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APOLLO EXPERIENCE REPORT - ASSESSMENT OF METABOLIC EXPENDITURES

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16. Abstract

A significant effort was made to assess the metabolic expenditure for extravehicular activity on the lunar surface. After evaluation of the real-time data available to the flight controller during extravehicular activity, three independent methods of metabolic assessment were chosen based on the relationship between heart rate and metabolic production, between oxygen consumption and metabolic production, and between the thermodynamics of the liquid-cooled garment and metabolic production. The metabolic assessment procedure is analyzed and discussed. Real-time use of this information by the Apollo flight surgeon is discussed. Results and analyses of the Apollo missions and comments concerning future applications are included.

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APOLLO EXPERIENCE REPORT

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ASSESSMENT OF METABOLIC EXPENDITURES

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SUMMARY

Before the first Apollo extravehicular activity, the staff of the NASA Lyndon B. Johnson Space Center (formerly the Manned Spacecraft Center) developed operational methods to determine the energy expenditures of the crewmen. These methods were required to allow adequate physiological evaluation of the crewmen, to determine the usage rate of life-support system consumables, and to provide information for real-time activity scheduling and for planning future missions.

Three independent methods were used to determine crewmen energy expenditures. The heart-rate method was based on the direct linear relationship between energy expenditure and heart rate, which was determined before each flight. The oxygen method was based on the proven clinical procedure that relates energy expenditure to oxygen consumption. The liquid-cooled-garment method was based on a modified direct calorimetric approach to energy measurement. Preflight testing of these methods demonstrated inadequacies and inaccuracies that were corrected, and a system was developed that facilitated integration of the three methods into an accurate estimate of energy expenditure.

During each extravehicular activity, this integrated estimate was reported to the mission control flight surgeon and to the life-support system monitors. Thus, the flight surgeon was prepared to make recommendations concerning the immediate and future well-being of the crewmen. Postflight analyses of the results, combined with motion analysis, permitted accurate assessments of energy expenditure for specific lunar surface tasks. It was concluded that these methods provided reliable information on crewmember energy expenditures, which ranged from 822×10^3 to 1267×10^3 J/hr (780 to 1200 Btu/hr) for the Apollo lunar surface extravehicular activities.

*Boeing Company.

INTRODUCTION

Information about energy expenditure at the onset of planning for Apollo extravehicular activity (EVA) was meager. The observations made during the Gemini EVA periods indicated that the energy expenditures were greater than expected. The basis for the comparison was the heart rates observed during altitude chamber simulations and those observed during the actual EVA. The greatest deviation between the expected heart rates and the observed heart rates occurred during the Gemini XI EVA. Instead of providing a quantitative measurement of metabolism, these observations only indicated that at times the metabolic rates were more than the life-support system could accommodate. Data were available from 1/6-g trainers of many types; however, there was a general lack of confidence in this type of lunar surface simulation, particularly when the data were applied to energy expenditures for movement on the unknown terrain of the lunar surface.

A measurement of crew metabolic rates was required for several reasons. The basic measurement was important to the flight surgeon because it provided a measure of how closely a crewman was approaching his maximum work rate either acutely, as during a maximum effort when a crewman's maximum oxygen consumption might be exceeded, or chronically, as when a sustained moderately high work rate might lead to exhaustion. The metabolic rate also provided data that could affect the flight surgeon's evaluation of other information regarding a crewman. For example, a heart rate of 130 beats/min would indicate one level of concern for a crewman vigorously at work and another for a crewman at rest.

The metabolic rate measurement was also important to the monitors of the portable life-support system (PLSS) because the useful life of a PLSS on the lunar surface depended on the usage rate of consumables (oxygen, sublimator water supply, and carbon dioxide absorber). The usage rate of these consumables is closely related to metabolic rate; this relationship was particularly significant in the case of the water supply to the sublimator that provided the cooling for the PLSS because there was no measurement of sublimator water supply.

