# Energy Expenditure During Extravehicular Activity Through Apollo

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**Monitoring crew health during manned space missions has always been an important factor to ensure that the astronauts can complete the missions successfully and within safe physiological limits. The necessity of real-time metabolic rate monitoring during extravehicular activities (EVAs) came into question during the Gemini missions, when the energy expenditure required to complete EVA tasks exceeded the life support capabilities for cooling and humidity control and, as a result, crew members ended the EVAs fatigued and overworked. This paper discusses the importance of real-time monitoring of metabolic rate during EVAs, and provides a historical look at energy expenditure during EVAs through the Apollo Program.**

## Nomenclature

| | | |
|---|---|---|
| AMU | = | Astronaut Maneuvering Unit |
| bpm | = | beats per minute |
| Btu | = | British thermal units |
| CDR | = | Commander |
| CM | = | crew member |
| CMP | = | Command Module Pilot |
| ECG | = | electrocardiogram |
| EV | = | extravehicular |
| EVA | = | extravehicular activity |
| Kcal | = | kilocalories |
| kJ | = | kilojoules |
| LCG | = | liquid cooling garment |
| LCVG | = | liquid cooling and ventilation garment |
| L/min | = | liters per minute |
| LM | = | Lunar Module |
| LMP | = | Lunar Module Pilot |
| LRV | = | Lunar Roving Vehicle |

## I. Introduction

Monitoring crew health during manned space missions has always been an important factor. Monitoring metabolic rate during extravehicular activities (EVAs) became a consideration during the Gemini missions, when it was discovered that EVA tasks required higher energy expenditure than anticipated, and the life support capabilities for cooling and humidity control were exceeded, resulting in crew member (CM) fatigue.

Metabolic rate is a term used to quantify an energy rate or energy per unit time. When considering human energy, heat is the dominant expression, as heat is generated by the human body during all activities, including rest. Heat is expressed in units such as British thermal units (Btu), kilojoules (kJ), or kilocalories (kcal). The higher the exertion required to conduct an activity, the more heat produced and the more energy expended.

Human energy expenditure is typically calculated by measuring or estimating oxygen consumption, the amount of oxygen required to conduct an activity. Absolute oxygen consumption is expressed in units of liters per minute (L/min). Laboratories typically measure oxygen consumption via open-circuit spirometry in which the subject wears either a mouthpiece and nose clip or a tight-fitting mask, and the expired breath is sent to a data acquisition system

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that measures the expired percentage of oxygen and carbon dioxide.[1] Heat generated by the human body can then be related to oxygen consumption, as 5 kcal (20.9 kJ, 19.8 Btu) is the approximate caloric equivalent of producing 1 liter of carbon dioxide. Stated differently, approximately 5 kcal of energy must be liberated to consume 1 liter of oxygen.[2]

Measuring oxygen consumption via open-circuit spirometry is a widely accepted and researched method to relate oxygen consumption to energy expenditure, yet it requires expensive, complex equipment and well-trained individuals to interpret the data; therefore, this method is not ideal for situations outside of the laboratory. In the case of EVAs that last several hours and rely on closed-loop life support systems, this type of measurement is not practical.

Determining metabolic rate real-time during an EVA has proven to be a challenge. Throughout human space flight, heart rate has been a measurement used to monitor crew health and physical exertion. As the energy required to conduct an activity increases, the heart rate increases to pump blood to the body tissues. Extensive research has been conducted to correlate heart rate to metabolic rate; however, heart rate is also affected by psychogenic factors, age, gender, body composition, and environmental influences such as temperature and gravity, thus these influences must be considered when using heart rate alone as a determinant of metabolic rate.[3] Currently, pressure decay of the oxygen supply is used to estimate CM metabolic rate; however, as pressure decay also results from space suit leakage, only estimations of metabolic rate can be made. It is understood that these estimates could have large amounts of error. Measurement of inlet and outlet water temperature for the liquid cooling and ventilation garment (LCVG) has also been used. As with an assumed flow rate, this method is similar to direct calorimetry methods to determine heat gained or lost in a system; however, this method is also considered to be unreliable when used alone to estimate metabolic rate. This paper takes a historical look at the EVAs throughout the U.S. manned missions of Mercury through Apollo, and provides details on the various methods used to monitor crew energy expenditure and estimate metabolic rate during EVAs.

