CHAPTER 4
METABOLISM AND HEAT DISSIPATION DURING APOLLO EVA PERIODS

by

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Introduction

Extravehicular activity, particularly on the lunar surface, was a key and essential part of the Apollo Program. However, the physical capabilities of the crewmen in the performance of extravehicular activity (EVA) and the physiological cost to the crewmen were some of the significant uncertainties of the program.

The space environment imposed life support requirements during EVA: the maintenance of a minimum oxygen pressure, the removal of expired carbon dioxide, the provision for useful mobility, and the maintenance of body temperature. To meet these requirements, a composite pressure suit of many layers and complex joints was developed.* The result of the development was a pressure suit that provided excellent thermal insulation in a vacuum, but imposed a much greater workload on the wearer in a one-g environment than the work required to perform the same activity without a suit. In addition to the difficulty of working in a pressure suit, Apollo crewmen had to contend with either zero g for the free-space EVA or one-sixth g for the lunar surface EVA.

Zero-g extravehicular activities were performed during five Gemini missions, and considerable difficulty was experienced by the crewmembers. Crewmen experienced high work rates and apparent overheating during Gemini 4, Gemini 9, and Gemini 11 EVAs. The crewmen also encountered unexpected difficulty performing specific tasks on each of the Gemini missions (Roth, 1968). After the particularly exhausting experience on the Gemini 11 EVA, the Gemini 12 EVA was redirected to serve as an evaluation of zero-g EVA capability and restraint technology. It was found that adequate body restraints,

*See Section VI, Chapter 6, Extravehicular Mobility Unit.

The following individuals shared responsibility for development of measurement methods and real-time data analysis during extravehicular activities: G.F. Humbert, L. Kuznetz, L.J. Nelson, A.P. Schachter, S.J. Vogel, and R.J. Kelley.

realistic zero-g preflight training in a water immersion simulator and detailed preplanning of activity were essential to insure task performance and reduce fatigue (Machel, 1967). Although metabolic rates were not measured during the Gemini EVAs, it was clear in several instances that crewmen worked at levels above the heat removal capability of the gas cooled life support system (Kelley et al., 1968).

Several researchers reported on the effect of one-sixth g on the cost of work in a pressure suit. The results were inconclusive. Wortz and Prescott (1966), Margaria and Cavagna (1964), and Shavelson (1968) predicted metabolic costs would decrease with subgravity walking. Roth (1966), Springer and co-workers (1963), and Shevelson and Seminara (1968) indicated that a metabolic increase would accompany low traction exercise. Another factor of uncertainty was the terrain and surface composition of the moon and its effect on mobility and metabolic rate. In response to these uncertainties, conservative biomedical estimates of the life support requirements were defined on the basis of available data. Methods to measure metabolic rate during EVA were developed by using operational data from the portable life support system (PLSS).

EVA Life Support Equipment

Because the pressure suit was well insulated to protect the crewman from external high and low temperature extremes, the portable life support system of the pressure suit had to dissipate the crewman's heat production. A liquid cooling system was developed to accommodate high heat production in the suit as a result of the high EVA workloads. This system consisted of plastic cooling tubes on the inside of an undergarment. The garment could suppress sweating at work rates as high as 1670×10^3 J/hr ($\approx$ 400 kcal/hr) and allowed sustained operation at rates as high as 2090×10^3 J/hr ($\approx$500 kcal/hr) (Waligora & Michel, 1968).

The PLSS used for the Apollo 9, 11, 12, and 14 missions could support a total metabolic heat production of approximately 5020×10^3 J (1200 kcal), produced either at 1670×10^3 J/hr ($\approx$400 kcal/hr) for three hours, or at 1260×10^3 J/hr ($\approx$300 kcal/hr) for four hours. An expanded PLSS was used for the Apollo 15 through 17 missions that could support a total metabolic heat production of 7530×10^3 J ($\approx$1800 kcal). This system provided for EVAs of seven hours at 1050×10^3 J/hr ($\approx$250 kcal/hr) or eight hours at 942×10^3 J/hr ($\approx$225 kcal/hr).

During the longer EVA periods a potential life support problem was dehydration. A drinking bag containing 100×10^{-5} m^3 of liquid was made available in the suit for replacement of water lost in sweat and respiration.

