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APOLLO PORTABLE LIFE SUPPORT SYSTEM PERFORMANCE REPORT

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INTRODUCTION

This paper discusses the performance of the Apollo portable life support system (PLSS) on actual lunar missions. Both subjective comments by the crewmen and recorded telemetry data are discussed although emphasis is on the telemetry data. Because the most important information yielded by the PLSS deals with determination of crewman metabolic rates, these data and their interpretation are explained in detail. System requirements are compared with actual performance, and the effect of performance margins on mission planning are described. Mission preparation testing is described to demonstrate how the mission readiness of the PLSS and the crewmen is verified, and to show how the PLSS and the crewmen are calibrated for mission evaluation. Finally, mission plans for extended lunar exploration are discussed, and the effect on PLSS design and performance is explained.

SYSTEM REQUIREMENTS

A system schematic of the Apollo 11 to 14 PLSS is shown in figure 4.1. The major subsystems of the PLSS and their functions are:

1. The primary oxygen subsystem, which supplies breathable oxygen at a regulated pressure of 3.85 psid.
2. The oxygen ventilation subsystem, which recirculates cooled oxygen and removes contaminants at a nominal rate of 5.5 absolute cubic ft/min (ACFM).
3. The feedwater subsystem, which supplies water to the porous plates of the sublimator for heat removal by means of sublimation to space vacuum.
4. The liquid-transport subsystem, which recirculates coolant water at a fixed rate of 4.0 lb/min.
5. The extravehicular communications subsystem (EVCS), which provides communications and instrumentation for the crewman and equipment.

One of the major planning and design problems before the lunar-surface missions was the prediction of crewman metabolic rate. Of course, this is the major parameter affecting PLSS duration and crewman comfort. As a man works harder, he generates more metabolic heat (which must be removed by the PLSS), he consumes more oxygen, and he generates more carbon dioxide and water vapor. Metabolic rates could be predicted for given tasks in earth gravity; however, it was not known whether metabolic rates in lunar gravity would be lower or higher than those on earth. The reduced weight of the man, suit, PLSS, and so forth on the moon would lead one to suspect that metabolic rate would be lower. However, reduced weight would mean reduced traction for walking. This, combined with the possibility of a loose or slippery lunar soil and a potential crewman/equipment balance problem, could lead to a net increase in metabolic rate.

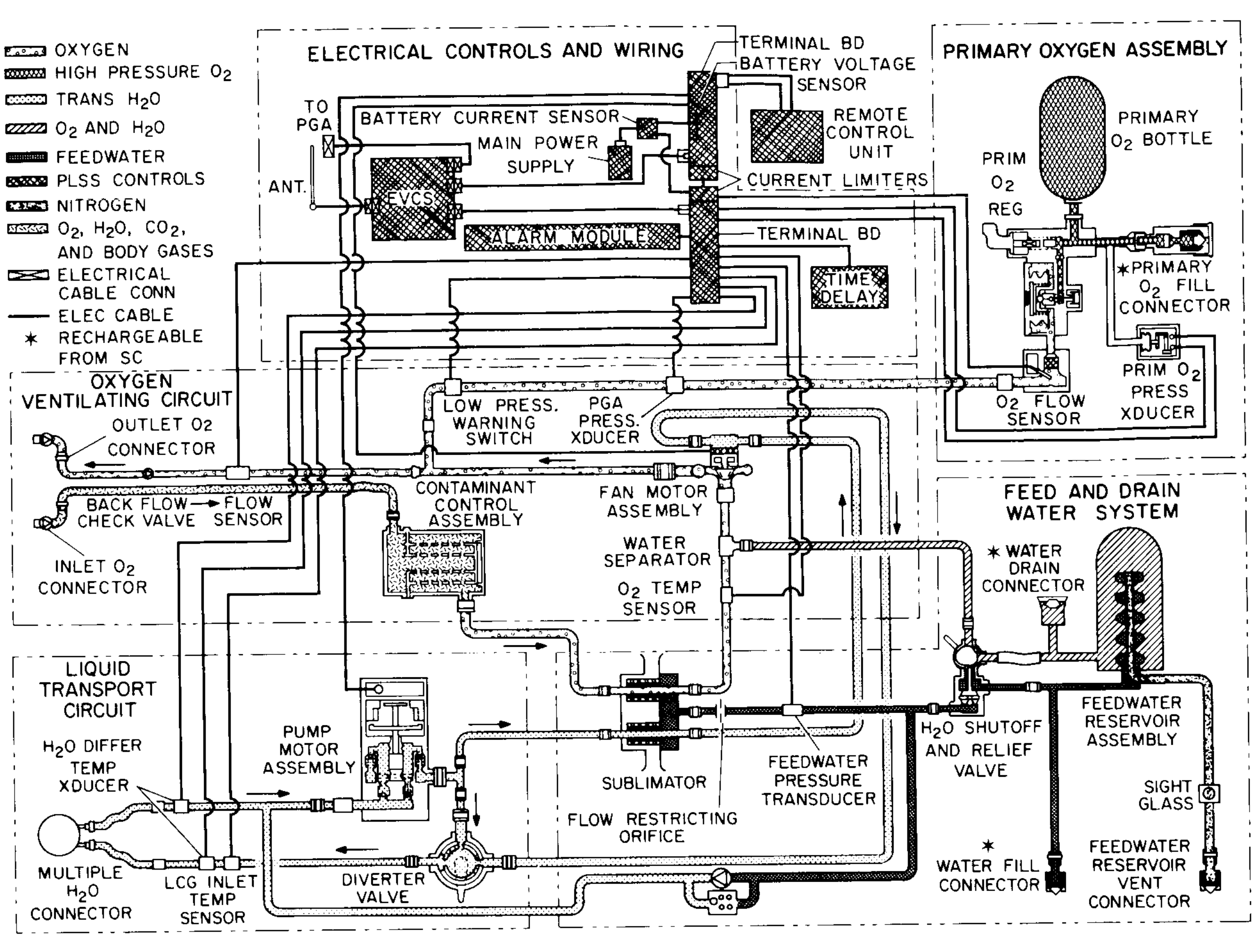

Figure 4.1 *The Apollo PLSS.*

Based on the best estimates of test data and analysis available at the time, the PLSS was designed for a 4-hr lunar exploration mission and an average crewman metabolic rate of 1200 Btu/hr. The requirement for two extravehicular activity (EVA) periods dictated that the PLSS be capable of being recharged with the consumable items (oxygen, water, lithium hydroxide, and battery) in the lunar module (LM) between EVA. The duration of each PLSS consumable as a function of a crewman metabolic rate is summarized in figure 4.2.