The metabolic rate measurement provided essential information for the lunar surface activity planners who assembled a schedule of crew activities based on preflight estimations of the metabolic expenditure and the time required to perform each activity. These planners were responsible for modifying the crewman's activity in real time if the metabolic expenditures for the activities or the time required to perform the activities deviated from the predicted values.

Before the first Apollo EVA, several groups at the NASA Lyndon B. Johnson Space Center (JSC) (formerly the Manned Spacecraft Center (MSC)) had been concerned with metabolic rates. A medical operations group was responsible for providing metabolic rate estimates for specific tasks and for monitoring the crew during 1/6-g training at MSC; a medical research group provided the metabolic requirements for the design of the life-support system and sponsored several research programs to evaluate various 1/6-g simulations. An engineering group attempted to use heat-loss data from the liquid-cooled garment (LCG) to estimate metabolic rate in calculating the usage of sublimator water supply. In 1969, before the first Apollo EVA (on the Apollo 9 mission), the Life Sciences Directorate formed a Metabolic Assessment Team that was composed of personnel from the Life Sciences Directorate and a member from the Engineering and Development Directorate, all of whom had been working in the area of metabolism. The team also benefited from support received from the Mission Evaluation Team and other MSC groups. The Metabolic Assessment Team was charged with the responsibility for reviewing and evaluating real-time data that would be available during EVA and for devising procedures to use these data in measuring the crewman's metabolic rates during EVA.

As a result of the team's initial studies, three independent methods based on the most common laboratory methods were implemented:

1. The relationship between heart rate and metabolic rate

2. The relationship between oxygen consumption and metabolic rate

3. The relationship between the heat removed from the crewman by the LCG and metabolic rate

Each method was used during ground-based tests and each was found to provide useful data but to have deficiencies when used alone. The advantages and deficiencies of these methods and the real-time modifications made to improve them are presented in the following sections.

HEART-RATE METHOD

Heart rates were used during Apollo flights to estimate metabolic expenditures during specific extravehicular activities. Because the heart rate is an indicator of total physiological and psychological stress, it is not entirely dependent on metabolic rate. The heart-rate method was, however, the only method with a timelag short enough to allow a minute-by-minute estimate of the energy expenditure.

In addition to the inaccuracies (psychogenic factor, heat storage, and fatigue) usually associated with this method of metabolic-rate estimation, three unique problems were encountered during the Apollo missions: calibration-curve inaccuracies, crewmember deconditioning, and the technique used to determine heart rate. Control of the usual inaccuracies was not considered feasible because insufficient data were available during the EVA; however, as explained in this report, control of the unique sources of inaccuracy was attempted.

Calibration curves (heart rate compared with metabolic rate) for each individual were determined before each mission by using standard ergometric calibration techniques. Heart-rate data were obtained under resting conditions and at several work rates; least-squares analysis was used to determine a linear regression curve. Standard errors as large as 211×10^3 J/hr (200 Btu/hr) were not unusual. Changes in test protocol (more data points at various work rates) did not significantly increase the accuracy, and it was concluded that this modification to the standard laboratory calibration procedures was not worthwhile.

Deconditioning of crewmen between preflight and postflight measurements resulted in a 10- to 35-beats/min increase in heart rate for any given workload experienced before deconditioning. Attempts were made to use this information to correct the EVA heart-rate/metabolic-rate curve by shifting (biasing) the curve. Furthermore, to obtain information that would allow inserting bias into the curve (which was assumed to be progressive with the length of exposure to weightlessness), efforts were made to obtain heart-rate data during successive in-flight sleep periods before the EVA. These corrective efforts improved the estimates only slightly because a wide variation in individual crewmember response contributed greatly to the inaccuracies inherent in this method.