During the Apollo 15 through 17 missions, zero-g extravehicular activities were performed from the Command Module (CM) by means of an umbilical that provided approximately 0.3 m^3/min (10 ft^3/min) of gas for cooling. These extravehicular activities were limited to less than one hour.

Temperature Control

Suit temperature was controlled by a three-position manual valve that regulated the temperature of the coolant water flowing through the liquid cooling garment (LCG).

During the Apollo 11, 12, and 14 missions, the valve positions provided cooling water at temperatures of approximately 294°K (21°C) at the minimum position, 288°K (15°C) at the intermediate position, and 280°K (7°C) at the maximum position. Typically during these missions the temperature control valve was usually switched from minimum to intermediate and back again. The Apollo 11 Lunar Module Pilot was the only crewman who frequently used the maximum cooling position. The expanded portable life support system used on the Apollo 15 through 17 missions had a diverter valve that provided cooling water temperatures of approximately 300°K (27°C), 291°K (18°C), and 280°K (7°C). The minimum and intermediate cooling temperatures were increased to avoid overcooling during riding of the lunar roving vehicle. These temperature settings were quite satisfactory. Although the minimum and intermediate settings were most commonly used, the maximum setting was frequently used during high workload periods experienced during the Apollo 15 and 17 missions.

During two EVA periods, crewmen were instructed to change a diverter valve setting from minimum to intermediate as a preventive measure, but no crewman ever appeared to have a serious thermal problem. Despite variations in the frequency of diverter valve changes, each crewman maintained a suitable average temperature during the EVA periods. In all cases, 60 to 80 percent of the heat generated by metabolism was dissipated through the LCG. The LCG used during the lunar surface extravehicular activities undoubtedly minimized water loss from sweating and prevented dehydration and excessive fatigue.

For the Command Module extravehicular activities performed during the Apollo 15 through 17 missions, the only cooling available to the crewmen was from gas ventilation at a rate of 0.3 m^3/min ($\approx$10 ft^3/min). This ventilation rate could not sustain prolonged work rates of more than 1050 x 10^3 J/hr ($\approx$250 kcal/hr). Despite this limitation, no overheating problems were experienced because good restraint systems were available, training in the water immersion facility was adequate, and the EVA periods were short.

Metabolic Rate Measurement Methods

Since it was desirable to measure metabolic rate during extravehicular activies on the lunar surface and in free space, several measurement approaches were evaluated. The standard laboratory methods would have required breaking pressure suit integrity if used in space or during vacuum chamber training on the ground. Therefore, the operational data available from the crewman and from his life support system were assessed to determine their usefulness in approximating metabolic rate.

The data available from the crewmen during the EVA periods consisted of voice data, electrocardiogram (ECG) data from each crewman, oxygen bottle pressure, liquid cooling garment (LCG) coolant-water entry and exit temperatures, and suit-gas entry temperature. In addition, the sublimator water usage was available after the majority of the EVAs. Sublimator water usage provided a measure of the total heat loss from the suit. All of the heat removed from the pressure suit was first transferred to a heat sink maintained by the sublimator which rejected heat by the change of state involved in sublimating ice to water vapor in the vacuum of space.

Three methods were developed and used to estimate real-time metabolic rates:

1. The heart rate, counted from the electrocardiographic signal, was related to metabolism on the basis of a correlation with bicycle ergometer workload which was established before the flight (figure 1).

2. The oxygen usage, computed from the decrease in oxygen bottle pressure per unit time, was related to metabolism. A correction was made for an assumed rate of suit leakage.

3. The difference between the temperatures of the coolant water flowing into and out from the liquid cooling garment was multiplied by an assumed water flow rate and related to metabolism directly. This relationship is illustrated in figure 2, and it is based on the assumption that the crewman is maintaining a comfortable LCG inlet temperature. A second mode of computation was available in which crewman comfort is not assumed, but a steady-state of the coolant inlet temperature is assumed. An example of this mode of the LCG program is illustrated in figure 3. The basic difference between the two modes of computation, then, is the fact that the LCG inlet temperature is used in the second mode. This provided a greater degree of precision but required a constant inlet temperature. An operational procedure was established to select the appropriate LCG calculation mode as a function of the constancy of the inlet temperature.

In both the LCG computational modes, the metabolic rate was corrected by subtracting an estimate of heat leaked into the pressure suit from the environment from the total heat removed from the pressure suit.

