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SUMMARY

An analysis of some measurements of metabolic costs of various lunar and corresponding earth locomotive activities has been made to determine the performance capabilities of man in carrying out lunar exploration. Comparisons of limited data from different sources have been made to establish the validity of the data obtained in simulated lunar gravity and used as the basis of this analysis. Various factors such as fatigue limit of the subjects, duty cycle, speed of locomotion, and lunar surface slope have been taken into account.

The results of the analysis indicate that the performance of the lunar explorer will be significantly greater than that of his earthly counterpart wearing the same equipment and that there is a very great need for evaluating the pressure suits actually intended for lunar locomotive activities in the simulated lunar gravity condition because of the gross effects of gravity on the locomotive performance.

INTRODUCTION

One of the prime obstacles in the development of optimum lunar pressure suits and life-support systems as well as in the effective planning of lunar exploration is uncertainty about the effects of the moon's reduced gravity on man's self-locomotive capabilities. The dearth of experimental data relative to these effects is primarily due to the difficulties of simulating lunar gravity under controlled laboratory conditions, which have forced space-suit engineers and mission planners to rely solely on data obtained under earth gravity conditions.

Recent developments in lunar-gravity simulation (refs. 1 to 4) have led to exploratory studies of the metabolic costs of various lunar locomotive activities. The purpose of this paper is to present some data from these studies and show a brief analysis of the relative performance in earth and lunar gravity fields and the effects of some other factors on the lunar performance. The data used in this paper were obtained primarily from reference 3, a study conducted by the Northrop Space Laboratories of Hawthorne, California, for the Langley Research Center. Data from other sources, obtained by other techniques including those of lunar-gravity simulation, are compared with those of reference 3 to support the use of these specific data in this analysis.

SYMBOLS

V	locomotive speed, miles/hour (kilometers/hour)
$\dot{Q}$	metabolic rate, Btu/hour (kilojoules/hour)

Subscripts:

ps	pressure suit
ss	shirt sleeve

BASIC CONSIDERATIONS AND ASSUMPTIONS

Space-suit-systems design and mission planning for lunar exploration activities depend on a large number of interrelated factors, some of which are:

1. Distance or range to be traveled
2. Duration of exploration mission
3. Speed or rate of locomotive activity
4. Type of locomotive gait
5. Operating limits of suit systems
6. Rate of energy expenditure
7. Work-rest duty cycle
8. Fatigue limits of explorer
9. Available expendable supplies
10. Variations in lunar surface conditions

The primary objective of lunar exploration is to determine the nature of the lunar environment at as many different locations as possible within a specific time. Consequently, in this analysis distance or range traveled, speed, and time are considered to be the primary factors and all other variables are related to these parameters.

The three lunar surface characteristics which probably affect locomotion most strongly are texture, firmness, and slope. Many types of studies have provided information about the variations of lunar slopes and texture. Certainly, the Ranger and Surveyor photographs have done much to establish the true nature of the surface. While no detailed engineering data on surface bearing strength are available at present, there is sufficient knowledge to make a reasonable assumption that at least some of the surface is strong enough to firmly support the lunar explorer during the locomotive activities. This assumption is necessary to this analysis inasmuch as the only data applicable to lunar locomotive activity has been obtained on firm surfaces and it is recognized that variations of surface strength can alter very significantly the energy expenditures. The high-resolution pictures of the Surveyor vehicle show that the texture of some of the lunar surface is quite uniform and does not impose any serious problem to locomotion. Average or mean values for the slopes of the rims and inner plains of craters, as given on page 50 of reference 5, are about 30° and 11.5°, respectively. Consequently, some consideration must be given to locomotive activity on sloping surfaces.

In order to place some realistic constraints on this analysis, the following values are assumed to be representative of possible extravehicular activities:

Maximum duration	4 hr
Life-support-system capacity (with appropriately proportioned CO_2, H_2O, and contaminate absorption and electric power supply)	4800 Btu (5070 kJ)
Maximum heat-dissipation rate	2000 Btu/hr (2100 kJ/hr)
Weight of backpack	60 lb
Equipment and tools	12 lb

All available data are in the form of metabolic rates measured during activity performed at a constant rate and do not take into account the energies required to initiate and terminate the activity. An assumption made for this analysis is that the total energy involved is the product of the metabolic rate and the time interval of the activity and that any additional energy involved in the starting and stopping transients is negligible in comparison with that required to maintain the steady activity.

PRESENTATION OF DATA

The basic data used in this analysis are given in figures 1 and 2, which show variations of metabolic rate in terms of Btu per hour with locomotive speed for simulated lunar gravity and earth gravity, respectively. The data, obtained from reference 3, are for two subjects wearing alternately lightweight coveralls (referred to as "shirt sleeve") and Mark IV (Models 3 and 4) pressure suits at 3.5 pounds per square inch (6.9 kilonewtons/meter^2) with a 72-pound (32.4-kilogram) backpack life-support system. These suits were designed primarily for high-altitude flying; however, special comparative tests reported in reference 3 showed that these particular suits, which are nearly identical in design, are comparable to current space suits for the locomotive types of activities under consideration. The tests consisted of walking and running at various speeds on a treadmill under conditions of earth gravity and of simulated lunar gravity which was produced by using the inclined-plane technique discussed in references 1 to 3. The equipment employed to produce the simulated lunar gravity imposes some constraints on the

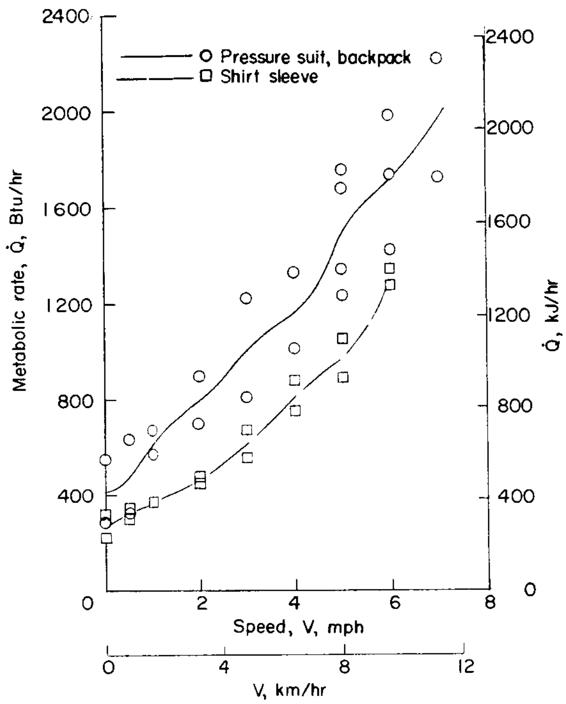


Figure 1.- Variations of metabolic rate with speed on a level surface in simulated lunar gravity for shirt-sleeve and pressure-suited conditions (basic data from ref. 3).