The use of heart rate alone as an independent indicator of metabolic rates under space-flight conditions is not recommended. Errors as large as 80 percent have been noted. However, the use of heart rate as a dependent method was useful when the total metabolic expenditure as measured by oxygen and LCG methods could be used as a reference. After the first Apollo flights, use of the heart-rate method as an independent real-time method was discontinued; the method was then used as a real-time and postflight dependent method. The relationship between heart rate and metabolic rate was based on hourly measurements of the total EVA energy expenditure as determined by the oxygen and LCG measurements. The heart-rate method then allowed real-time and postflight measurement of specific activities on a minute-by-minute basis. An example of the heart-rate method is the measurement of metabolic rate during deployment of the heavy Apollo lunar surface experiments package by the lunar module pilot. This activity took 2 to 3 minutes to accomplish. The response of the oxygen and LCG methods did not allow isolation of this activity, but the heart-rate method responded quickly to this activity and provided the best information on energy expenditure for the activity.

OXYGEN METHOD

The oxygen method involved using the PLSS oxygen bottle pressure decay to estimate oxygen consumption and thereby metabolic rate. The oxygen bottle pressure was telemetered from each EVA crewman and displayed in real time.

Special problems were associated with using this method as a metabolic-rate indicator. For best accuracy of the oxygen method, a measurement of respiratory quotient (RQ) as well as oxygen consumption is required. The RQ is a ratio of the amount of carbon dioxide produced and the amount of oxygen consumed. There was no measurement of carbon dioxide production; therefore, the RQ had to be estimated.

A random noise error was experienced in the telemetered oxygen bottle pressure data. To minimize this error, a metabolic computation was not performed until a significant drop in bottle pressure occurred. Consequently, at lower metabolic rates, updates did not yield information frequently enough during EVA for adequate evaluation of consumables status and crewmember condition.

The suit oxygen leakage rate was variable and had to be estimated. The maximum oxygen leakage rate allowed by the pressure suit specification was equivalent to a metabolic rate of approximately 211×10^3 J/hr (200 Btu/hr).

The following attempts were made to reduce errors associated with the oxygen method. The RQ was determined on several occasions during crew training and during manned tests in the thermal-vacuum facilities; this determination enabled more accurate estimates during missions. A suit-leak check was performed at the NASA John F. Kennedy Space Center before launch readiness to provide an indication of leak rates to be expected during the mission. These leak rates were used as initial values in the oxygen-consumption metabolic program. A pressure integrity check was performed before each lunar surface EVA, and the measured leak rates were used to update the program. Experience indicates that the suit leak will increase during use, especially if activity is vigorous. Accordingly, upward adjustments were made in the program as the EVA progressed.

LIQUID-COOLED-GARMENT METHOD

Because of the limitations of the other methods available to estimate metabolic rate, direct calorimetry was the third method to be considered. All the energy produced by metabolism is accountable either as heat produced or as physical work; direct calorimetry is the measurement of this energy production. A complete energy accounting required measurement of heat removed by the LCG, heat (both sensible and latent) removed by the gas stream, heat leak into or out of the pressure suit, and energy dissipated outside the suit either as work or as heat from frictional work.

The available PLSS data were limited to LCG inlet and outlet temperature and gas inlet temperature and, at first, appeared to be inadequate to calculate an energy balance. However, the availability of a thermal model of man in a pressure suit (ref. 1) together with considerable empirical data on heat removal from man in a pressure suit (ref. 2) allowed estimates of the types of heat loss not directly measured.

An LCG heat-balance computer program was constructed to estimate metabolic rate. Using the thermoregulatory model, a relationship between LCG heat removal and metabolic rate for each LCG inlet temperature (fig. 1) was defined. This estimate of metabolic rate was not dependent on proper crew selection of inlet temperature. The estimate provided valid data on the metabolic rate of a crewman who had