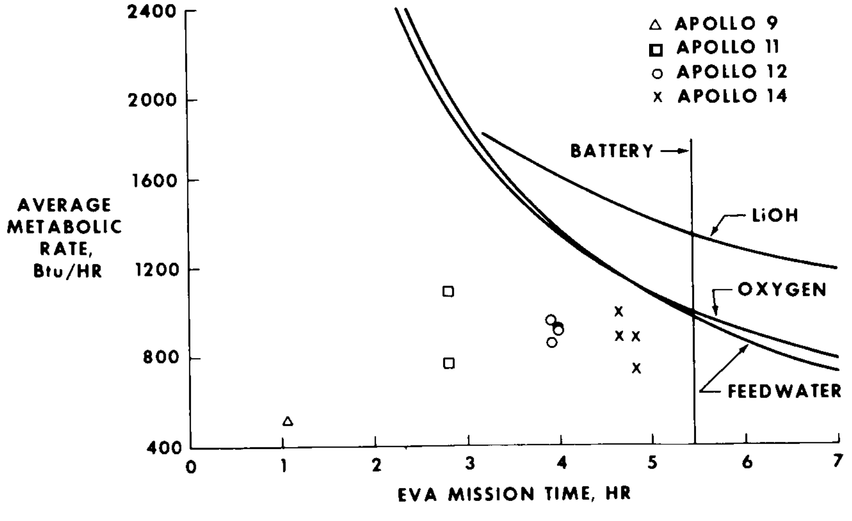

Figure 4.2 *The PLSS expendables duration compared with metabolic rate.*

In the event of a PLSS failure, a completely independent backup system, the oxygen purge system

(OPS), is provided. This system supplies sufficient breathing oxygen for a minimum of 0.5 hr. Carbon dioxide control is provided by purging suit gas overboard. The OPS neither provides recirculation of suit gas nor liquid cooling.

MISSION PREPARATION

Because the proper functioning of the PLSS is absolutely necessary to sustain the life of the astronaut during lunar traverse, each PLSS must be tested thoroughly before the mission to which it is assigned. Almost as important, each crewman must be trained thoroughly in the use of the PLSS, and each PLSS must be tested to obtain calibration points for later use in metabolic-rate and expendables-status determinations.

Each PLSS, upon receipt at the Manned Spacecraft Center, undergoes an acceptance test that includes detailed visual examination and leakage, proof-pressure, and basic functional tests. The PLSS then undergoes a "canned man" test, which is an unmanned performance test in a vacuum chamber wherein all human metabolic products are simulated. Specifically, carbon dioxide, water vapor, and some metabolic heat are introduced into the oxygen vent subsystem while oxygen is removed. Also, metabolic heat is introduced into the liquid-transport subsystem. Rates of heat input, carbon dioxide and water-vapor generation, and oxygen removal are keyed to a metabolic-rate profile for the test. Having passed this test, the PLSS next undergoes a crew altitude-training test. This is a manned test performed in a vacuum chamber for the basic purpose of familiarizing the crewman with the operation, performance, and response of the PLSS (and OPS) under actual space-vacuum conditions. Controls actuation, PLSS and OPS operation, and warning tones are checked at this point. Then, the PLSS is acceptance tested both before and after shipment to Kennedy Space Center. Next, a spacecraft-interface test is performed in which the fit of the PLSS and OPS into their respective stowage locations in the flight LM is checked. In addition, recharge of the PLSS and communications checkout with the LM electrical systems are performed during this test.

Subsequent to successful completion of these tests, a final preinstallation acceptance test is conducted. After preflight charging, the PLSS and OPS are installed in the flight vehicle.

MISSION RESULTS

Mission data from the Apollo 9, 11, 12, and 14 missions were indicative that the PLSS meets or exceeds its system requirements. This conclusion is based on subjective comments from the crewmen and on telemetered data received during the missions. Extravehicular activity durations and the average metabolic rate calculated from telemetered data are given in table 4.1, which shows that the metabolic rate has been consistently lower than the 1200 Btu/hr design point. Hence, the question of whether metabolic rate would be lower or higher for tasks on the moon than for the same tasks on earth appears to be answered. As a result of the lower rates encountered on the Apollo 11 and 12 missions, it was possible to extend the EVA duration for the Apollo 14 mission beyond the 4-hr limit imposed previously.

Telemetry data for all missions indicate that a reserve of consumables existed in all cases. The amount of oxygen, feedwater, lithium hydroxide, and electric power remaining for each Apollo 11, 12, and 14 crewman at the end of each EVA are shown in tables 4.2 to 4.4.

Table 4.1 *Extravehicular activity times and metabolic rates.*

Mission	*Crewman*	*EVA time, min (a)*	*Average metabolic rate, Btu/hr (b)*
Apollo 11	Armstrong	168	777
Apollo 11	Aldrin	168	1118
Apollo 12	Conrad (EVA-1)	241	925
Apollo 12	Bean (EVA-1)	241	930
Apollo 12	Conrad (EVA-2)	235	840
Apollo 12	Bean (EVA-2)	235	950
Apollo 14	Shepard (EVA-1)	288	750
Apollo 14	Mitchell (EVA-1)	288	900
Apollo 14	Shepard (EVA-2)	275	900
Apollo 14	Mitchell (EVA-2)	275	1050

(a) The official EVA times listed here begin with LM cabin pressure at 3.5 psia during depressurization and end with LM cabin pressure at 3.5 psia during repressurization. The EVA time interval used in the Apollo 12 EVA-1 Conrad sample calculations (tables 4.5, 4.7, and 4.9) is based on PLSS expendables usage, and thus is slightly less than the EVA time listed here.