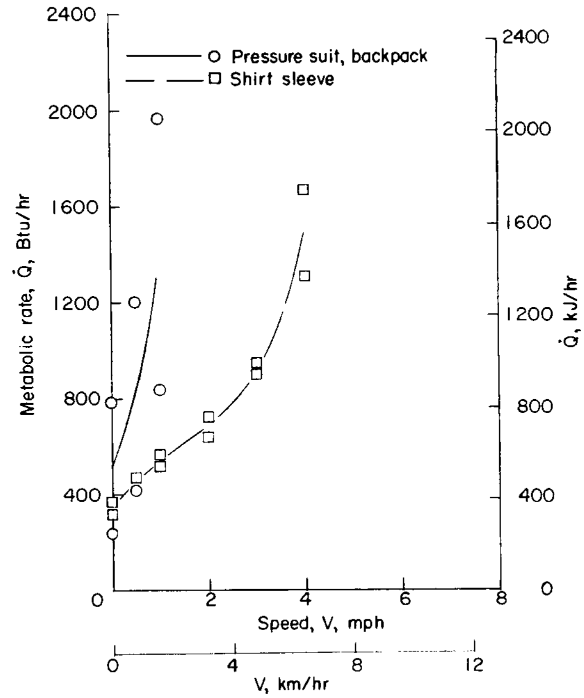
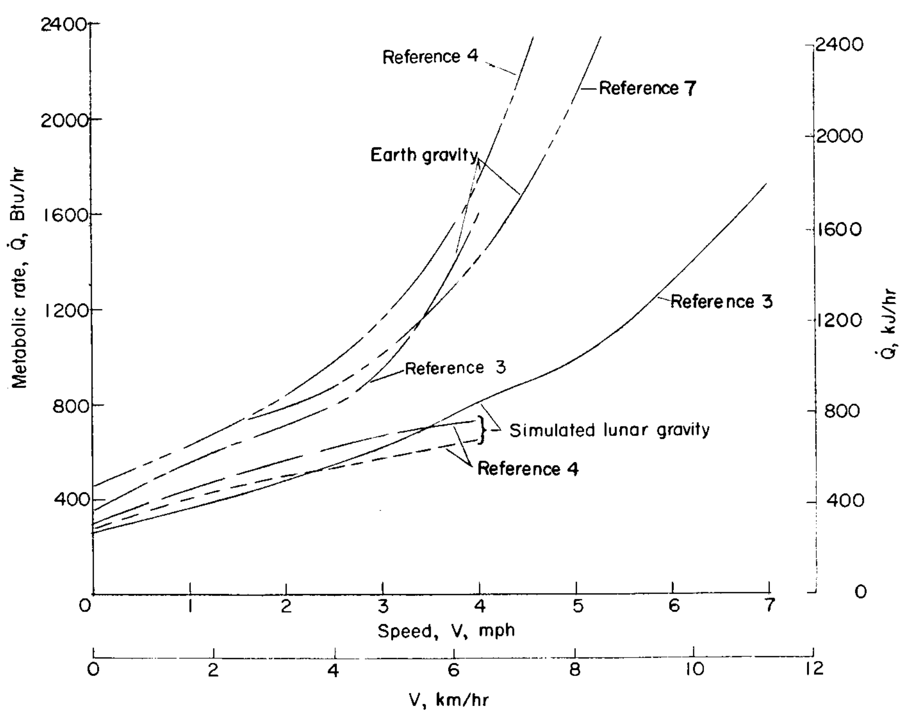


Figure 2.- Variations of metabolic rate with speed on a level surface in earth gravity for shirt-sleeve and pressure-suited conditions (basic data from ref. 3).



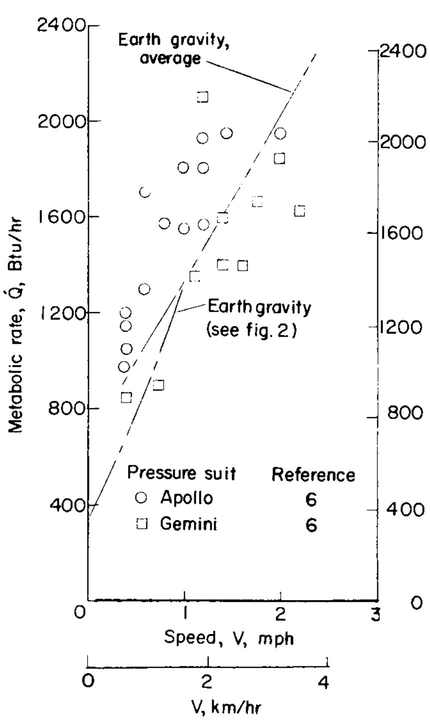
(a) Shirt sleeve.

Figure 3.- Comparison of test data from various sources and for different conditions.

test subject; however, an analysis of these constraints on the bodily motions (ref. 2) showed that they were generally small and, consequently, they are assumed to be negligible for the locomotive activities considered herein.

Measurements of the metabolic rates were obtained by the indirect method of calorimetry, in which samples of the subject's respiratory products were obtained during the test activities and subsequently analyzed. These tests were performed with the subjects breathing 100 percent oxygen, as is currently planned for the initial lunar missions. Samples of the respiratory gases, O_2 and CO_2, generally were taken only when the subjects had attained equilibrium after initiation of a particular test activity. The results of the measurements were reported in terms of total metabolic rate, which includes both the basal metabolic energy expenditure and the energy expenditure due to the work activity without correction for body surface area.

Curves have been faired through the data points of figures 1 and 2, to show the variations of the average metabolic rates for each test condition with speed. Comparisons of some of these curves with corresponding curves and data points obtained from some other sources are shown in figure 3. Curves for the shirt-sleeve condition obtained in recent work (ref. 4) with two vertical-suspension lunar-gravity simulators which employ a technique basically different from that of reference 3 show good agreement where the speeds are comparable. No comparable data are available for the lunar-gravity pressurized-suit condition; however, data for some suits in earth gravity are available (ref. 6) and are shown in figure 3(b). An average curve drawn through these data points shows generally good agreement with the average curve for the data obtained from reference 3 (see fig. 2). From these comparisons it is concluded that the basic data of figures 1 and 2 are valid, and they are considered to be directly applicable to the interpretation of actual lunar performance.



(b) Pressure suit.

Figure 3.- Concluded.