## II. Importance of Monitoring Metabolic Rate During Extravehicular Activity

Real-time monitoring of metabolic rate is important during EVA for CM medical safety, tracking life support system consumables, and planning EVA operations. From the medical perspective, such monitoring provides critical health information to the flight surgeon, indicating whether a CM is approaching maximum work rate acutely, during a short-term maximum effort that could lead to instantaneous physical injury, or chronically, by sustaining a high work load over a longer duration that could lead to fatigue and possible exhaustion. Metabolic rate is also directly related to usage of life support system consumables in a closed-loop environment such as the space suit. Higher metabolic rates result in faster use of oxygen and cooling water, and impose a greater demand on the carbon dioxide and humidity control systems; therefore, it is critical that real-time monitoring occur to ensure that these consumables are available for the duration of the planned EVA. Metabolic rate monitoring is also essential for planning EVA operations. EVA planners meticulously choreograph each EVA. These operations are practiced on Earth multiple times prior to flight to improve crew familiarity with procedures and operations. During EVA, planners are responsible for modifying EVA operations real-time in the event that work rates or durations to complete tasks exceed what was planned.

## III. Historical Look at Extravehicular Activity Through Apollo

### A. Mercury

Mercury was the first successful effort by the U.S. to send humans to space. The Mercury Program existed from 1959 to 1963[4] with the objectives to: “1) place a manned spacecraft in orbital flight around the earth, 2) investigate man's performance capabilities and his ability to function in the environment of space, and 3) recover the man and the spacecraft safely”.[5] NASA completed six manned missions, with durations ranging from 15 minutes, 28 seconds to 34 hours, 19 minutes, and 49 seconds.[6]

Astronauts did not conduct EVAs during the Mercury Program. The CM remained in the vehicle for the duration of the flight, and the CM wore the same suit for launch and reentry as during in-space flight. This suit design, shown in Fig. 1, was derived from the US Navy Mark IV pressure suit.[4]

**Figure 1. Mercury space suit.**

The Mercury Program provided insight into what biomedical information was necessary to monitor CM physical condition during space flight. Biomedical data were monitored from the time the CM entered the vehicle to prepare for launch until landing, primarily to enable the flight surgeon to monitor crew health to determine whether the CM was physiologically capable of continuing the mission. Body temperature was monitored for all manned flights using a rectal temperature thermistor, with the exception of Mercury-Atlantis 9, which used an oral temperature thermistor. Respiration rate and electrocardiogram (ECG) data were also monitored. Mercury-Atlantis 6 introduced blood pressure monitoring, and this was continued in subsequent missions. Voice transmissions were also used throughout the manned Mercury flights to further evaluate the pilot's physical and mental condition. In-flight photography and video were initially used for crew monitoring, but these were unsuccessful due to inadequate camera positioning and changing lighting conditions.[7,8,9,10,11]

### B. Gemini

Gemini was the second human space flight effort by the U.S. The Gemini Program existed from 1962 to 1966 with the objectives to: "1) subject man and equipment to space flight up to two weeks in duration, 2) to rendezvous and dock with orbiting vehicles and to maneuver the docked combination by using the target vehicle's propulsion system, and 3) to perfect methods of entering the atmosphere and landing at a preselected point on land".[12] (NASA eventually canceled landing on land as an objective.) The specific Gemini EVA objectives were to: "1) develop the capability for an EVA in free space, 2) use EVA to increase the basic capability of the Gemini spacecraft, and 3) develop operational techniques and evaluate advanced equipment in support of EVAs for future programs."[4] NASA completed 10 piloted missions with durations ranging from 4 hours, 52 minutes, and 31 seconds to 13 days, 18 hours, 35 minutes, and 1 seconds.[12]

Astronauts completed EVAs in microgravity, or "zero-G," during five of the Gemini missions[13] from June 3, 1965 – November 14, 1965, accumulating 12 hours and 25 minutes of EVA experience. EVA durations ranged from 36 minutes to 5 hours, 30 minutes. Table 1 summarizes a portion of the statistics for the Gemini EVAs provided by Kelly, Coons, and Carpentier.[3]

**Table 1. Summary of Gemini Extravehicular Activity Statistics**

| Gemini Mission | IV | IX-A | X | XI | XII |
|---|---|---|---|---|---|
| **Umbilical EVA (hr:min)** | 0:36 | 2:07 | 0:39 | 0:33 | 2:06 |
| **Standup (hr:min)** | - | - | 0:50 | 2:10 | 3:24 |
| **Total EVA (hr:min)** | 0:36 | 2:07 | 1:29 | 2:43 | 5:30 |

The CM wore the same suit for launch and reentry as during in-space flight and EVAs, and the CM wore the suit for the duration of the flight.[14] This suit was derived from a US Air Force AP/22 high altitude aircraft pressure suit, and was the first suit designed for both intra- and extravehicular activity. Figure 2 shows a picture of Ed White on the first U.S. EVA, wearing the Gemini suit.