(b) Average of metabolic rates calculated by the thermal-balance, feedwater-consumption, and oxygen-consumption methods (see text).

Table 4.2 *Extravehicular time remaining for indicated consumables – Apollo 11.*

Consumables	*Armstrong, hr*	*Aldrin, hr*
Oxygen	3.88	2.97
Feedwater	5.00	2.50
LiOH	2.34+	2.34+
Electric power	3.43	3.27

Table 4.3 *Extravehicular time remaining for indicated consumables – Apollo 12.*

Consumables	EVA-1		EVA-2	
	Conrad, hr	Bean, hr	Conrad, hr	Bean, hr
Oxygen	2.21	2.29	1.74	1.52
Feedwater	2.42	2.44	3.58	2.35
LiOH	2.06+	2.06+	2.19+	2.19+
Electric power	2.29	2.29	2.59	2.51

Table 4.4 *Extravehicular time remaining for indicated consumables – Apollo 14.*

Consumables	EVA-1		EVA-2	
	Shepard, hr	Mitchell, hr	Shepard, hr	Mitchell, hr
Oxygen	2.92	0.64	1.44	0.74
Feedwater	3.14	1.88	1.70	.96
LiOH	1.10+	1.10+	1.50+	1.50+
Electric power	.72	.43	1.38	1.20

Some typical PLSS telemetry data are shown in figures 4.3 to 4.9. These time plots are of liquid cooling garment (LCG) inlet temperature, liquid cooling garment temperature differential (LCG ΔT), oxygen pressure, feedwater pressure, sublimator-outlet gas temperature, suit pressure, battery current, battery voltage, and carbon dioxide partial pressure. All curves, except carbon dioxide partial pressure as a function of time, are for the Apollo 12 commander during the first EVA. No carbon dioxide data exist for missions before Apollo 14 because the PLSS for these misssions did not have carbon dioxide sensors.

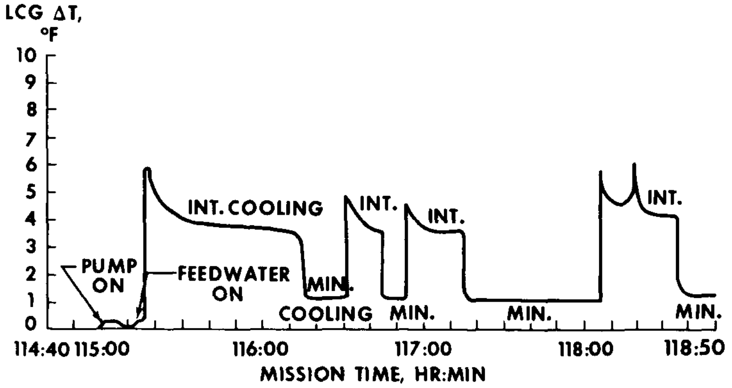

Figure 4.3 *Apollo 12 telemetry data on* H_2O *temperature differential for commander's LCG during first EVA.*

Switching from the minimum cooling to the intermediate cooling position of the diverter valve is indicated clearly by the step change in the delta temperatures (figs. 4.3 and 4.4). In some cases, the time interval between changes in diverter-valve position is too short to allow LCG inlet temperature to stabilize. Hence, some changes in valve position appear as spikes on the LCG inlet temperature curves of figure 4.4. Switch-on of the pump is shown by the sudden jump in LCG inlet temperature at mission time 115 hr 00 min.

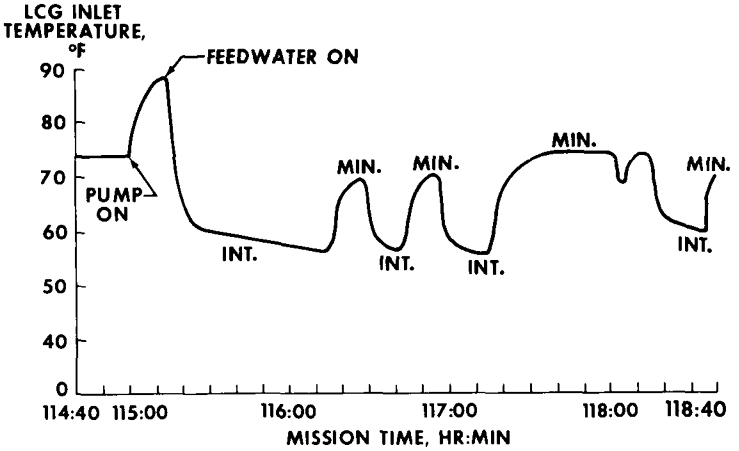

Figure 4.4 *Apollo 12 telemetry data on* H_2O *inlet temperature for commander's LCG during first EVA.*

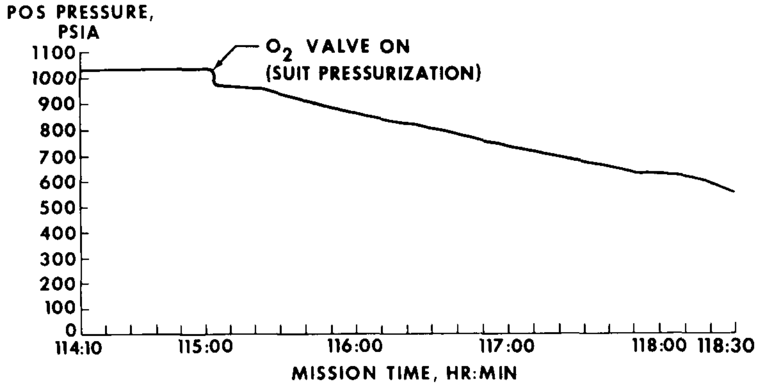

Figure 4.5 *Apollo 12 telemetry data on PLSS POS (*O_2 *supply bottle) for commander during first EVA.*