After the mission was completed, the estimations made by each method of calculation were independently reassessed with respect to the information gained during the EVA including data on the sublimator feedwater remaining; real-time data were recalculated when required. The best metabolic rate estimate for the EVA and for EVA segments was then obtained by averaging the oxygen method and the LCG method. Because of apparent changes in the correlation of heart rate with metabolism, the heart rate method was not used independently. A postflight relationship of heart rate to metabolism was defined using the average heart and metabolic rates as a point and basing the slope of the relationship between heart rate and metabolic rate on the average of the preflight and postflight slopes.

Two types of task-identification methods were used for separating the activities performed during the EVA periods. The metabolic rate monitors divided the operational tasks into four types that were of interest to mission planners. These tasks consisted of overhead activities (that is, tasks required for each EVA, such as egressing and ingressing the vehicle, rather than those directed to a specific objective), deploying the Apollo lunar surface experiments package (ALSEP), making geological surveys, and riding in the lunar roving vehicle (LRV). Although these tasks were easy to separate according to time required for completion, the subtasks within a major task varied considerably from mission to mission. The oxygen and LCG methods could be used to obtain accurate metabolic rates for these activites. A more extensive task separation was accomplished in conjunction with a time and motion study.* This effort resulted in dividing the EVA

*Performed by Fordham University under contract to NASA.

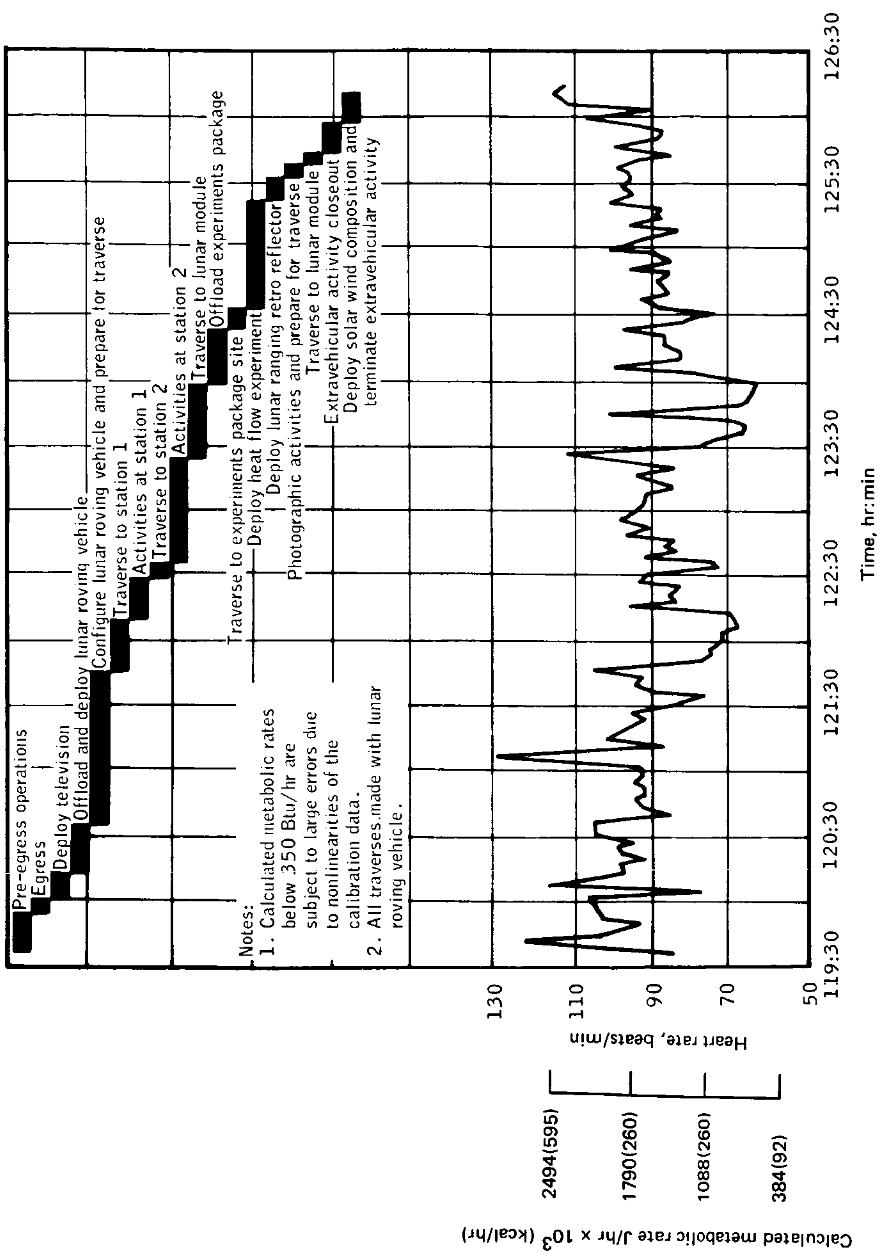

Figure 1. Heart rates and calculated metabolic rates of the Apollo 15 Commander during EVA-1.