The data of figures 1 and 2 were obtained from tests lasting several minutes, and it is not known how long the test subjects could have maintained their activity for each test point before tiring. Inasmuch as duration and fatigue limits are important factors for the lunar mission, the data presented on page 182 of reference 7 were used to establish some fatigue limits for this analysis, as shown in figure 4. The data from reference 7 show the estimated duration of sustained

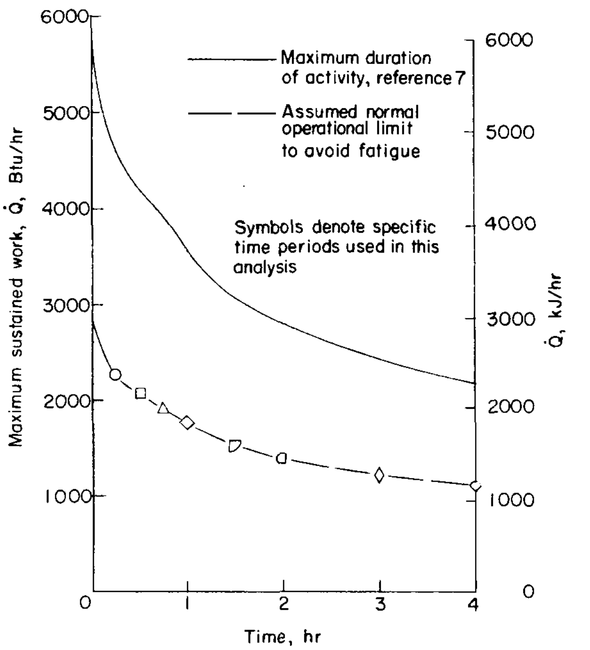


Figure 4.- Variation of maximum sustained work activity and assumed fatigue limit with duration of activity.

work as a function of Btu per hour for a class of healthy men who were described as young, physically active, and conditioned to these work levels. Duration of activity is defined as the time from the start of activity to the point of exhaustion. In order to render these data more applicable to normal lunar mission activities, where it would be extremely undesirable and hazardous to work the astronauts to the point of exhaustion, the working rates for a given period of activity have been reduced arbitrarily 50 percent for this analysis, and the resulting curve (dashed) shown in figure 4 is taken as the normal operational limit. The results of this analysis, therefore, may be considered as somewhat conservative for special cases of emergency in which the maximum effort of the astronaut would be available.

A list of various activity times and the corresponding maximum operational energy limits obtained from this dashed curve are given in table I, along with a work-level classification. The work-level classifications (from ref. 7) are defined in table II. The values given in table I appear to be quite reasonable on the basis of comparisons with normal

TABLE I.- ESTIMATED MAXIMUM ENERGY EXPENDITURE FOR SPECIFIC PERIODS OF ACTIVITY

[From dashed curve of fig. 4]

Activity duration, hours	Energy expenditure		Work-level classification
	Btu/hr	kJ/hr	
0.25	2300	2429	Heavy
.5	2100	2218	Heavy
.75	1900	1196	Heavy
1.00	1800	1901	Heavy
1.50	1500	1584	Moderate
2.00	1400	1478	Moderate
3.00	1200	1267	Moderate
4.00	1100	1162	Light

TABLE II.- WORK-LEVEL CLASSIFICATION DEFINITIONS

[From pp. 173-176 of ref. 7]

Work-level classification	Range of energy expenditure		Typical activity
	Btu/hr	kJ/hr	
Very heavy	2380 to 2975	2513 to 3142	Playing basketball, climbing stairs
Heavy	1785 to 2380	1885 to 2513	Shoveling sand, hand-sawing hardwood, cycling at 10 miles (16 km) per hour, rapid marching
Moderate	1190 to 1785	1257 to 1885	Playing table tennis, golf
Light	595 to 1190	628 to 1257	Standing, slow walking, driving car

everyday experience. For example, "light" work is described as consisting of activities such as standing and slow walking; this type of work obviously can be sustained for periods in excess of 5 hours. Also, "heavy" work consists of shoveling sand, hand-sawing hardwood, and cycling at 10 miles (16 km) per hour; all of these activities, quite evidently, can be sustained for only relatively short periods of probably 15 minutes to 1 hour. It is recognized that these limits are subject to considerable variation, as they depend on a great number of factors, and much research is required to establish actual limits; however, the values shown here are considered to be sufficiently accurate for purposes of this analysis.

DISCUSSION OF DATA AND MISSION ANALYSIS

The data of figures 1 and 2 show an appreciable scatter of test points for corresponding test conditions. This scatter is to be expected, of course, when dealing with human subjects because of differences in physical characteristics and capabilities and the variations of each subject's performance with the time of day, his work-rest cycle, and motivation. Also, variations in the daily adjustments and the physical characteristics of the suit can be expected to account for some of the data scatter. In general, the deviations of data points from the average curve are less than about 350 Btu/hr (370 kJ/hr) or ± 15 percent of the maximum value for the average curve. For the subsequent analysis, the effects of the several variables on range capability of a pressure-suited lunar explorer carrying a 72-pound (32.4-kg) backpack load are determined on the basis of the average curves, and the effect of the ± 15 percent data deviations is treated as an additional factor.

Sustained Speed of Locomotion

The maximum speed of locomotion that can be sustained by the lunar explorer for any given period of activity can be determined by applying the fatigue limits as presented in figure 4 and table I to the energy-expenditure data of figure 1. The results are shown in figure 5, which defines the maximum speed that can be sustained for periods up to 4 hours without exposing the explorer to possible fatigue.

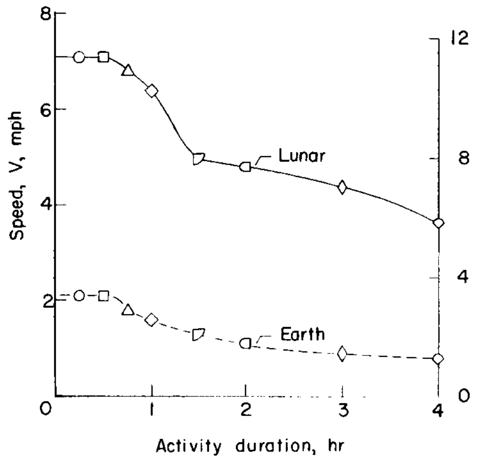


Figure 5.- Variation of maximum locomotive speed with duration of constant locomotive activity.

The available data for the pressure-suit tests do not indicate the maximum possible running speed which can be generated for very short durations. However, if the assumed maximum heat-dissipation rate of 2000 Btu/hr (2100 kJ/hr) for the suit system is used as a limiting criterion, the maximum possible speed without exceeding this limit is indicated to be about 7 miles (11 km) per hour for the lunar explorer, which can be sustained for periods up to 30 minutes. Undoubtedly higher speeds can be generated for shorter periods of time or shorter distances in emergencies to escape imminent danger, and these speeds probably will be dictated by the physical capabilities of the explorers rather than their fatigue limits or the suit-system limits. For general mission considerations, however, the maximum speeds predicted by these data appear to be reasonable limits.