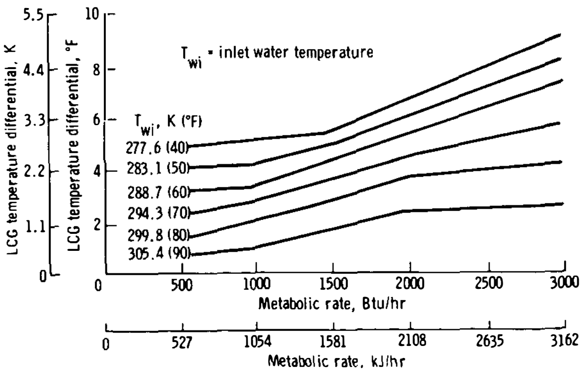

Figure 1. - Example of factor 1 LCG program; metabolic rate plotted as a function of heat picked up by the LCG for each of a family of inlet temperatures. Relationship is based on the assumption that a steady state exists; crewman comfort is not assumed.

not selected a comfortable water temperature (provided he was in or near steady state). This estimate of metabolic rate, based on inlet temperature and the difference between inlet and outlet temperature, was accurate only when the data were rather stable. The estimate was not accurate during a rapid transient of water temperature or metabolic rate. To provide data during transient periods, a simpler estimate of metabolic rate was used that consisted of a linear equation relating metabolic rate to LCG heat removal (fig. 2). This estimate was accurate only when comfortable coolant temperatures were selected by the crewman. A difference in the two estimates over a period of time indicated that the crewman was functioning at either a hotter or cooler body temperature than optimum. On several occasions, this condition led to the flight surgeon's recommendation to change the LCG diverter valve setting.

A manual input, identified as "factor," was made available in the program. When the factor equaled zero, the metabolic rate was based on the estimate using the difference between inlet and outlet temperature; when the factor equaled 1, the metabolic rate was based on the estimate using the difference between inlet and outlet temperature combined with the absolute value of the inlet temperature. An operational procedure was developed for control of the factor input in a consistent manner. Factor 1 was chosen after obtaining two consistent 12-minute readouts. After any transient change, factor zero was reselected. Other real-time inputs to the program included the heat leak into the suit and the LCG flow rate. These values were based on analysis and were provided by the Mission Evaluation Team before flight and, after the Apollo 14 mission, during each EVA by means of a telephone link to the medical science support room.

Because of its analytical nature, the LCG method was of no value until it could be verified with test data from training runs in the MSC Space Environmental Simulation Laboratory chamber. The test data indicated that the LCG method predicted the sublimator water usage and the carbon dioxide absorption in lithium hydroxide canisters as accurately as or more accurately than the other methods and that the method would be of value.

In calculating an estimate of sublimator water usage, the LCG method was of special value because a heat leak into or out of the suit affected both the LCG method and the sublimator water usage. Therefore, the accuracy of the heat-leak estimate was not critical for estimating sublimator water usage, although it was critical for estimating metabolic rate.

Experience with the heat-balance program during early Apollo missions increased confidence in the program and provided familiarity with its strengths and weaknesses. The LCG method provided the best prediction of sublimator water usage when predictions were

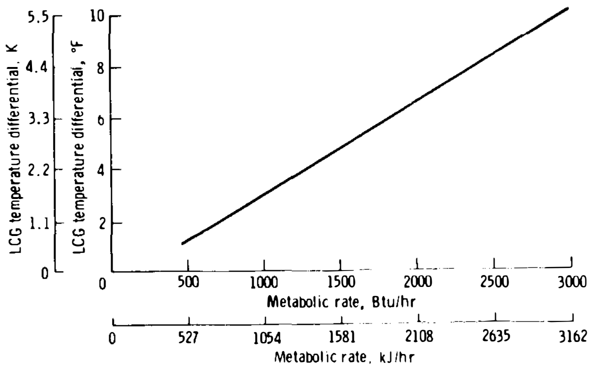

Figure 2. - Example of factor zero LCG program; metabolic rate plotted as a function of heat picked up by the LCG. Relationship is based on the assumption that the crewman is maintaining a comfortable LCG inlet temperature.

compared with measurements of remaining feedwater. Comparisons of LCG and oxygen data indicated that the heat-balance program, as designed, compensated for inappropriate diverter-valve settings; however, accuracy was reduced if comfortable settings were not maintained by the crewman. The response of the heat-balance program was demonstrated to be slow, which was expected, but the program did begin to respond almost immediately to a change in metabolic rate.