timeline into as many definable activities as possible. Because of the short duration of some of these activities, metabolic rates could be assigned only by using the postflight heart rate method.

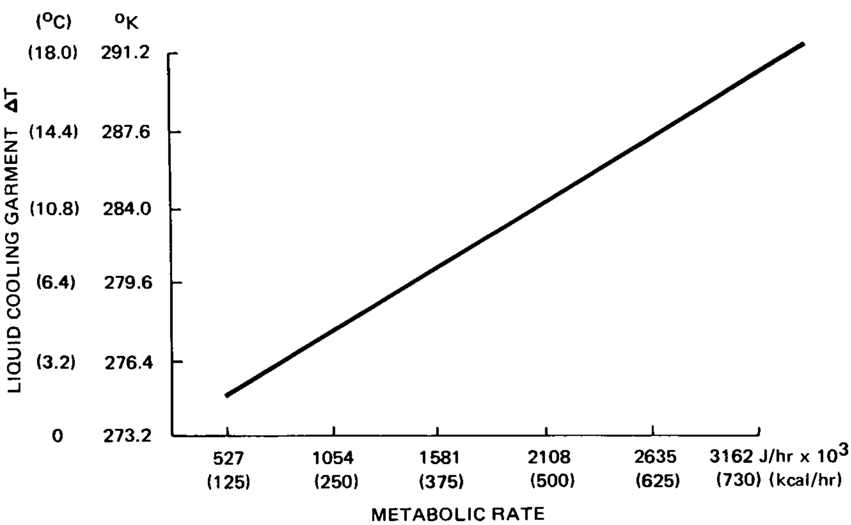

Figure 2. Example of mode 1 LCG program; metabolic rate plotted as a function of heat picked up by LCG. Relationship is based on the assumption that crewman is maintaining comfortable LCG inlet temperature.

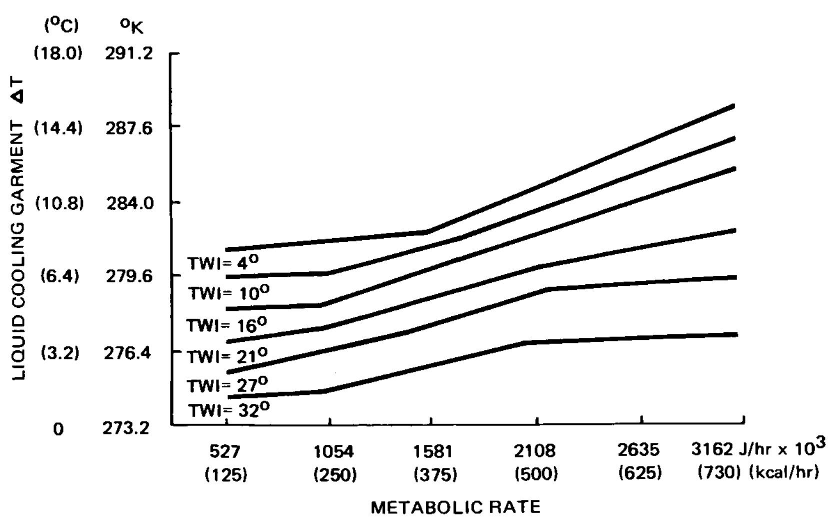

Figure 3. Example of mode 2 LCG program; metabolic rate plotted as a function of heat picked up by the LCG for each of a family of inlet temperatures. Relationship is based on the assumption that a steady-state exists; crewman comfort is not assumed.

Preflight data during one-g training was quite valuable in assessing the validity of the techniques of measurement but only of limited value in predicting actual workloads on the lunar surface and during free-space EVAs. Table 1 shows some of the data obtained prior to Apollo 15 as compared with the inflight data. As inflight data from previous missions became available, it became the best indicator of workloads to expect on succeeding missions.