An interesting comparison is made in figure 5, which also shows the results for earth-gravity conditions obtained by using the average curve for the pressure-suit data given in figure 3. This comparison shows that for the assumed limitations the sustained locomotive speed of the lunar explorer can be from 4 to 5 times that of his earthly counterpart for the same period of activity.

Range Capability for Sustained Locomotion

The combined influence of speed, activity duration, fatigue, and suit-system limitations on the range capabilities for sustained lunar locomotion is shown in figure 6 where range and a range factor, expressed as miles per 1000 Btu (km/MJ), are plotted against locomotive speed. The range factor was obtained by applying the following formula:

$$\text{Range factor} = \frac{V}{\dot{Q}} \times 1000 \tag{1}$$

where the values for V and $\dot{Q}$ were obtained from the averaged curve of figure 1. The factor of 1000 is used to provide a convenient scale. The straight lines radiating from the origin of the lower plot in figure 6 correspond to constant rates of energy expenditure and are identified by the corresponding fatigue limits in hours given in table I. The intersection (indicated by the symbol) of each line with the experimentally derived range-factor curve corresponds to the maximum speed which can be sustained for a specific period of time without exceeding the assumed fatigue limits as given in figure 5.

The maximum range attainable for a given speed without consideration of other factors except total life-support-system capacity is determined by multiplying the range-factor value in figure 6 by the value for the system capacity (assumed to be 4800 Btu or 5070 kJ for this analysis) and dividing by 1000. The maximum range for all speeds is shown in the upper plot of figure 6 by the solid curve which appears similar to the curve in the lower plot and is designated 100%. The two additional curves, marked 50% and 25%, were obtained merely by dividing the values for the 100% curve by 2 and 4, respectively. These two curves denote the maximum range attainable after one-half and three-quarters of the normal supply has been used.

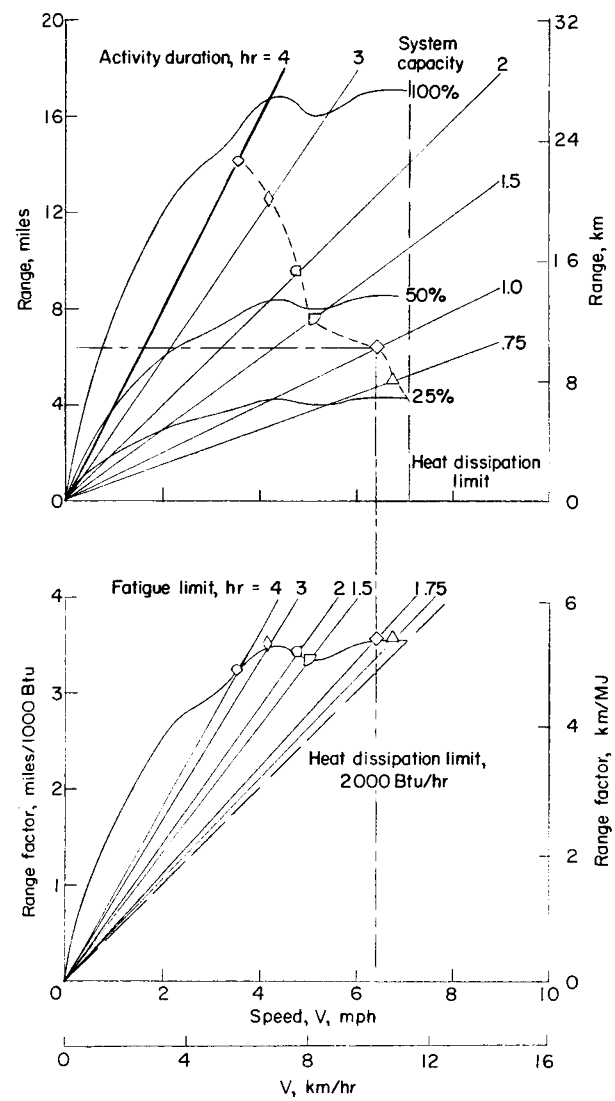


Figure 6.- Estimated effects of speed, activity duration, fatigue, and suit-system limits on range capability of lunar explorers as derived from data of reference 3.

The maximum range attainable for a given speed, if only the duration of the mission is considered, is defined in the upper plot of figure 6 by the straight lines radiating from the origin and designated by the specific values of activity duration ranging from 0.75 to 4 hours. The heavy straight line corresponding to a 4-hour period represents the maximum range as limited by the assumed maximum mission-duration limit. The effect of the assumed fatigue limits on the maximum range attainable for a given period of activity is determined by graphically projecting the various intersection points in the lower plot to the corresponding activity duration lines in the upper plot, as illustrated for the case of the 1-hour period. The resulting intersections in the upper plot, denoted by the symbols, are connected by the short-dash line, which therefore represents the fatigue boundary.

The heavy long-dash line to the right of the upper plot in figure 6 corresponds to the speed at which the metabolic rate reaches the maximum heat-dissipation capability of the life-support system (assumed to be 2000 Btu/hr or 2100 kJ/hr for this analysis), as determined in the lower plot by the intersection of the heat-dissipation limit line with the range-factor curve at about 7 miles (11 km) per hour.

The net range capability of the lunar explorer is defined, therefore, by the area bounded by the various curves presented in the upper plot of figure 6. That is to say, the explorer can achieve any combination of speed and range that falls within the area beneath these curves without exceeding the suit-system operational limits or his physical capabilities. For combinations of speed and range falling in the upper left-hand corner of the plot above these curves, the mission duration is exceeded and the system supplies are completely depleted; for other combinations in the upper right, the fatigue limits are exceeded; and for the far right, the cooling system is overloaded and heat buildup leading to heat prostration is encountered.

The upper plot of figure 6 reveals that the maximum range of 14.2 miles (22.7 km) for sustained locomotion with a fully loaded system is achieved at a speed of about 3.5 miles (5.6 km) per hour maintained throughout the total mission time. Use of any higher speed to increase the range exposes the explorer to the possibility of fatigue. It is interesting to note that for this situation of sustained locomotion the maximum range is not achieved, as might be expected at the most efficient speeds where the range factor is maximum, because of the limitations of fatigue. However, if the locomotive activity is broken into two periods of 1.5 hours each, interrupted by a 1-hour rest, the total for the maximum 4-hour period can be extended beyond that for continuous running to about 15 miles or 24 km (that is, 7.5 miles or 12 km for each 1.5-hour period). The effects of various duty cycles such as this are discussed subsequently.