INTEGRATION OF METHODS

Because early studies indicated many sources of uncertainty in each method when used individually, the decision was made to use all three methods simultaneously. The metabolic team received all incoming raw data, processed the data in accordance with the best real-time estimates for values of the unmeasurable factors involved, used the results obtained from each of the individual methods to provide correction factors for the other methods, and provided one integrated value for the flight surgeon. It was realized that this process could be iterative and that updates could, as the EVA progressed, cause retrospective changes in values. However, after completion of the mission and after complete postflight analysis of the data, the results could be compared with the EVA crewman's subjective evaluation of the workloads; thus, a better base for planning future lunar traverses could be established.

The results obtained from the Apollo 11 mission were used to plan rest periods and to establish limits on heart and respiratory rates (not only absolute limits but also limits for predictions of developing difficulties). These results led to an extension of the lunar surface stay time for the Apollo 12 mission without loss of confidence. Similarly, the experience and information gained from preceding missions were incorporated into the planning for the next mission. The confidence level increased as the information base increased; both stay times and useful work on the lunar surface increased, and a high level of confidence was maintained that safety had not been adversely affected.

During the actual EVA, the flight surgeon had to be ready at all times to make recommendations concerning the advisability of continuing an activity or to aid in planning a deviation in the mission plan. The principal concerns of the flight surgeon were the reserve capacity of the crewman and his physiological status. The physiological status was based on a variety of factors, some of which were historical (e.g., the extent of deconditioning resulting from 3 days of weightlessness during translunar coast, the amount of fatigue, the preflight physical condition of the crewman, the individual crewman response observed during training for specific activities, the amount and kind of exercise used by the crewman during translunar coast, and the amount and depth of sleep obtained by the crewman). Other factors were real time in that they were derived from current activity. Within this context, the flight surgeon required data on both the cumulative and the peak energy demands being experienced by the crewman during the EVA. Data on cumulative energy expenditures are most directly applied in determining the status of consumables and in determining the general physical status and reserve. Excessively high heart rates, hyperventilation, and heat storage can be related to instantaneous peaks of energy expenditure. Therefore, data that tend to quantitate these peaks are evaluated and used as specifics in the total consideration of crew status.

The integration of the three methods has provided both cumulative and peak data. Use of these data during the mission has prevented the crewmen from exceeding preset heart-rate and respiratory-rate limits and has assured that physiological limits for heat storage were not exceeded.

Heart rates higher than those expected were noted during Apollo EVA periods. Because these increases were present during both rest and work periods, it is thought that they resulted from deconditioning experienced during the first 3 days of translunar coast weightlessness. These higher heart rates have been carefully included in all considerations. With more understanding of the biomedical effects of both weightlessness and lunar surface exposure, techniques may be developed to minimize the undesirable changes.

RESULTS AND ANALYSIS

Because of the problems experienced in using each of the three assessment methods, the real-time values reported to the flight surgeon and the PLSS consumables analysts were integrated values. When determining an assessed metabolic rate, the team leader examined the results of all three methods together with all other PLSS telemetry data. After the flight, this integrated result was further updated by comparing the results of actual sublimator water supply measurements, water tank warning tones,[1] PLSS lithium hydroxide canister analysis (Apollo 9 only), and oxygen-method maximum (assuming suit oxygen leakage was zero). Actual sublimator water supply measurements, which were made by the crewmen immediately after the EVA, and water tank warning tones supplied a maximum limit to the integrated results. All errors (such as water spillage) decreased the measured water remaining, increasing the apparent metabolic rate. Total oxygen used also provided an upper limit to the average metabolic rate (assuming suit oxygen leakage was zero). Lithium hydroxide analysis, performed on the Apollo 9 canister, provided a basis for determining carbon dioxide production, thus an assessment of RQ, which was then used to refine the oxygen-method and LCG-method results. The postflight integrated metabolic results for the Apollo Program extravehicular activities are shown in table I. The overall error of integrated metabolic assessments made during the Apollo flights was estimated to be 10 to 15 percent, based on method variability.