Table 1

Metabolic Rate Measurement During Training and Flight – Apollo 15

Activity	KSC Training EVA 2 & 3 J/hr x 10^3 (kcal/hr)	Apollo 15 EVA 2 & 3 J/hr x 10^3 (kcal/hr)	Percent Difference
Overhead	359 (379)	261 (275)	+38
Station activity	422 (445)	216 (228)	+95
Lunar rover	192 (203)	463 (123)	+65
Average	372 (393)	218 (230)	+70

Energy Production

The metabolic rates experienced during the Apollo lunar surface extravehicular activities are summarized in table 2. Representative data for the first Apollo 15 EVA are given in table 3. The metabolic rates experienced during the EVA periods were lower than had been predicted before the Apollo missions, and the crewmen were able to move easily and confidently on the lunar surface. The overhead activities were the most energy consuming tasks performed. These activities included egress, offloading and setup of equipment around the Lunar Module (LM), ingress, and stowage of lunar samples. The ALSEP deployment and geological survey resulted in lower metabolic rates than did the overhead activity. This difference may have been attributable to the fact that the details of these activities as a group were less predictable and required more time for judgment and, in some cases, for precise manual manipulation.

The lowest metabolic rates occurred while astronauts drove and rode in the LRV (figure 4). This was the most clearly defined operational activity. Metabolic rates for this activity approached rates reported for shirt sleeve riding in an automobile (Webb, 1973). The low metabolic rates experienced during this lunar activity were important factors contributing to the success of the Apollo 15 through 17 missions through reduction in both the use of consumables and the fatigue experienced by crewmen during the long EVA periods.

The highest average metabolic rate during an EVA was exhibited by the Apollo 11 Lunar Module Pilot (LMP). This crewman had been assigned the task of evaluating modes of locomotion and was quite active in performing this task. Several crewmen experienced the minimum average metabolic rate of approximately 837 x 10^3 J/hr (200 kcal/hr) on different missions. The highest metabolic rates experienced during the performance of discrete activities were associated with LMP transport of the ALSEP pallet, LM ingress

Table 2

Metabolic Expenditures During Apollo
Lunar Surface Extravehicular Activities

Mission No.	EVA No.	Crewman	Metabolic Rate, J/hr x 10^3 (kcal/hr)					EVA Duration (hr)
			ALSEP Deployment	Geological Station Activity	Overhead	Lunar Roving Vehicle Operations	Total For Activities	
11	1	CDR	818 (195)	1023 (244)	899 (214)		949 (227)	2.43
		LMP	1267 (302)	1471 (351)	1269 (303)		1267 (302)	2.43
12	1	CDR	864 (206)	1017 (243)	1232 (294)		1028 (246)	3.90
		LMP	1006 (240)	1028 (245)	1119 (267)		1054 (252)	3.90
	2	CDR		913 (218)	902 (215)		922 (221)	3.78
		LMP		1058 (253)	1038 (248)		1054 (252)	3.78
14	1	CDR	762 (182)	1230 (294)	920 (219)		843 (202)	4.80
		LMP	947 (226)	729 (174)	1084 (259)		980 (234)	4.80
	2	CDR	494 (118)	996 (238)	895 (213)		959 (229)	3.58
		LMP	851 (203)	1120 (267)	894 (213)		1054 (252)	3.58
15	1	CDR	1182 (282)	1153 (275)	1417 (338)	639 (152)	1159 (277)	6.53
		LMP	1369 (327)	778 (186)	1226 (293)	435 (104)	1033 (247)	6.53
	2	CDR	1019 (243)	1227 (293)	1202 (287)	624 (149)	1054 (252)	7.22
		LMP	1110 (265)	792 (189)	1116 (266)	414 (99)	854 (204)	7.22
	3	CDR	1095 (261)	1013 (242)	1303 (311)	578 (138)	1086 (260)	4.83
		LMP	962 (230)	788 (188)	981 (234)	447 (106)	854 (204)	4.83
16	1	CDR	869 (207)	905 (216)	1146 (273)	725 (173)	917 (219)	7.18
		LMP	1081 (258)	1125 (268)	1154 (275)	666 (159)	1065 (255)	7.18
	2	CDR		933 (223)	1044 (249)	470 (112)	822 (197)	7.38
		LMP		1023 (244)	987 (236)	438 (105)	874 (209)	7.38
	3	CDR		966 (231)	983 (235)	518 (124)	854 (204)	5.67
		LMP		1013 (242)	1107 (264)	430 (103)	864 (207)	5.67
17	1	CDR	1192 (285)	1094 (261)	1267 (302)	506 (121)	1150 (275)	7.20
		LMP	1166 (278)	1255 (300)	1193 (285)	472 (113)	1139 (272)	7.20
	2	CDR		1094 (261)	1267 (302)	506 (121)	864 (207)	7.62
		LMP		1255 (300)	1193 (285)	472 (113)	874 (209)	7.62
	3	CDR		1094 (261)	1267 (302)	506 (121)	980 (234)	7.25
		LMP		1255 (300)	1193 (285)	472 (113)	990 (237)	7.25
Mean			1018 (244)	1018 (244)	1123 (270)	518 (123)	980 (234)	
Total time (hr)			28.18	52.47	52.83	25.28	158.74	