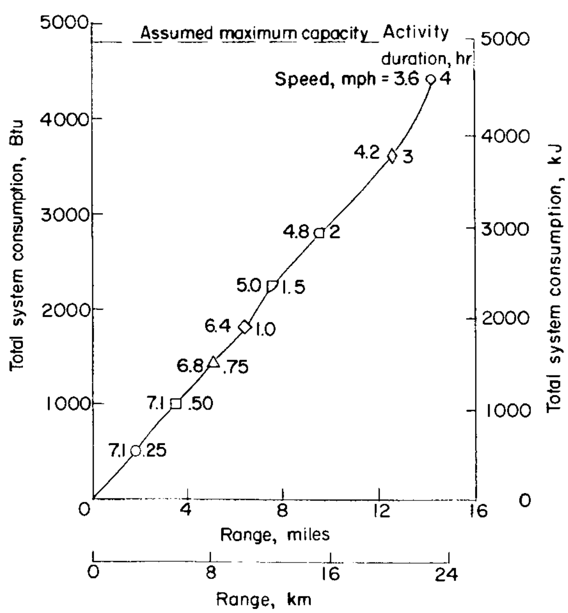


Figure 7.- Estimated variation of total system consumption with calculated range of lunar explorers.

Compared with the effects of the other factors, the assumed heat-dissipation limit for the suit system appears to impose only a negligible constraint on the total range capability of the lunar explorer. Furthermore, the assumed maximum system capacity is adequate for the sustained locomotive activities intended to yield maximum range for a given period of activity. This is also evident in figure 7, which shows the variation of the total system consumption in Btu (kJ) with range.

Returning to the upper plot of figure 6, it is evident that for long-range activity, say for distances of 8 miles (12.8 km) or greater, the locomotive speed must be closely regulated in order to avoid the operational limitations. For short-range activity of 4 miles (6.4 km) or less, even with nearly depleted life-support supplies there is a fairly large latitude in the selection of locomotive speeds which will not seriously restrict the range capabilities. For these short ranges explorer fatigue is not a critical factor. The limiting factors are primarily the life-support-system capacity and heat-dissipation capability.

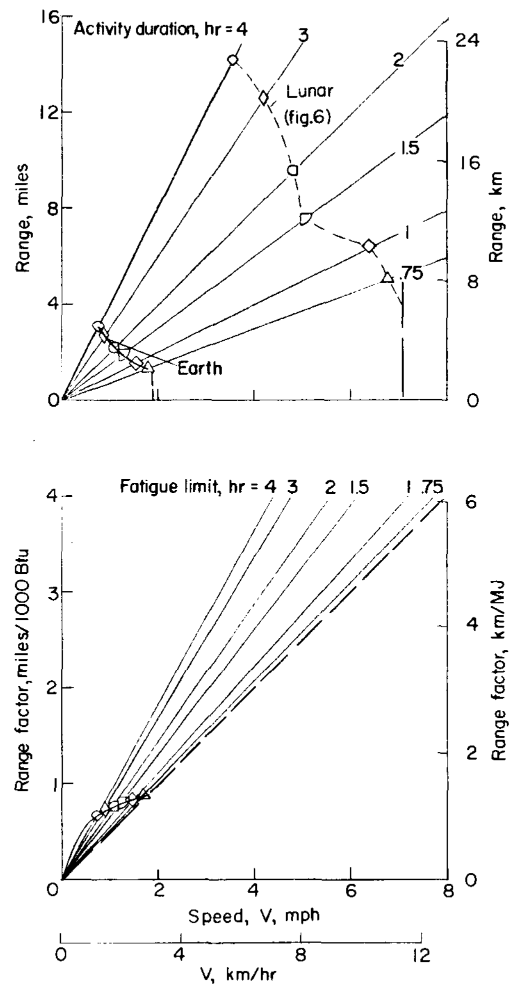


Figure 8.- Estimated effect of gravity on range capability of pressure-suited explorers.

Gravity

The corresponding results for earth-gravity locomotive activity are shown in figures 8 and 9, which are of the same forms as figures 6 and 7, respectively. The curves for lunar-gravity activity are repeated in these figures to show the very significant differences produced by the change in gravity level. The maximum range for earth conditions is about 3.1 miles (5 km), or about 20 percent of that for lunar conditions; also, the maximum range factor of about 0.9 mile per 1000 Btu (1.5 km/MJ) is obtained at about 2 miles (3.2 km) per hour. This factor is about 27 percent of that obtained for the lunar condition, and for comparable range values (see fig. 9) the total system load for earth activity is from 300 to 450 percent of that for lunar activity.

Some of the data in figures 6 to 9 are replotted in figure 10 to show more clearly the effect of gravity on the maximum speed and minimum time for a given range. These data show that the lunar explorer is able to cover a distance of 3 miles (4.8 km) at about 9 times the speed the same distance is covered on earth and, consequently, in only about 11 percent of the time. It is readily apparent from these comparisons that the use of data derived from earth-gravity tests will lead to grossly conservative estimates of the performance of the lunar explorers.

Mission Duty Cycle

It was noted earlier that if the locomotive activity is broken up with a rest period an increase in total range beyond that for sustained locomotion can be achieved. Because most lunar explorations will consist of combined periods of locomotion, rest, and non-locomotive work activities, it is important to consider the possible effects of such interruptions on the total range capability. For this purpose, assumptions are made that the rest period consists of minimal activity, expending energy at the rate of 400 Btu/hr (422 kJ/hr) for a period of 0.25 hour, and that this period and activity level are such that complete recovery from the limited oxygen debt incurred during the preceding locomotive activity is achieved and the normal operational fatigue limits are restored. There are no known data to substantiate the compounded assumptions for this analysis; however, the assumptions appear reasonable as a first approximation on the basis of general observations of normal everyday work experience.

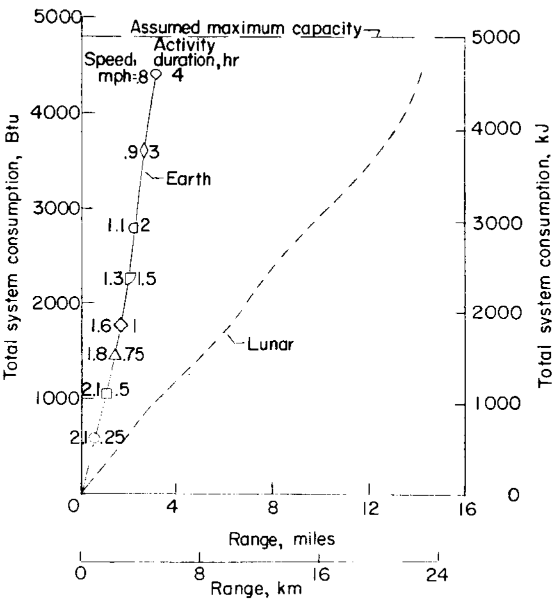


Figure 9.- Estimated variation of total system consumption with range in earth gravity and comparison with variation for lunar gravity.