**Figure 2. Gemini space suit.**

Metabolic rate data were not recorded during Gemini EVAs; however, heart rate and respiration rate data provided details on CM health and exertion. The following sections provide further details for each EVA.

*1. Gemini IV*

On June 3, 1965, Ed White became the first U.S. astronaut to perform an EVA. The umbilical EVA lasted 36 minutes; however, only 20 minutes were spent outside of the vehicle [4] During the EVA, real-time monitoring included the astronaut's ECG and respiration, as well as suit pressure and temperature. Figure 3 shows the heart rate and respiration rate monitored during the Gemini IV umbilical EVA.[3] The highest heart rate was observed at the end of the EVA when the CMs had difficulty closing the hatch. The elevated energy expenditure exceeded the gas cooling system capability, and the CM's visor fogged. It took several hours after repressurization of the vehicle for the CM to return to thermal equilibrium.[4]

The EVA was successful and proved that EVA was possible without causing disorientation or physiological issues; however, it was apparent that the life support system needed improvement to better meet the metabolic load. After completion and success of the mission and EVA on Gemini IV, it was determined that EVAs could be accomplished with minimal physiological impact, and only one lead of ECG and one impedance pneumogram were monitored during EVAs in following flights.[3]

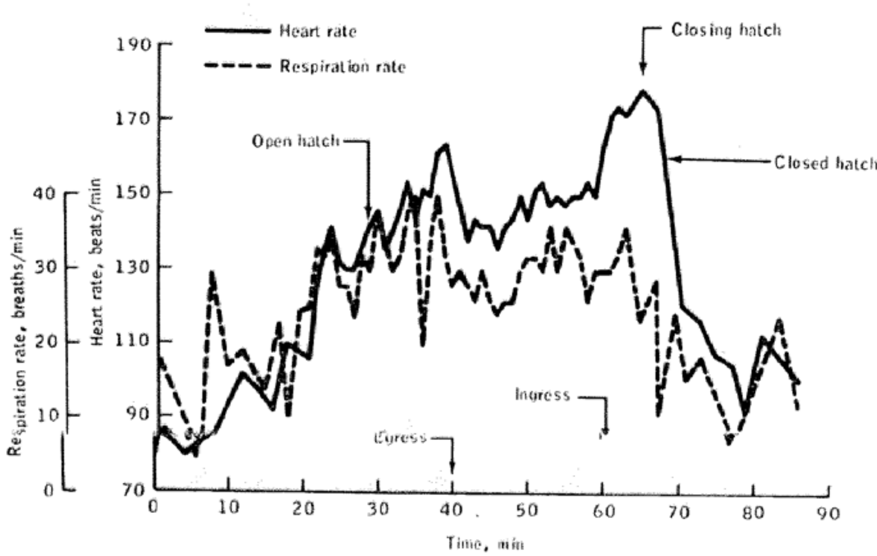


**Figure 3. Heart and respiration rates during Gemini IV umbilical extravehicular activity.**

*2. Gemini IX-A*

The planned EVA for Gemini VIII was not completed due to the early termination of the flight; therefore, the Gemini IX-A extravehicular (EV) CM attempted the Gemini VIII operations. During the EVA, the CM experienced a lot of difficulty maintaining body position, resulting in higher heart rates than anticipated. The CM was not able to activate the Astronaut Maneuvering Unit (AMU), a device to be used for movement during EVA and to provide independent life support to the suited astronaut. Due to the high exertion encountered during these activities, the CM's visor fogged, and the EVA was terminated early. Figure 4 shows the heart and respiration rates experienced during the Gemini IX-A umbilical EVA.[3]