CDR = Commander
LMP = Lunar Module Pilot

with lunar samples, and drilling and removal of drill bits. The flight surgeon never had to limit the work rate of any crewman during an EVA. The lowest rates experienced for discrete activities were associated with riding the LRV, picture taking, and with periods of observation and description.

Table 3

Metabolic Expenditures for the Apollo 15 Commander During EVA-1

Surface Activity	End Time (hr:min)	Duration (min)	Average Metabolic Rate J/hr x 10^3 (kcal/hr)
Preegress operations	119:51	12	1569 (374)
Egress	119:59	8	1726 (412)
Television deployment	120:11	12	1895 (452)
Lunar roving vehicle (LRV) offloading and deployment	120:32	21	1463 (349)
LRV configuration	121:45	73	1239 (296)
LRV traverse (LM to station 1)	122:11	26	513 (122)
Station 1 activities	122:29	18	1032 (246)
Geological site selection	122:15	4	1045 (249)
Radial sample	122:24	9	852 (203)
Traverse preparation	122:29	5	1343 (321)
LRV traverse (station 1 to station 2)	122:35	6	486 (116)
Station 2 activities	123:26	51	1196 (285)
Description and documented sample	122:57	22	1120 (267)
Comprehensive sample	123:05	8	1212 (289)
Double core tube	123:16	11	1112 (265)
500-mm photography and traverse preparation	123:26	10	1444 (345)
LRV traverse (station 2 to LM)	124:00	34	617 (155)
ALSEP offloading	124:24	24	1054 (252)
ALSEP traverse (LRV)	124:33	9	795 (190)
Heat flow experiment deployment	125:24	51	1184 (283)
Laser ranging retroreflector deployment	125:33	9	1393 (333)
Photography and traverse preparation	125:38	5	1394 (333)
LRV traverse (ALSEP site to LM)	125:43	5	1343 (321)
EVA closeout	125:58	15	1305 (311)
Solar wind composition experiment deployment and EVA termination	126:11	13	1701 (406)

During the Apollo 14 mission, which included some of the most extensive walking traverses (figure 5), a specific effort was made to relate walking speed to metabolic rate. The results of this effort are presented in table 4. These data indicate a very poor correlation between traverse rate and metabolic rate. During these operational traverses, the crewman apparently maintained a comfortable walking effort, and, to a large extent, the rate of travel at this level of effort varied with the terrain and the operational requirements of each traverse.

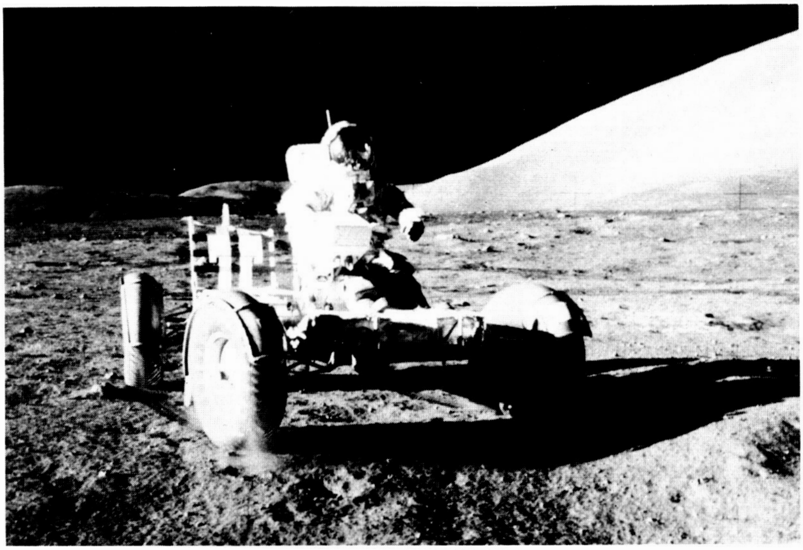

Figure 4. Apollo 17 astronaut riding in the lunar roving vehicle.