In figure 11, the variations of the total system load and total mission time with range are shown for three cases: no rest, one 0.25-hour rest, and two 0.25-hour rest periods. The two cases with rest periods have equal periods of locomotion preceding and succeeding each rest period. The curves for the "no rest" condition are identical with the corresponding curves of figures 7 and 10. The other two curves were derived by considering the two or three locomotive periods as separate missions and adding the activity time and the energy requirements of the rest periods to the sums of the corresponding factors for the separate locomotive activities.

These results indicate that for short-range explorations, less than about 6 miles (9.6 km), it is more efficient in terms of both time and system load not to stop and take a rest, but for longer-range ventures it is better to stop and take one or two rests, depending on how far the explorer intends to go. The explorer is able to travel at his most efficient higher speeds for the short periods (see fig. 10) required to cover the short distances. In attempting to cover longer distances, he is forced to travel more slowly and less efficiently in order to avoid fatigue. Consequently, he can break his activities into shorter range missions with rest in between, and the gains in efficiency will exceed the losses that occur during the rest periods. Note that for the assumed conditions, with one or two

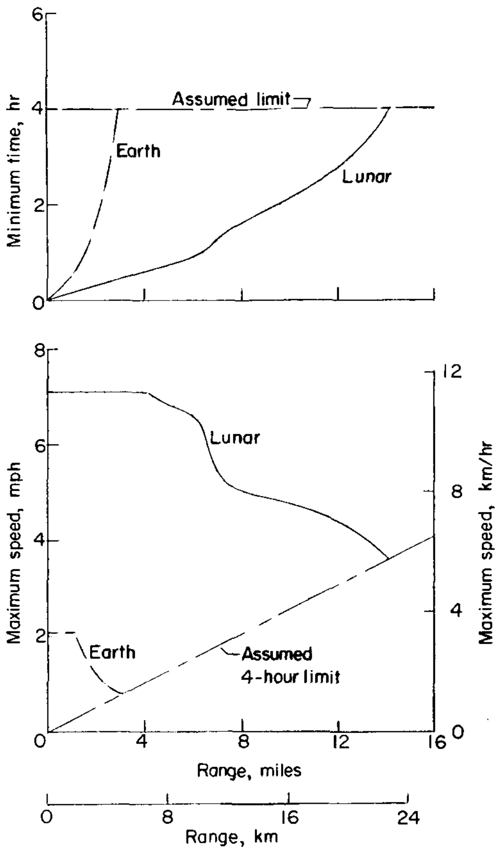


Figure 10.- Estimated effect of gravity on maximum speed and minimum time of locomotive activity.

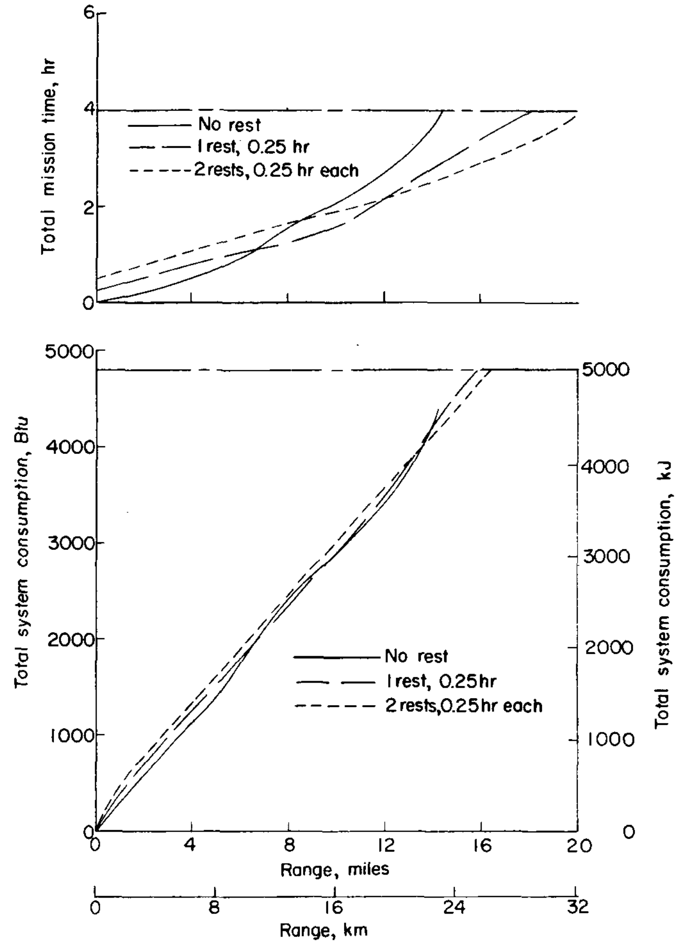


Figure 11.- Estimated effect of lunar mission duty cycle (work-rest) on total mission time and total system consumption.

rests, the oxygen supply is depleted before the mission time limit is reached, whereas for the no-rest case, mission time is exceeded while there is still a reserve supply of oxygen. In the case of the two rest periods, the explorer can actually cover more distance, about 16.4 miles (26.2 km), than in either of the other two cases. If more supplies are provided, the explorer can go much farther – in excess of 20 miles (32 km) – with two rest stops, before exceeding the assumed time limit.

The previous comments are related to a rest and minimum work period of 0.25 hour, assumed to insure complete recovery from possible fatigue. The curve in figure 12 indicates the effect of increasing the duration of a single rest period up to 1 hour, by showing the variation of maximum range with rest-period duration for a total mission time of 4 hours. The range advantage of the single rest period over continuous locomotive activity is evident for rest periods up to and slightly in excess of 1 hour. This trend is the direct result of using locomotive speeds as close as possible to the optimum value where the range factor is maximum.