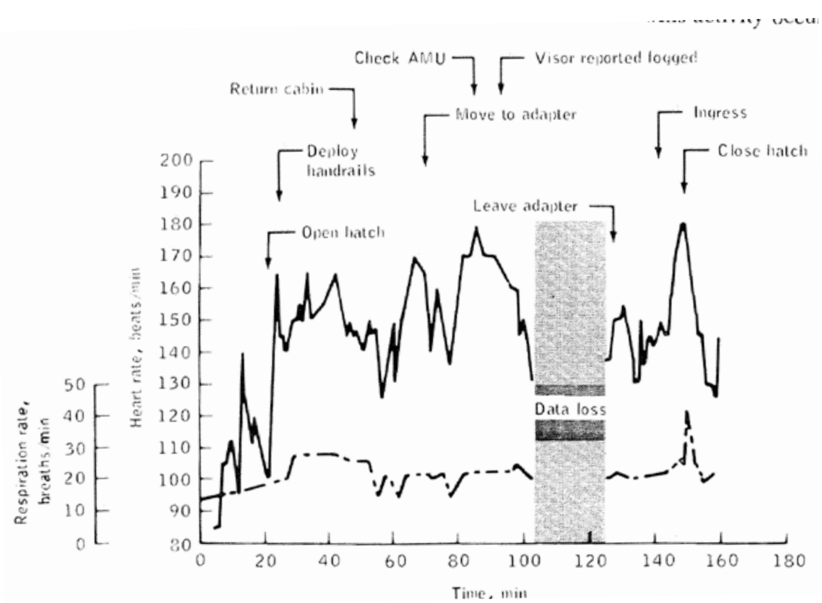


**Figure 4. Heart and respiration rates during Gemini IX-A umbilical extravehicular activity.**

*3. Gemini X*

Gemini X included two EVAs, one in which the CMs depressurized the vehicle and the EV CM stood up to take photographs ("standup"), and one in which the EV CM went outside of the vehicle on umbilical life support. Lessons learned from the Gemini IX-A experience resulted in the decision to simplify the umbilical EVA for Gemini X. The suit did not include an AMU and no procedures were planned on the adapter sections of the vehicle, which created high work rates on Gemini IX-A. Heart rate remained relatively low and consistent compared to previous EVAs; however, higher heart rates were once again encountered during hatch closure (similar to Gemini IV). Figure 5 shows the heart rate and respiration rates for the Gemini X umbilical EVA.[3]