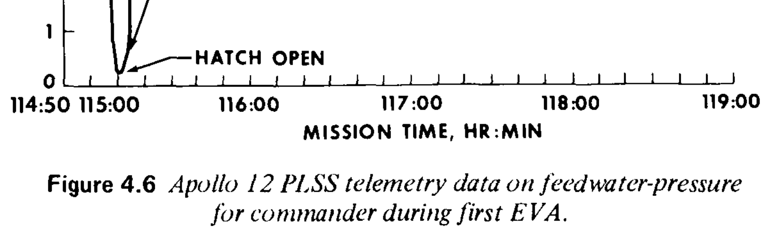

Figure 4.6 *Apollo 12 PLSS telemetry data on feedwater-pressure for commander during first EVA.*

The sudden dip in primary oxygen system (POS) pressure at 115 hr 02 min (fig. 4.5) occurred at the initiation of PLSS oxygen flow, and the dip represents the amount of oxygen needed to pressurize the commander's space suit. From that point on, steady pressure decay results from metabolic oxygen consumption and leakage from the suit.

The feedwater pressure curve of figure 4.6 is indicative of LM cabin pressure up to time 115 hr 10 min, because the empty sublimator is exposed to cabin ambient conditions. Feedwater pressure holds steady at 4.5 psia until cabin depressurization, at which time it drops off sharply, indicating the falling cabin pressure. When the feedwater valve is opened, the pressure rises to within its design range of 2.7 to 3.3 psia, where it remains for the duration of the EVA. If the EVA had been run to the point of feedwater depletion or if sublimator breakthrough had occurred, these conditions would have been indicated by falling feedwater pressure (and actuation of the low feedwater warning tone and flag).

Sublimator-outlet gas temperature (fig. 4.7) climbs steadily after fan switch-on because of the body heat of the crewman. This increase continues until the cabin is depressurized fully (hatch open) and the feedwater is turned on (to begin sublimator cooling). Then, the temperature drops off to about 44° F and remains steady for the duration of EVA. Suit pressure (fig. 4.7) increases suddenly to 3.9 psid as the oxygen valve is opened, then climbs to 5.0 psid as cabin depressurization proceeds. This increase reflects a decrease in cabin pressure rather than an increase in suit total pressure. Suit pressure decreases to 3.9 psid because of metabolic oxygen consumption and remains steady at that value.

After switch-on of fan and pump, the PLSS battery current and voltage (fig. 4.8) remain steady for the duration of EVA. Fan and pump switch-on show up as transients in the voltage curve and as step changes in the current curve. Telemetry data of carbon dioxide partial pressure for the commander during EVA-2 of the Apollo 14 mission are shown in figure 4.9. Specification requirements also are plotted on the same curve. It can be seen that the carbon dioxide removal capability of the PLSS is well within the requirements. Although Apollo 14 is the only mission to date for which carbon dioxide telemetry data are available, the performance shown in figure 4.9 is typical of test data. Because the most valuable information derived from PLSS data is the crewman metabolic rate, the procedures used for this derivation are discussed in detail. Determination of actual crewman metabolic rates during lunar mission enables mission planners to predict metabolic rates for future missions with good accuracy and is useful for understanding crewman limitations and equipment limitations in the planning of lunar excursions.

Metabolic rate is determined from telemetry data by use of four different methods: thermal balance, oxygen consumption, feedwater usage, and heart rate. These methods, with the

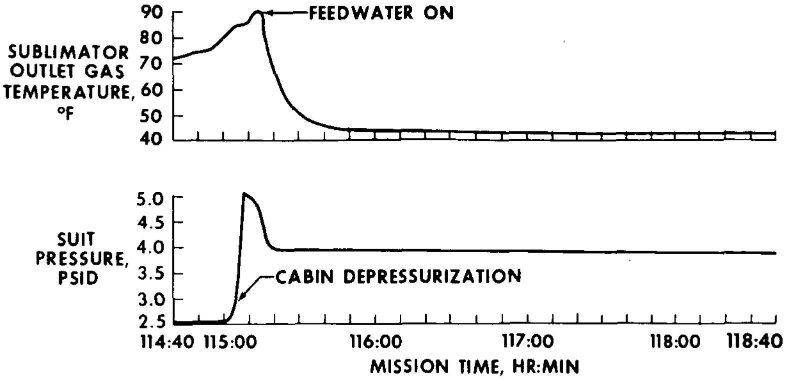

Figure 4.7 *Apollo 12 telemetry data on sublimator-outlet gas temperature and suit pressure for commander during first EVA.*

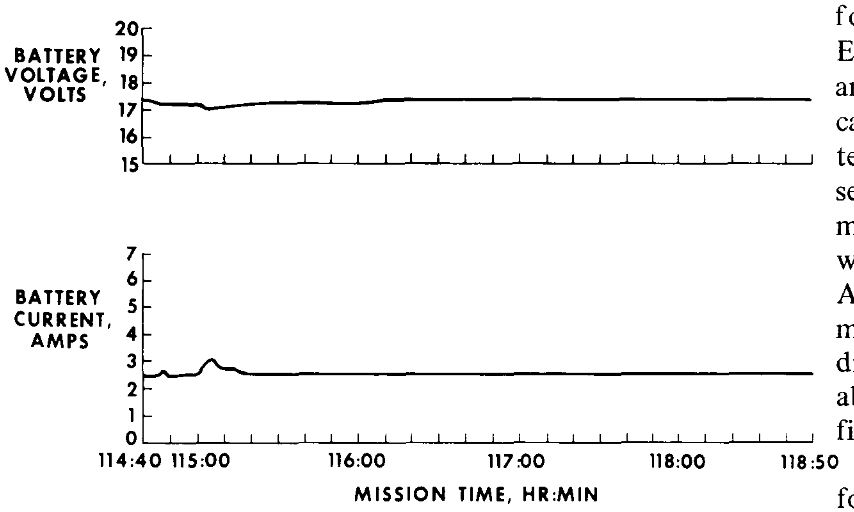

Figure 4.8 *Apollo 12 PLSS telemetry data on battery voltage and current for commander during first EVA.*

