough without improvement.</td><td rowspan="6">Acceptable: may have deficiencies which warrant improvement, but adequate for mission. Pilot compensation if required to achieve acceptable performance is feasible.</td><td rowspan="9">Controllable: capable of being controlled or managed in context of mission, with available pilot attention.</td></tr>
<tr><td>$A_2$</td><td>Good</td></tr>
<tr><td>$A_3$</td><td>Fair</td></tr>
<tr><td>$A_4$</td><td>Some annoying minor deficiencies</td><td rowspan="3">Unsatisfactory: reluctantly acceptable, deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.</td></tr>
<tr><td>$A_5$</td><td>Moderately objectionable deficiencies</td></tr>
<tr><td>$A_6$</td><td>Very objectionable deficiencies</td></tr>
<tr><td>$U_7$</td><td>Major deficiencies</td><td rowspan="3"></td><td rowspan="3">Unacceptable: deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation</td></tr>
<tr><td>$U_8$</td><td>Controllable with difficulty</td></tr>
<tr><td>$U_9$</td><td>Marginally controllable</td></tr>
<tr><td>10</td><td>Uncontrollable</td><td colspan="3">Uncontrollable: Control will be lost during some portion of mission.</td></tr>
</table>

[a] Note: this pilot rating scale was developed in Ref. 6.

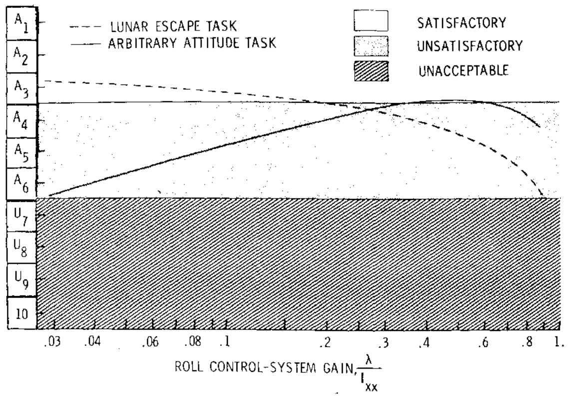


**Fig. 5 Results of pilot ratings of LES handling qualities.**

sets of runs cover the full study range of moments of inertia but otherwise only nominal conditions were used.

The significant result shown in Table 5 is that both $p$ and $q$ are reduced close to zero in the reduced-thrust runs, although neither appeared to be very high in the single-thrust runs. Thus, it is concluded that the technique of reducing the thrust near burnout is an effective means of achieving low ngular rates at orbit insertion.

### Effects of Large Moments of Inertias

The moments of inertia of the LES design configurations considered were generally less than 1750 kg-m$^2$ about any axis. But during a number of kinesthetic control flights, the inertias were increased to very large values in order to determine if the vehicle became unmanageable. To achieve the high inertias, the same mass was retained and the propellant tanks were spread farther apart. In particular, values of roll inertia ($I_{xx}$) up to 16,200 kg-m$^2$ and values of pitch inertia up to 3250 kg-m$^2$ were investigated.

Trajectory results while using the larger inertia configurations were about as good as those for the lower inertias. The pilots, however, preferred configurations having sluggish roll response and relatively quick pitch response. In particular, they preferred configurations where $I_{yy}$ was about 800 to 1200 kg-m$^2$ and $I_{xx} > 2I_{yy}$.

The pilots evaluated the handling qualities of a group of configurations having the same $I_{yy}$ and the full range of $I_{xx}$'s. The result of this evaluation is shown by the dashed curve in Fig. 5 where pilot rating is plotted against the control-system roll gain, which is a parameter related to $I_{xx}$ and another parameter $\lambda$ described as the "kinesthetic torquing gain." ($\lambda$ is a function of $T/m$, mass of pilot, and the distance between pilot's c.g. and the c.g. of the vehicle.) The ordinate in Fig. 5 is the index scale of Table 3. As shown, the pilots rated vehicle kinesthetic control handling qualities best for the medium and large values of $I_{xx}$ (small values of control-system gain).

**Table 4 Effect of pressure suit on trajectory results**

| Parameters | Nonsuit runs | | Pressure-suit runs | |
|---|---|---|---|---|
| Orbit altitudes | m | ft | m | ft |
| Insertion, avg. | 112,791 | 370,049 | 117,687 | 386,112 |
| Std. deviation | 4,253 | 13,953 | 4,984 | 16,352 |
| Pericynthion, avg. | 101,198 | 332,014 | 98,175 | 322,096 |
| Std. deviation | 19,338 | 63,445 | 15,129 | 49,636 |
| Apocynthion, avg. | 143,436 | 470,592 | 155,886 | 511,437 |
| Std. deviation | 18,002 | 59,062 | 22,440 | 73,622 |
| Insertion velocities | m/sec | fps | m/sec | fps |
| Horizontal, avg. | 1631.59 | 5352.98 | 1629.24 | 5345.28 |
| Std. deviation | 9.45 | 31.00 | 6.41 | 21.04 |
| Vertical,[a] avg. | −1.64 | −5.38 | −10.52 | −34.50 |
| Std. deviation | 10.17 | 33.37 | 16.77 | 55.02 |

[a] Positive values indicate downward velocities.