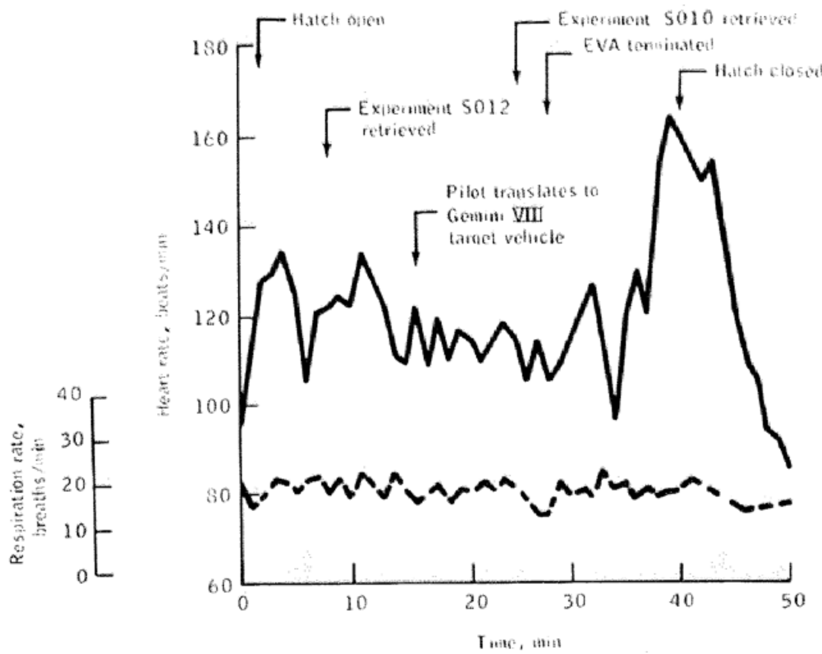


**Figure 5. Heart and respiration rates during Gemini X umbilical extravehicular activity.**

*4. Gemini XI*

Gemini XI included two EVAs. During the first EVA, the EV CM went outside of the vehicle on umbilical life support. The second EVA was a standup EVA. The umbilical EVA for Gemini XI was the most physically exhausting. The EV CM experienced difficulty during EVA preparation procedures connecting the life support system and attaching the EV visor, resulting in considerable energy expended during this time. The CM also experienced difficulty during EVA while moving around the spacecraft and maintaining body position. Excessive energy expenditure led to significant sweat production, to the point that sweat ran into the CM's eyes. The CM's physical exertion was excessive enough to overcome the life support system capabilities to the point that the CM possibly encountered high levels of carbon dioxide.[4] It was determined unsafe to continue the planned EVA, thus the EVA was terminated early. Figure 6 shows the heart rate and respiration rate data from the Gemini XI umbilical EVA.[3]

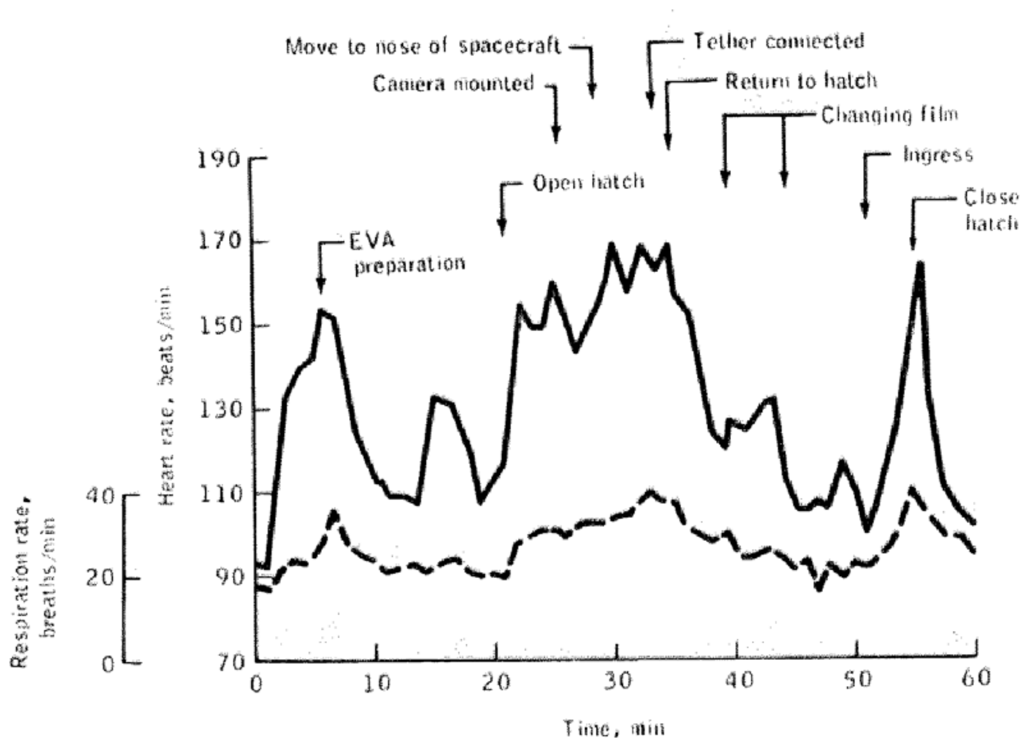


**Figure 6. Heart and respiration rates during Gemini XI umbilical extravehicular activity.**

*5. Gemini XII*

Gemini XII included three EVAs: two standup EVAs, and one in which the EV CM went outside of the vehicle on umbilical life support.

Lessons learned from Gemini XI indicated that the umbilical EVA experience was overly exhausting for the CM. It was hypothesized that excessive environmental thermal loads were imposed on the EV CM that could have contributed to the higher heart rates, but since environmental temperature was not measured, there were no data to prove this theory. The fact that there was no direct measurement of metabolic rate was called into question, and it was determined that instantaneous data were a necessity for future EVAs. Real-time heart rate monitoring was conducted as with other flights; however, heart rate was monitored much more closely during the Gemini XII umbilical EVA, and the CM was advised when the heart rate was sustained at or above 140 beats per minute (bpm). The Gemini XII umbilical EVA was also reevaluated to assess zero-g capability and restraints.[13] It was determined that the major factors that contributed to the excessive energy expenditure experienced during the Gemini XI umbilical EVA were "insufficient suit mobility, inadequate position restraints, and human engineering factors."[3] To limit and monitor energy expenditure during the Gemini XII umbilical EVA, design changes were made to the EVA equipment, planned operations were changed, and in-flight real-time monitoring during EVA became a requirement. In addition, extensive pre-flight training in the parabolic flight aircraft and underwater emphasized the importance of CM familiarity with tasks, and provided practice for the CM to "pace" himself to ensure that energy expenditure did not become excessive.