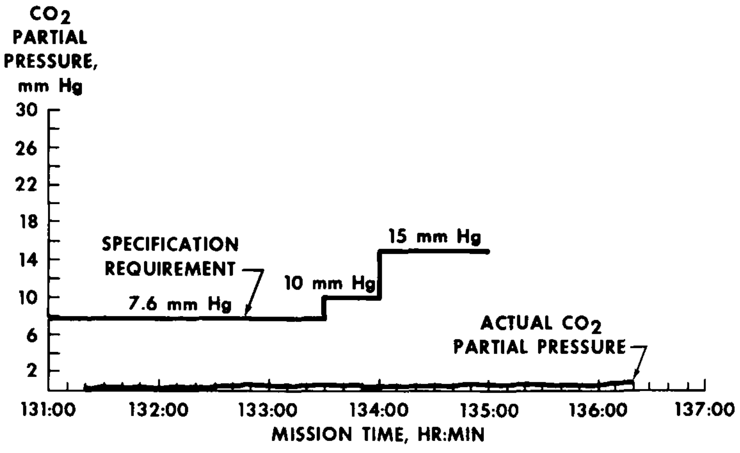

Figure 4.9 *Apollo 14 PLSS telemetry data on CO_2 partial pressure for commander during second EVA.*

exception of heart rate, are explained below; sample calculations are included and a discussion of the errors and uncertainties associated with each is presented. The sample calculations shown are also for the Apollo 12 commander on EVA-1.

Thermal-Balance Method

The thermal-balance method involves calculation of the total heat removed by the liquid-transport loop and the latent heat removed by the oxygen-ventilation loop. This total is equated to the sum of metabolic heat, heat leakage into the suit, and heat stored by the crewman. The sensible heat removed by the ventilation loop is considered to be negligible and is disregarded.

The basic equations (fig. 4.10) are

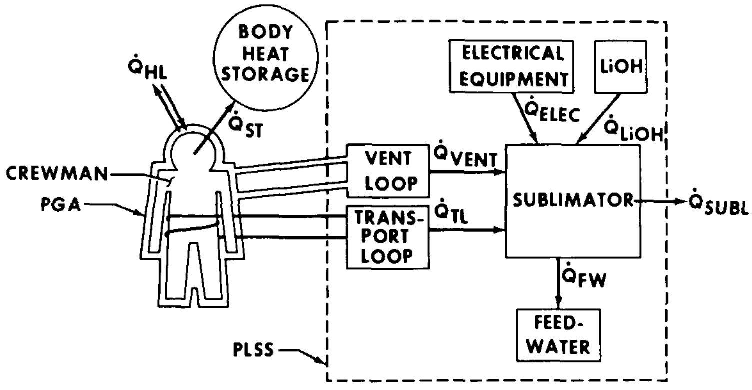

Figure 4.10 *Heat-balance diagram.*

$$\dot{Q}_{TL} + \dot{Q}_{VENT} = \dot{Q}_{MET} + \dot{Q}_{HL} - \dot{Q}_{ST}$$

$$\dot{Q}_{TL} = \dot{m}_{TL}\, C\, \Delta T$$

$$\dot{Q}_{VENT} = \dot{m}_{O_2}\, \Delta h$$

where

$\dot{Q}$	heat transfer, storage, or generation, Btu/hr
$\dot{m}$	mass flow rate, lb/hr
C	specific heat, Btu/lb-°F
ΔT	delta temperature across LCG, °F
Δh	delta enthalpy, Btu/lb

subscripts are defined

TL	transport loop
VENT	ventilation loop
MET	metabolic
HL	heat leak
O_2	dry oxygen
ST	stored

Liquid cooling garment ΔT values are taken directly from telemetry. Transport-loop flow rates are found from preflight test data by using pump-pressure rise compared with flow-rate curves

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and LCG pressure drop compared with flow-rate curves for the various diverter-valve positions. Flow rates thus obtained are corrected for flow variations resulting from changes in LCG inlet temperatures by using experimentally determined correction factors.

Latent heat removal by the ventilation flow is calculated by multiplying the enthalpy change of the ventilating gas by the actual flow rate of dry oxygen. The enthalpy can be determined from psychrometric charts for oxygen at suit pressure if the inlet and outlet dewpoints are known. The PLSS outlet dewpoint is equal to sublimator-outlet gas temperature. The PLSS inlet dewpoints are assumed based on preflight manned-test data. Then, ventilation-loop flow rate is determined by using fan-pressure rise compared with flow curves and suit-pressure drop compared with flow curves. Dry oxygen flow rate is found by subtracting water-vapor flow rate from ventilation flow rate.

The sample calculations of table 4.5 are indicative of a metabolic rate ranging from 915 to 1060 Btu/hr for the Apollo 12 commander during EVA-1. This method has the disadvantages of having to assume PLSS inlet dewpoint and of having several other error sources, among which are uncertainties in determination of the transport and ventilation flows, LCG ΔT, and heat leak. Error sources and their effects are tabulated in table 4.6.

Table 4.5 *Sample calculations for the thermal-balance method.*

With reference to figure 4.10.

$$\dot{Q}_{MET} = \frac{Q_{TL} + Q_{VENT} - Q_{HL} + Q_{ST}}{t}$$

$$Q_{TL} = \dot{m}_{TL} C \, \Delta T(t)$$

$$Q_{VENT} = \dot{m}_{O_2} C \, \Delta h(t)$$

where

Q	heat transferred, stored, or generated, Btu/hr	ΔT	delta temperature across LCG, °F
t	EVA time, hr	C	specific heat, Btu/lb–°F
$\dot{m}$	mass flow rate, lb/hr	Δh	delta enthalpy, Btu/lb

Subscripts are defined

MET	metabolic	HL	heat leak
TL	transport loop	ST	stored
$VENT$	ventilation loop	O_2	dry oxygen

$Q_{HL} = 0$; $Q_{ST} = 0$ for Conrad's first EVA

(EVA time for this and other sample calculations is defined as the interval from PLSS regulator takeover to cabin repressurization.)