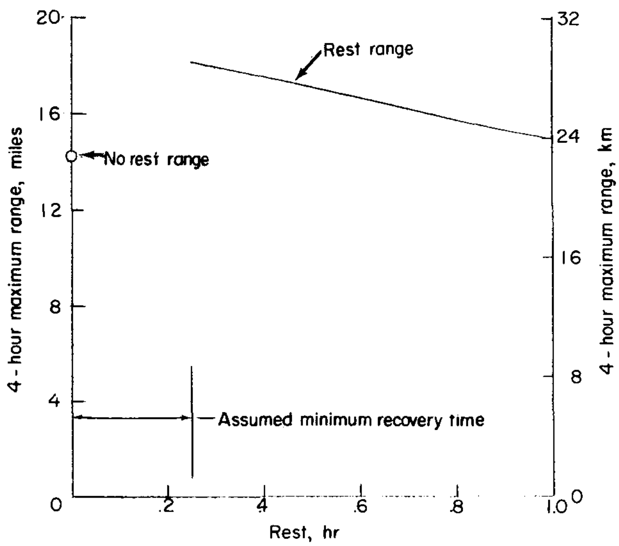


Figure 12.- Estimated effect of rest period on the 4-hour range of lunar explorers.

These results serve to point out the importance of mission planning and the need of providing the explorer with the means of evaluating various trade-offs and updating the mission as it proceeds so as to achieve maximum efficiency and insure safe return to his base. This analysis of the mission duty cycle was made on the basis of several assumptions which have not been verified; consequently, the absolute values obtained are considered to be useful primarily to indicate expected trends. There is a great need for appropriate research to verify these assumptions and provide much more detailed information than that used for this analysis.

Pressure-Suit System

All of the previous discussion has been concerned with the performance of the lunar explorer without regard to the effect of the suit system itself. The range penalties incurred by wearing the pressure suit and backpack are illustrated in figure 13, which shows the range reduction, in terms of percentage of shirt-sleeve range, for various speeds under both lunar and earth conditions. The values for range reduction were obtained from the data of figures 1 and 2 by use of the following expression:

$$\text{Percent range reduction} = 100\left[1 - \frac{(\text{Range factor})_{ps}}{(\text{Range factor})_{ss}}\right] = 100\left(1 - \frac{\dot{Q}_{ss}}{\dot{Q}_{ps}}\right) \qquad (2)$$

The restrictions of the pressure-suit system on range capability are shown to be appreciably affected by both gravity and locomotive speed. The general effects of increased speed are a decrease in range penalties for lunar gravity and an increase for earth gravity. These effects are attributed to the changes in gait characteristics (stride and stepping rate) required to produce the speed changes for the two different gravity conditions. Results of recent tests (ref. 2) show that in earth gravity locomotive speed is increased primarily by increasing the stepping

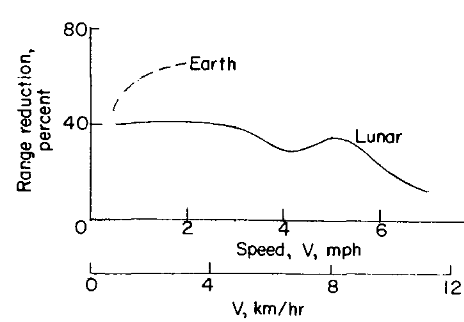


Figure 13.- Estimated combined effect of pressure-suit-system bulk and stiffness on the maximum range of lunar explorers.

rate, whereas in lunar gravity large increases in stride can be used more naturally to increase speed, with a corresponding reduction in stepping rate. The energy losses incurred as a result of wearing the suit are believed to depend primarily on the rate of flexing of the suit resulting from stepping rate. Consequently, the energy losses chargeable to the suit are reduced in the lunar case as the locomotive speed is increased.

These results imply that the bulk and constraints of current pressure suits do not impose as severe penalties on the lunar explorer as has been supposed on the basis of earth-gravity data. It is possible that this new knowledge will permit greater freedom in making pressure-suit-system trade-offs and selecting the optimum combination of suit features.

Lunar Surface Characteristics

Limited tests with one subject on a sloping treadmill were performed in the study of reference 3. The data from these tests of 10° ascending and descending slopes were used to prepare the curves given in figure 14, which are of a form discussed previously. It was necessary to extrapolate slightly some of the reference data in order to make a meaningful comparison. Inasmuch as surface slope was the only test variable, it is felt that the relative effects of slope are representative. In general, the data show that activity on a 10° sloping surface, whether ascending or descending, reduces the range capability, the effect of ascending being about three times that of descending. Inasmuch as a complete round trip over sloping terrain will usually result in the same uphill distance as downhill distance traversed, the effects of the slope can be averaged together to give a more realistic indication for operating over uneven terrain. The average curve given in figure 14 shows that the range capability on 10° sloping surfaces is about half of that for a level surface.

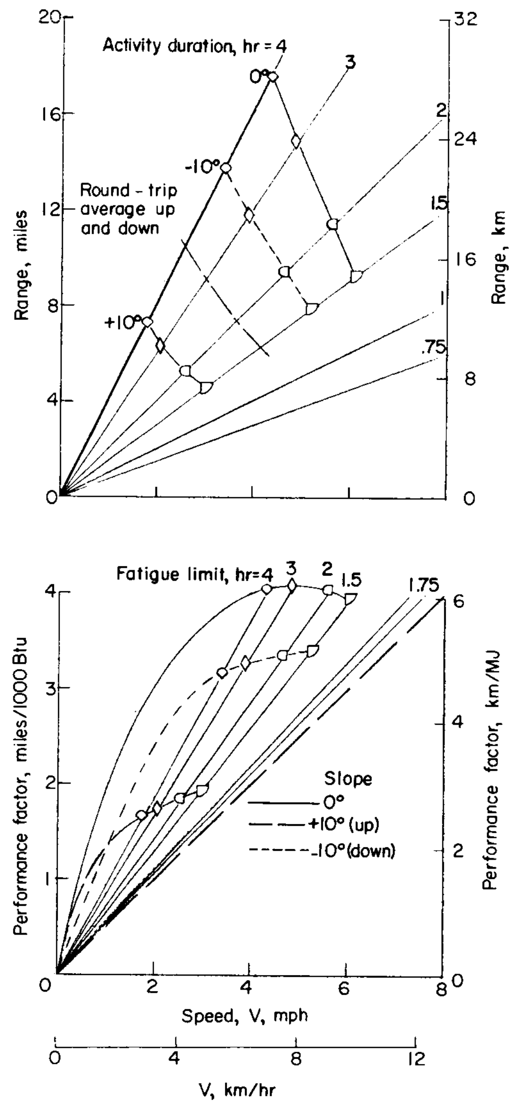


Figure 14.- Estimated effect of surface-slope variations on the range capability of lunar explorers. These curves are based on data from reference 3 for one subject.