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[1]On the Apollo 15 to 17 missions, which had auxiliary sublimator water tanks, a warning tone sounded when the main tank was depleted.

TABLE I. - METABOLIC EXPENDITURES FOR APOLLO LUNAR SURFACE EVA

Apollo mission	EVA	Crewman (a)	Metabolic rate: ALSEP deployment, kJ/hr	ALSEP deployment, Btu/hr	Geological station activity, kJ/hr	Geological station activity, Btu/hr	Overhead, kJ/hr	Overhead, Btu/hr	Lunar roving vehicle operations, kJ/hr	Lunar roving vehicle operations, Btu/hr	Total for all activities, kJ/hr	Total for all activities, Btu/hr	EVA duration, hr
11	1	CDR	818	775	1023	969	899	851	--	--	949	900	2.43
		LMP	1267	1200	1471	1393	1269	1202	--	--	1267	1200	
12	1	CDR	864	818	1017	963	1232	1167	--	--	1028	975	3.90
		LMP	1006	953	1028	974	1119	1060	--	--	1054	1000	
	2	CDR	--	--	913	865	902	854	--	--	922	875	3.78
		LMP	--	--	1058	1002	1038	983	--	--	1054	1000	
14	1	CDR	762	722	1230	1165	920	871	--	--	843	800	4.80
		LMP	947	897	729	690	1084	1027	--	--	980	930	
	2	CDR	494	468	996	943	895	848	--	--	959	910	3.58
		LMP	851	806	1120	1061	894	847	--	--	1054	1000	
15	1	CDR	1182	1119	1153	1092	1417	1342	639	605	1159	1100	6.53
		LMP	1369	1297	778	737	1226	1161	435	412	1033	980	
	2	CDR	1019	965	1227	1162	1202	1138	624	591	1054	1000	7.22
		LMP	1110	1051	792	750	1116	1057	414	392	854	810	
	3	CDR	1095	1037	1013	959	1303	1234	578	547	1086	1030	4.83
		LMP	962	911	788	746	981	929	447	423	854	810	
16	1	CDR	869	823	905	857	1146	1085	725	687	917	870	7.18
		LMP	1081	1024	1125	1065	1154	1093	666	631	1065	1010	
	2	CDR	--	--	933	884	1044	989	470	445	822	780	7.38
		LMP	--	--	1023	969	987	935	438	415	874	830	
	3	CDR	--	--	966	915	983	931	518	491	854	810	5.67
		LMP	--	--	1013	959	1107	1048	430	407	864	820	
17	1	CDR	1192	1129	1094	1036	1267	1200	506	479	1150	1090	7.20
		LMP	1166	1104	1255	1189	1193	1130	472	447	1139	1080	
	2	CDR	--	--	1094	1036	1267	1200	506	479	864	820	7.62
		LMP	--	--	1255	1189	1193	1130	472	447	874	830	
	3	CDR	--	--	1094	1036	1267	1200	506	479	980	930	7.25
		LMP	--	--	1255	1189	1193	1130	472	447	990	940	
Mean			1024	970	1024	970	1130	1070	518	490	980	930	
Total time, hr			28.18		52.47		52.83		25.28		158.76		

[a] CDR = commander, LMP = lunar module pilot.

CONCLUDING REMARKS

The following conclusions are based on Apollo Program metabolic expenditure measurement estimations. The three methods of metabolic assessment, used with knowledge of their deficiencies, proved to be valuable indicators of crewman metabolic production. The overall average metabolic production of Apollo crewmen during extravehicular activity on the lunar surface ranged from 823×10^3 to 1267×10^3 J/hr (780 to 1200 Btu/hr).

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, September 25, 1974
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