$$t = 3.85$$

$$\dot{Q}_{MET} = \frac{Q_{TL} + Q_{VENT}}{3.85} = \frac{Q_{TL}}{3.85} + \dot{Q}_{VENT}$$

Table 4.5 *Sample calculations for the thermal-balance method.(Continued)*

(1) Transport loop

Duration, hr	*LCG ΔT °F*	*Flow rate, lb/min*
2.30	3.8	[a] 240
1.55	1.2	[a] 273
3.85 (total)		

[a] Based on preflight PLSS pump test data corrected for the effects of varying LCG inlet temperature.

$$Q_1 = (240)\,(1.0)\,(3.8)\,(2.30) = 2208.5 \text{ Btu}$$

$$Q_2 = (273)\,(1.0)\,(1.2)\,(1.55) = 507.8 \text{ Btu}$$

$$Q_{TL} = Q_1 + Q_2 = 2710.3 \text{ Btu}$$

$$\dot{Q}_{TL} = \frac{Q_{TL}}{3.85} = 704 \text{ Btu/hr}$$

(2) O_2 ventilation loop

$$Q_{VENT} = \dot{m}_{O_2}\,\Delta h\; t$$

From test data, m_m = 7.695 lb/hr (flow rate of oxygen/water-vapor mixture in veltilation loop) PLSS outlet dewpoint = 42° F (from telemetry data, fig. 4.7); at this dewpoint, absolute humidity w is

$$w = 0.022 \text{ lb } H_2O \text{ vapor/lb dry } O_2$$

Because $m_m = m_{O_2} + m_v$ (where m_v is mass flow rate of water vapor)

$$\dot{m}_v = 0.022\,\dot{m}_{O_2}$$

$$\dot{m}_m = \dot{m}_{O_2} + 0.022\,\dot{m}_{O_2}$$

$$\dot{m}_{O_2} = \frac{\dot{m}_m}{1.022} = 7.500$$

$\dot{Q}_{VENT}$ is found from various PLSS inlet dewpoints (assumed) and $\dot{Q}_{MET}$ is found by summing $\dot{Q}_{VENT}$ and $\dot{Q}_{TL}$

$$\dot{Q}_{VENT} = \dot{m}_{O_2}\Delta h$$

Table 4.5 *Sample calculations for the thermal-balance method. (Concluded)*

The enthalpy change Δh across the sublimator is per pound of dry oxygen flow and is found from psychrometric charts fro oxygen at suit pressure

PLSS inlet dewpoint, °F	Δh, Btu/hr	$\dot{Q}_{VENT}$, Btu/hr	$\dot{Q}_{TL}$, Btu/hr	$\dot{Q}_{MET}$, Btu/hr
68	47.5	356.3	704.0	1060.3
64	37.1	278.3	704.0	982.3
60	28.1	210.7	704.0	914.7

The tabulation above shows values of Q_{VENT} and corresponding values of Q_{MET} for various values of PLSS inlet dewpoint. As there is no instrumentation in the PLSS that provides an indication of actual PLSS dewpoint versus time, it is necessary to assume a range of dewpoints and calculate a range of metabolic rates. Dewpoints shown above were estimated based on results of extensive manned testing on earth.

Table 4.6 *Possible errors for the thermal-balance method.*

Parameter	*Variation*	*Error, Btu/hr*
Heat storage	100 Btu	25
Transport loop flow	0.1 lb/min	6
LCG ΔT	0.1°F	25
Ventilation flow	0.1 lb/hr	4
Dewpoint	1°F	20

Feedwater-Consumption Method

The amount of feedwater sublimated to space vacuum is a measure of the total heat load on the PLSS during EVA. This heat load consists of crewman metabolic-heat generation, heat generated by electrical equipment, heat generated by the reaction of carbon dioxide with lithium hydroxide in the lithium hydroxide canister, heat leak into the suit, crewman heat storage just before EVA, and heat storage in the feedwater (i.e., temperature difference between feedwater at start of EVA and 32° F at which sublimation occurs). Feedwater remaining in the PLSS at the end of the EVA is drained and weighed. This weight, plus an allowance for water remaining in the PLSS, is subtracted from the total weight of water with which the PLSS is charged before EVA. The difference is the weight of feedwater sublimated into space. The water usage is multiplied by the heat of conversion (from liquid to solid to vapor at 32° F) of water to obtain the total heat removed. To obtain metabolic rate, factors are included to account for heat storage in the feedwater, electrical heat load, and heat load caused by reaction of carbon dioxide with lithium hydroxide. The overall equation is

$$\dot{Q}_{MET} = \frac{m_{FW}\left[h_c - C\left(T_{FW} - 32\right)\right] - Q_{ELEC}}{1.276t}$$

where

Q_{MET}	metabolic rate, Btu/hr
m_{FW}	mass feedwater sublimated, lb
h_C	heat of conversion, Btu/lb
T_{FW}	feedwater temperature at start of EVA, °F
Q_{ELEC}	electrical heat load, Btu
t	EVA time, hr
C	specific heat of water, Btu/lb–°F

This equation is derived and a sample calculation is performed (table 4.7). For the Apollo 12 commander's first EVA, this method yields a metabolic rate of 894.4 Btu/hr. As with the thermal-balance method, this procedure does not take into account crewman heat storage. Other sources of error are scale reading (during weighing of feedwater on lunar surface) and amount of residual feedwater remaining in the sublimator porous plate after the EVA. These possible errors and their effect are summarized in table 4.8.