**Table 5 Effect of main thrust change on angular rates at burnout**

| Parameters | Average tumbling rate, rad/sec | Worst-case tumbling rate, rad/sec | Standard deviation, rad/sec |
|---|---|---|---|
| No thrust change | | | |
| Rolling rate, ($p$) | −0.0123 | −0.0718 | 0.0317 |
| Pitching rate, ($q$) | −0.0129 | −0.0732 | 0.0315 |
| Yawing rate, ($r$) | 0.0001 | 0.0113 | 0.0049 |
| With thrust change | | | |
| Rolling rate, ($p$) | 0.0021 | 0.0575 | 0.0185 |
| Pitching rate, ($q$) | −0.0008 | 0.0382 | 0.0116 |
| Yawing rate, ($r$) | 0.0001 | 0.0035 | 0.0015 |

For comparison, a series of arbitrary runs involving both pitch and roll maneuvers was made using the same thrust and inertia conditions; the results of evaluating vehicle handling qualities during these runs is shown by the solid curve in Fig. 5. Note in particular that the handling qualities become poorer with increasing $I_{xx}$ because the vehicle becomes too sluggish in roll for the pilot to perform the roll maneuvers effectively.

From Fig. 5, it appears that the roll-axis control system gain should be greater than about 0.2 and less than 0.4 for the best kinesthetic control handling qualities. The arbitrary-task curve in this range suggests that a change in kinesthetic control task requirements should not significantly affect vehicle handling qualities.

## Conclusions

The following conclusions were drawn from the LESS trajectory results and pilot evaluations of LES vehicle handling qualities.

1) Safe lunar orbits can be achieved with very basic LES vehicles while using kinesthetic attitude control and any of several simplified manually executed guidance schemes.

2) Satisfactory kinesthetic control of an LES vehicle can be achieved while wearing a full pressure suit, although the task is more difficult.

3) The pilots preferred the all-jet and TVC control modes over kinesthetic control, although comparable trajectory results were obtained while using each mode.

4) $V_Z$-cue LES guidance schemes produced slightly better trajectory results than time-cue schemes. Time-cue schemes will, however, produce satisfactory results if the thrust level can be guaranteed to within 1% (and no weight uncertainty exists).

5) Vehicle handling qualities were best for kinesthetic control when the control system roll gain was between the values of 0.2 and 0.4. More specifically, the pilots preferred the following conditions during LESS flights: a) $800 \leq I_{yy} \leq 1200$ kg-m$^2$; b) $I_{xx} > 2I_{yy}$; c) $T/m < 3$ m/sec.$^2$

6) An effective means of obtaining near-zero angular rates at orbit insertion is to reduce main thrust significantly just before burnout. Vehicle handling qualities are thus improved and the pilot can concentrate more on nulling these rates.

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# Periodic Swing-By Orbits Connecting Earth and Mars

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**Periodic swing-by orbits which go back and forth between Earth and Mars indefinitely are found through use of a patched conic analysis. An approach is developed which combines two round trips to Mars and two separate series of trajectories that return directly to Earth in an arrangement that is symmetric in time. The exact terminal dates for the periodic orbits are first established by computer solution in the case where the two planets are in circular, coplanar orbits; then a solution is attempted for the eccentric, inclined case. As few as four spacecraft on periodic orbits can provide fast transfers to and from Mars during every opposition period.**

## Introduction

THE term "periodic swing-by orbit" is taken to mean an interplanetary, free-fall (unthrusted) trajectory which visits one or more planets and revisits these same planets repeatedly for an indefinite period of time. Such orbits are the logical conclusion of multiple flyby trajectories that consist of a series of trajectory legs separated by unthrusted planetary swing-bys. Periodic orbits consist of a series of an indefinitely large number of trajectory legs. Periodicity exists, because the order of the planets encountered, the planets' positions, the types of trajectory legs, the hyperbolic excess speeds at the planets, and the minimum passing distances during the encounters repeat or almost repeat periodically.

Interplanetary periodic orbits can be used to make available a scheduled transportation system between two planets. The continuing propulsive requirements of such a system consist of only that needed for guidance and resupply of the vehicles on the periodic orbit.

Hollister[1,2] and Menning[2] found periodic orbits that connect Earth and Venus; however, for periodic orbits connecting Earth and Mars, the small mass of Mars means that much less change in velocity occurs from a close flyby of that planet. This velocity change is necessary to insure that the periodic orbit vehicle can attain the hyperbolic excess velocity vector necessary for the next trajectory leg without propulsive effort and without colliding with the encountered planet. Because the velocity change available at Mars is small, finding a periodic orbit which includes encounters of that planet is more difficult and requires an approach different from that of Hollister and Menning.

Both the method of Hollister and Menning and the method presented below do not guarantee that all periodic orbits connecting the planets of interest will be found. They do, however, supply means of narrowing the search for such orbits.

## Method

Periodic swing-by orbits consist of a series of interplanetary trajectory legs that are separated by planetary encounters. There are two types of trajectory legs: interplanetary legs between different planets; and direct returns, which return to the planet from which the trajectory leg last departed. The means by which legs of the two types are combined into a continuous series constitutes a method of searching for periodic orbits. A patched conic analysis, which neglects the finite size of planetary spheres of influence, is used for the search. The resulting orbit must, of course, not collide with an encountered planet.

There are several types of direct returns involving one-half, one, or more revolutions of the vehicle and the planet around the sun. Half-revolution return and full-revolution return trajectories re-encounter the departure planet after completion of one-half a revolution around the sun and a full revolution about the sun, respectively. In addition, there are symmetric return trajectories which return to the departure planet after more than one planetary period and which lie in the plane of the planet's orbit. The symmetry exists in the sense used by Ross[3]: the departure and arrival encounters are symmetrically arranged in space about the line of apsides of the sun-centered ellipse that the symmetric return follows. The departure and arrival speeds are functions of the length of time for each symmetric return. Additional types of direct returns exist but were not included in the investigation.

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