Accuracy of Energy-Expenditure Measurements and Fatigue Limits

The two major sources of error in the results of this analysis stem from the accuracy of the basic data and the assumptions relative to the fatigue limits. As discussed previously, the basic data of reference 3 showed a scatter which generally did not exceed

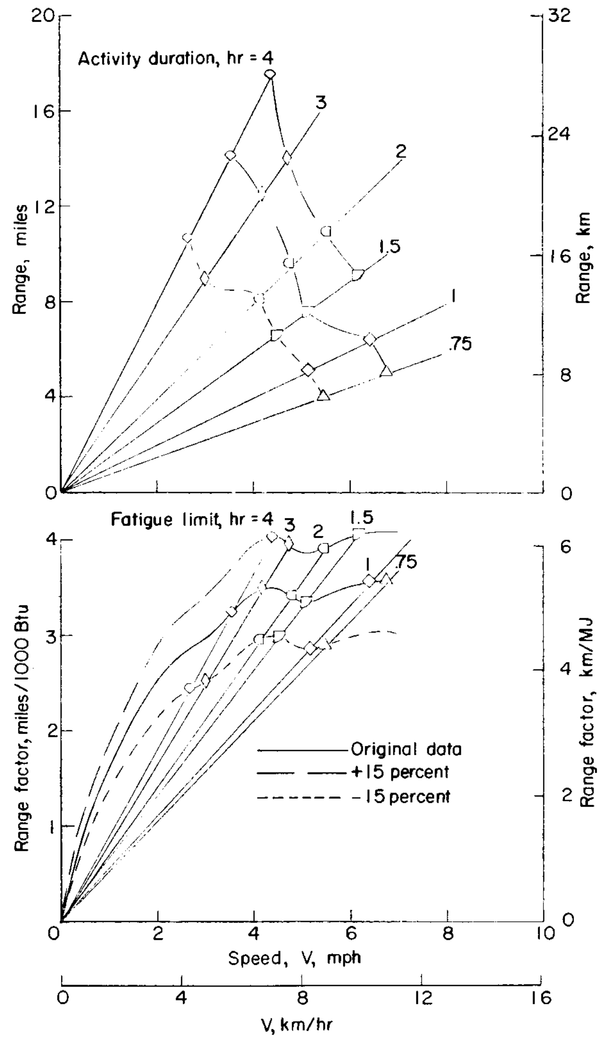


Figure 15.- Estimated effect of variations in experimental data on the range capability of lunar explorers.

±15 percent of the maximum values measured. The effects of ±15 percent variations on the range capabilities are shown in figure 15, where curves corresponding to +15 percent and -15 percent changes in the range-factor curve of figure 6 are shown along with the corresponding curves for range capability. In general, the effect of a change in the range factor is a somewhat larger change in maximum range.

It is recognized that the fatigue limits were defined somewhat arbitrarily in this analysis, and large errors in the calculated range capabilities may be incurred from this source. Consequently, the fatigue limit values, that is, the energy expenditure values listed in table I, were increased and decreased by 30 percent. The effects of these changes on the range capabilities of the lunar explorer are shown in figure 16, which includes the curve from figure 6 for the original fatigue limit. The changes in the fatigue limit also produced somewhat larger changes in maximum range.

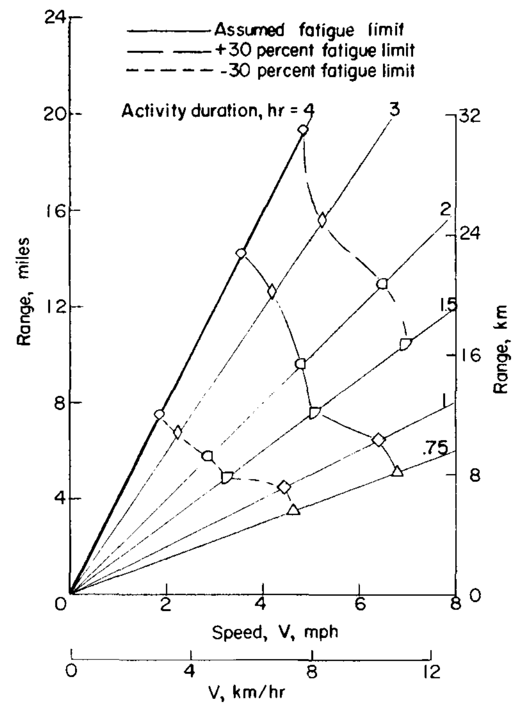


Figure 16.- Estimated effect of changes in assumed fatigue limits on range capability of lunar explorers.

Although both sources of error produced corresponding changes in the absolute range values, it is believed that the trends or relative effects produced by all other factors discussed are essentially unaltered. Consequently, this analysis should be helpful in obtaining an understanding of the effects of various factors on the range capabilities of lunar explorers. Steps must be taken, however, to establish realistic fatigue limits in order to be able to predict accurately the absolute performance.

SUMMARY OF RESULTS

The results of this analysis of the self-locomotive performance of lunar explorers as determined from experimental data are summarized as follows:

1. Maximum sustained speed of locomotion for the lunar explorer without exceeding the assumed heat-dissipation limitation of the life-support system was indicated to be about 7 miles (11 km) per hour. Short bursts of higher speeds may be possible if required for emergency situations.

2. For a continuous 4-hour period of locomotion, the lunar explorer was shown to be able to cover a total distance of about 14 miles (22 km) at a speed of approximately 3.5 miles (5.6 km) per hour over smooth, firm, level surfaces. Furthermore, this distance could be extended by employing rest periods or periods of low work activity within the total 4-hour mission time.

3. Comparisons with earth-gravity data showed that the maximum range capability of a pressure-suited subject on earth for comparable conditions was only 20 percent of

that of the lunar explorers. This result shows that use of earth-gravity test data will lead to grossly conservative estimates of the performance of lunar explorers.

4. The bulk and constraints of the pressurized suit do not impose as severe a penalty on the performance capability of the lunar explorers as they do for their earthly counterparts.

5. Both climbing and descending 10° slopes were shown to decrease the range capabilities, and the combined effect produced a reduction of about 50 percent.

6. The current uncertainties pertaining to the accuracy of the data and assumed fatigue limits were shown to have significant effects on the calculated performance values. However, these uncertainties are not expected to alter the trends noted.

RÉSUMÉ

The results of this paper have revealed the relative importance of various factors in the self-locomotive performance of lunar explorers. The gross effects of changes in gravity level point out the very great need for reevaluating the Apollo pressure suits and life-support systems intended for lunar self-locomotion. It appears to be very important to test the actual Apollo suits in simulated lunar gravity and to determine accurately the fatigue limits for the astronaut population. Tests should be performed with various work-rest duty cycles so as to include the effects of unsteady energy expenditures on total system requirements. Furthermore, variations in payload carried by the explorer and in surface conditions must be incorporated in future tests for proper evaluation.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 16, 1967,
127-51-03-02-23.

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