Table 4.7 *Sample calculation for the feedwater-consumption method.*

Heat balance (see figure 4.10)

$$\dot{Q}_{MET} + Q_{\mathrm{LiOH}} + \frac{Q_{ELEC}}{t} + \frac{Q_{FW}}{t} + \dot{Q}_{HL} - \frac{Q_{ST}}{t} = \frac{m_{FW}\,h_c}{t}$$

where

$\dot{Q}_{ST}$	heat storage, Btu = 0
$\dot{Q}_{MET}$	metabolic rate Btu/hr
$\dot{Q}_{\mathrm{LiOH}}$	heat generation rate of LiOH/CO_2 reaction, Btu/hr
Q_{ELEC}	electrical heat load, Btu
Q_{FW}	heat load of PLSS required to reduce feedwater temperature to 32° F, Btu
$\dot{Q}_{HL}$	heat leak, Btu/hr
t	EVA duration, hr
m_{FW}	mass of feedwater sublimated, lb
h_c	heat of conversion, Btu/hr

Table 4.7 *Sample calculation for the feedwater-consumption method. (Continued)*

From test data

$$\dot{Q}_{\mathrm{LiOH}} = 0.276\ \dot{Q}_{MET}$$

$$Q_{ELEC} = 545\ \text{Btu, from test data}$$

$$Q_{FW} = m_{FW}C_P\left(T_{FW} - 32\right);\ C_P = 1.0\ \text{Btu/lb-° F}$$

$$T_{FW} = T_{cabin}\quad \text{(assumed)}$$

$$T_{cabin} = 68\text{° F}$$

$$Q_{FW} = m_{FW}(68 - 32) = 36m_{FW}$$

$$t = 3.85\ \text{hr}$$

$$Q_{HL} = 0$$

$$\dot{Q}_{MET} = \frac{m_{FW}\left[h_c - C_P\left(T_{FW} - 32\right)\right] - Q_{ELEC}}{1.276t}$$

Feedwater collected	2.98 lb (earth weight)
Residual feedwater	0.83 lb (after collection)
Total unsublimated feedwater	3.81 lb

Initial feedwater charge	8.56 lb
	3.81 lb
Feedwater sublimated	4.75 lb

Table 4.7 *Sample calculation for the feedwater-consumption method. (Concluded)*

$$h_c = h\,(\text{liquid to ice}) + h\,(\text{ice to solid})$$

$$h_c = 143.3 + 1219.1 = 1075.8 \text{ Btu/lb}$$

From reference 1

$$\dot{Q}_{MET} = \frac{(4.75)\,(1075.8 - 36.0) - 545}{1.276\,(3.85)}$$

$$\dot{Q}_{MET} = 894.4 \text{ Btu/hr}$$

Table 4.8 *Possible errors for the feedwater-consumption method.*

Parameter	*Variation*	*Error, Btu/hr*
Scale reading	0 to 0.6 lb H_2O remaining in sublimator	0 to 130
Heat leak	±100 Btu/hr	±75
Heat storage	0 to 100 Btu	0 to 25

Oxygen-Consumption Method

Primarily, oxygen consumption is a function of metabolic rate only. Hence, this method is the most direct measure of metabolic rate available from PLSS telemetry data. The relationship between oxygen consumption and metabolic rate has been known quantitatively for many years (ref. 2). The basic equation is

$$Q_{MET} = \frac{m_{O_2}}{0.0001708 - \left[\left(\frac{RQ - 0.707}{0.293}\right) 0.0000123\right]}$$

where

Q_{MET} metabolic load, Btu

m_{O_2} mass of oxygen consumed, lb

RQ respiratory quotient, defined as the ratio of volume of carbon dioxide produced to the volume of oxygen consumed.

The mass of oxygen supplied by the PLSS is calculated from the pressure decay of the bottle (telemetered data) using compressibility factors to account for the deviation of the oxygen from the ideal-gas law. The mass of oxygen consumed is found by subtracting suit leakage from the mass of oxygen supplied by the PLSS. The respiratory quotient is assumed based on ground-test data.

A sample calculation is shown in table 4.9 where a metabolic rate for the Apollo 12 commander's first EVA is 846 Btu/hr. Error sources for this method are determination of suit leakage, error in POS pressure reading, and assumption of respiratory quotient (table 4.10). Suit leakage of 0.0044 lb/hr of oxygen during the EVA was based on preflight data. Postflight leakage tests on the suit were indicative of a leakage of 0.0169 lb/hr. This value was used in calculating the metabolic rate for EVA-2.

Table 4.9 *Sample calculation for the oxygen-consumption method.*

$$Q_{MET} = \frac{m_{O_2}}{0.0001708 - \left[\left(\frac{RQ - 0.707}{0.293}\right) 0.0000123\right]}$$

where

Q_{MET} metabolic load, Btu

m_{O_2} mass of oxygen consumed, lb

RQ respiratory quotient (dimensionless) = volume of CO_2 produced divided by volume of O_2 consumed

but

$$m_{O_2} = m_{POS} - m_{LEAK}$$

where

m_{POS} mass of oxygen supplied by POS bottle

m_{LEAK} mass of oxygen leaked overboard.

Hence

$$Q_{MET} = \frac{m_{POS} - m_{LEAK}}{0.0001708 - \left[\left(\frac{RQ - 0.707}{0.293}\right) 0.0000123\right]}$$

Table 4.9 *Sample calculation for the oxygen-consumption method. (Continued).*

First, calculate m_{POS}

$$m_{POS} = m_i - m_f$$

where subscripts i and f refer to initial and final conditions, respectively.

$$m_i = \frac{P_i V}{Z_i R T}$$

Z_i = compressibility factor = 0.974

P_i = 960 psia; T = 530° R

V = 378 in.^{3}; R = 48.28 ft lb/lb-° R

$$m_i = \frac{(960)\ (144)\ (378)}{(0.974)\ (48.28)\ (5.30)\ (1728)} = 1.21 \text{ lb}$$

$$m_f = \frac{P_i V}{Z_f R T}$$

Z_f = 0.987

P_f = 475 psia; T_f = 530° R

V = 378 in.^{3}; R = 48.28 ft lb/lb-° R

$$m_f = \frac{(475)\ (144)\ (378)}{(0.987)\ (48128)\ (530)\ (1728)} = 0.582 \text{ lb}$$

and

$$m_{POS} = 1.210 - 0.582 = 0.622 \text{ lb}$$

From preflight test data m_{LEAK} = 0.017

Table 4.9 *Sample calculation for the oxygen-consumption method. (Concluded)*

Based on manned test experience and analysis, $RQ = 0.85$ and

$$Q_{MET} = \frac{0.622 - 0.017}{0.0001708 - \left[\left(\frac{0.85 - 0.707}{0.293}\right) 0.0000123\right]}$$

$$Q_{MET} = 3670 \text{ Btu}$$

$$\dot{Q}_{MET} = \frac{3670 \text{ Btu}}{3.85 \text{ hr}} = 953 \text{ Btu/hr (average)}$$