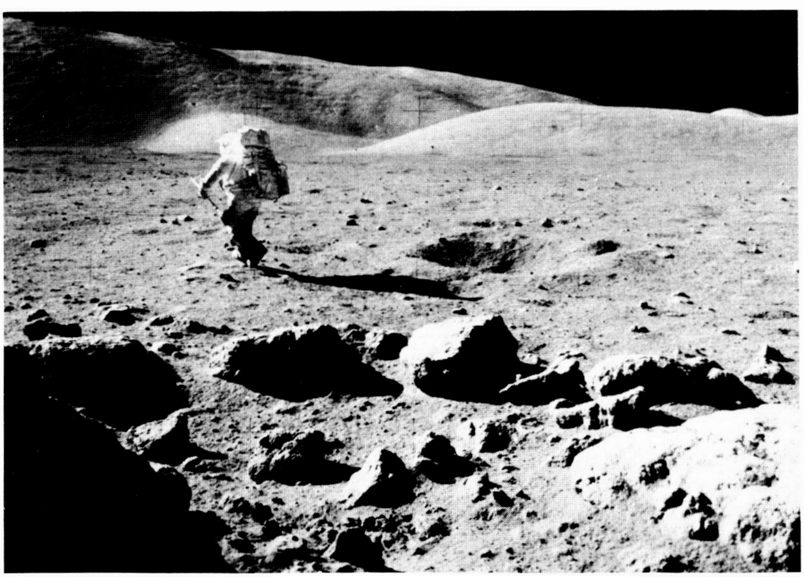

Figure 5. Apollo 17 astronaut walking on the lunar surface.

Table 4

Metabolic Analyses of Apollo 14 EVA Traverses

Traverse	Duration (min)	Traverse Distance (m)	Net Elevation Change (m)	Net Slope Percent	Traverse Rate (km/hr)	Metabolic Rate, J/hr x 10^3 (kcal/hr)	
						CDR	LMP
EVA-1							
ALSEP out	15	172	0	0	.688	1039 (248)	1159 (277)
ALSEP return	16	204	0	0	.765	1344 (321)	1099 (262)
ALSEP overall	31	376	0	0	.728	1192 (285)	1130 (270)
EVA-2							
LM to A*	7.4	193	5	2.6	1.56	593 (142)	875 (209)
A to B	7.8	185	− 5	− 2.7	1.42	804 (192)	887 (212)
B to B1	7.2	319	15	4.7	2.65	1009 (241)	1144 (273)
B1 to B2	5.1	145	15	10.3	1.71	1438 (343)	1218 (291)
B2 to B3	14.4	399	45	11.3	1.66	1575 (376)	1321 (315)
B3 to C′	6.7	220	15	5.8	1.97	1911 (456)	2179 (520)
C′ to C1	1.4	86	3	3.5	3.69	1024 (244)	1355 (323)
C1 to C2	5.6	240	−33	−13.8	2.57	998 (238)	1116 (266)
C2 to E	6.0	480	−45	− 9.4	4.8	1314 (314)	1412 (337)
E to F	3.9	292	−10	− 3.4	4.49	1353 (323)	1545 (367)
F to G	1.8	172	0	0	5.7	1180 (282)	1638 (391)
G to G1	2.5	110	5	4.5	2.64	1125 (268)	1588 (379)
G1 to LM	3.0	159	−10	− 6.3	3.18	1277 (305)	1645 (393)
Subtotals							
LM to C1	50.0	1547	93	5.0	1.86	1247 (298)	1262 (301)
C1 to LM	22.8	1453	−93	− 6.4	3.82	1205 (288)	1439 (343)
Totals							
LM to LM	72.8	3000	0	0	2.47	1233 (294)	1318 (315)

*Letter designations represent stations.