Table 4.10 *Possible errors for the oxygen-consumption method.*

Parameter	*Variation*	*Error, Btu/hr*
PGA leakage	1 cc/min	1
RQ change	0.01	2
Cr pressure	1 psi	2

Heart-rate Method

The heart-rate method is the least accurate of the methods used, and, for that reason, it is not included in the average metabolic-rate tabulation of table 4.1. However, it does offer the advantage of a real-time update of approximate metabolic rate during the mission. It also allows the estimation of metabolic rates for specific tasks on the lunar surface that have durations too short to be determined by other methods. It may be used as a backup method in the event of a data loss that prevents the use of one of the other methods.

Primarily, the heart-rate method involves preflight calibration curves (heart rate as a function of work rate) generated for the crewman in question; these data are compared with telemetered heart-rate data received on the mission. Because physiological parameters are involved (which require interpretation by medically trained personnel), the details of this method will not be discussed in this paper.

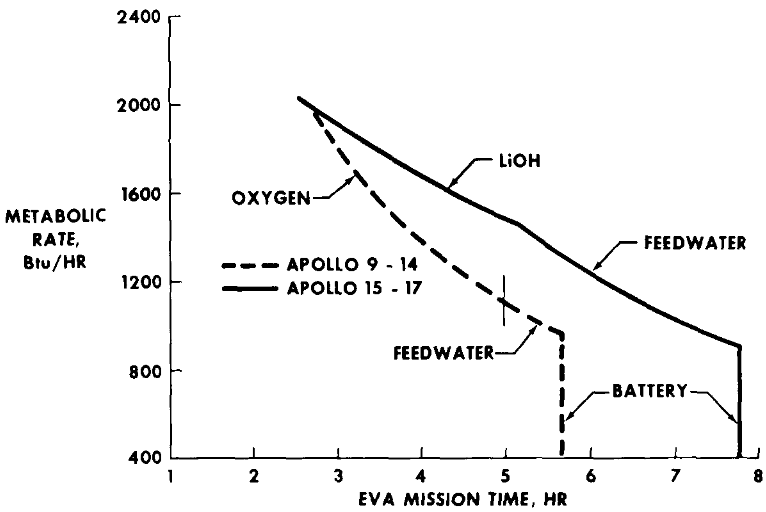

Figure 4.11 *Apollo 9 to 14 missions compared with Apollo 15 to 17 missions with respect to PLSS-limiting expandables.*

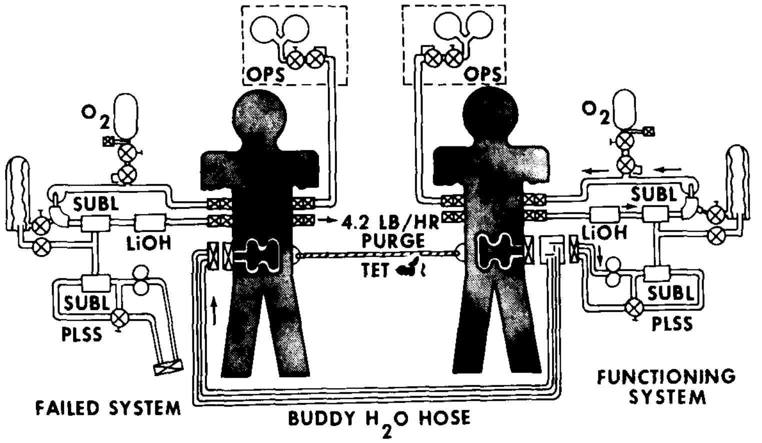

Figure 4.12 *The BSLSS/EMU schematic.*

FUTURE MISSIONS

Requirements for more and longer EVAs on Apollo missions have necessitated several design changes to the PLSS. Among these changes are a higher pressure oxygen bottle, an auxiliary feedwater tank, a lithium hydroxide canister that has increased capacity, and a larger battery. These changes have increased the PLSS performance to the levels shown in figure 4.11. Because of the increased EVA duration and the use of the lunar-roving vehicle, the range of lunar exploration has increased significantly. This capability has required increased emergency return capability in the event of a failure of one of the PLSSs. On the early Apollo missions, the OPS functioned as a backup system in the event of a PLSS failure. The OPS provided a 0.5-hr flow of oxygen that was dumped overboard through a purge valve in the suit. This purge flow provided breathing oxygen, carbon dioxide removal, and some cooling. For later Apollo missions, the buddy secondary life support system (BSLSS), (fig. 4.12), supplements the OPS. The BSLSS consists of two water hoses with a PLSS water connector at one end and a water-flow-dividing connector on the other. In the event of a failure of one PLSS, the flow-divider connector is connected to the suit water connector of the crewman with the working PLSS. The connector at the other end of the BSLSS hoses is attached to the suit-water connector of the crewman that has the failed PLSS. The water connector of the operating PLSS is installed in the BSLSS water-divider connector. Thus, both crewmen share the cooling capability of the operating PLSS. The crewman with the failed PLSS receives oxygen for breathing and has carbon dioxide removed by his OPS. For use with the BSLSS where gas cooling from the OPS is not required, the crewmen have two-position purge valves, allowing them to select two purge flow rates. During this operation, the purge valve would be set in the low-flow position for which the OPS would provide a 1.25-hr supply of oxygen.

Although EVA durations will increase, the telemetry data transmitted during the mission will be the same. Hence, the PLSS on future missions will continue to provide both complete environmental control for the crewman and vital PLSS performance data that can be used to determine crewmember metabolic rates for scientific purposes.

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