In general, both the speed and the efficiency of lunar walking were greater than could be achieved while wearing a pressure suit in a one-g environment; neither speed nor efficiency was equivalent to that of a shirt sleeve operation at one g.

Operational film and kinescope were used in performing a time and motion study of Apollo 15 and 16 activities. This study compared the facility for, and energy cost of performing several specific activities at one g during training wearing the Apollo space suit with one-sixth g on the lunar surface. One of the observations of this study was that tasks were completed more rapidly at one g than at one-sixth g, but that greater metabolic costs were involved (Kubis et al., 1972a; Kubis et al., 1972b).

In addition to the 14 periods of lunar surface activity, there were four periods of zero-g EVA. The metabolic data from these EVA periods are summarized in table 5. During the Command Module extravehicular activities performed during the Apollo 15 through 17 missions, the Command Module Pilot retrieved a film canister from the Service Module while the Lunar Module Pilot tended his umbilical in the doorway of the Command Module (figure 6). During the Command Module extravehicular activities, heart rate was the only data available for estimating metabolic rate. Because the errors in the heart rate method all tended to increase the metabolic rate estimate, these rates can be considered maximum values. Voice contact with crewmen during these periods did not indicate that they were working strenuously. The metabolic rates obtained from heart rate data were not used to constrain extravehicular activities; in some cases, the actual metabolic rates were much lower than the values obtained by means of heart rate calibration data. Elevation of these heart rates was attributed more to excitement than to exercise.

Table 5

Metabolic Expenditures
During Apollo Zero-G EVA Periods

Mission Number	Crewman	Metabolic Rate, J/hr x 10^3 (kcal/hr)	Duration (min)
9	LMP	634 (150)	59
15	CMP	< 992 (235)	40
	LMP*	< 486 (115)	40
16	CMP	<2108 (500)	85
	LMP*	**	85
17	CMP	<1267 (300)	67
	LMP*	<602 (145)	67
		Total	443

*Standup EVA

**Not measured

LMP = Lunar Module Pilot

CMP = Command Module Pilot

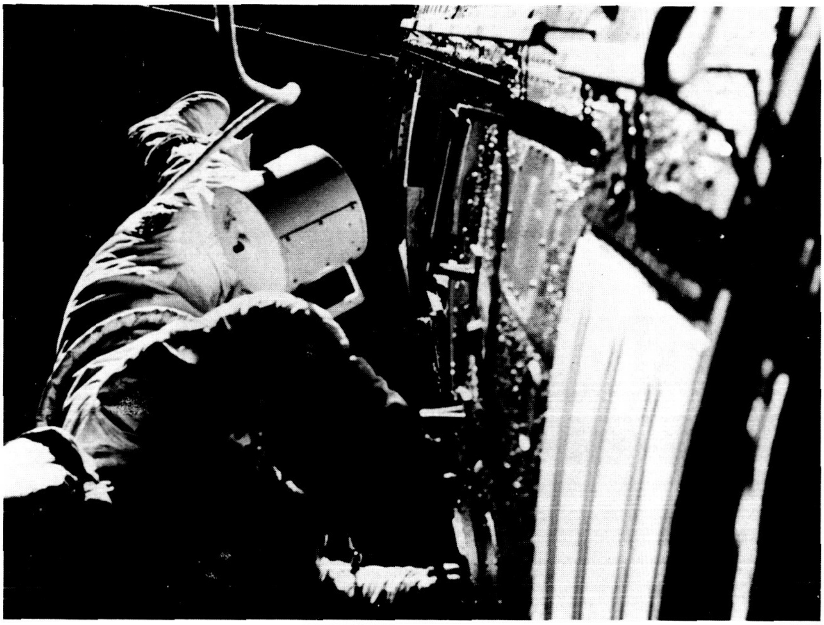

Figure 6. Apollo 17 CMP retrieving film canister from the Service Module.

Concluding Remarks

The Apollo crewmen were able to perform planned extravehicular activities and to extend them to the maximum time allowable without medical problems. The metabolic rates experienced during the lunar surface extravehicular activities were lower than conservative premission estimates.

A manually controlled liquid cooling garment was effectively used to minimize fatigue and water loss from sweating during lunar surface extravehicular activities.

Gas cooling was adequate during the short zero-g extravehicular activities performed from the Command Module.

The prediction of EVA workloads became more reliable as inflight data was accumulated. The prediction of the average metabolic cost of an EVA was more reliable than the cost of an individual short-term task.

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