Figure 7 shows the heart rate data from the Gemini XII umbilical EVA. Overall heart rate was lower and more stable than in previous flights; however, there was one instance when the heart rate spiked above 140 bpm, noted on Fig. 7 as "Messages for Houston." Because this spike was encountered during a time in which the CM was communicating with mission control, it was determined that the spike was due to psychogenic factors rather than increased exertion.[3]

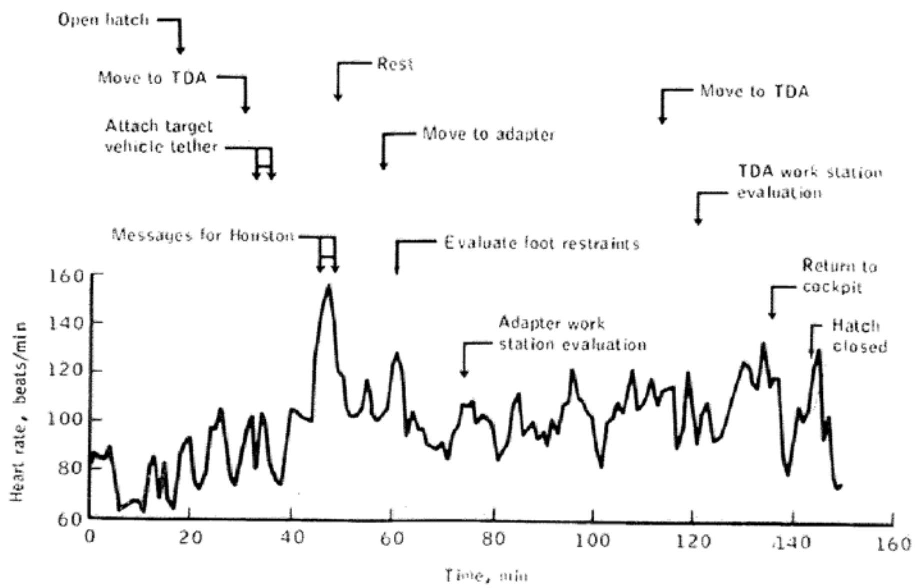


**Figure 7. Heart rates during Gemini XII umbilical extravehicular activity.**

*6. Gemini Lessons Learned*

The Gemini EVAs successfully met the stated objectives. As each mission and associated EVA provided a new round of test operations and challenges, subsequent missions relied heavily upon the lessons learned and experience gained from preceding flights. Overall observations from Gemini indicated that the CMs worked at higher work rates than expected during the umbilical EVAs. While metabolic rate was not measured, higher energy expenditure was evident from the heart rate and respiration rate data, and there was apparent overheating during EVAs on Gemini 4, 9, and 11,[13] in several instances surpassing the cooling capability provided by the gas cooling from the life support system.[3, 15] Real-time instantaneous monitoring of CM energy expenditure for flight controllers was deemed necessary, but definition of what data should be monitored needed to be reevaluated as post-flight analysis determined that it was dangerous to use heart rate as the single index of work performed due to the influence of psychogenic factors.[3]

**C. Apollo**

Apollo was the third human space flight program developed by the U.S. The Apollo Program was conceived on May 25, 1961, when President John F. Kennedy announced the U.S. goal to go to the moon by the end of the decade. The program existed through 1972.[4] The goals were as follows[16]:

- "Establishing the technology to meet other national interests in space.
- Achieving preeminence in space for the United States.
- Carrying out a program of scientific exploration of the Moon.
- Developing man's capability to work in the lunar environment"

Apollo completed 11 manned missions with six missions that landed on the surface of the moon (Apollo 11, 12, 14, 15, 16, and 17.[14] Mission durations ranged from 142.9 hours (5.95 days) to 301.8 hours (12.58 days).[14] EVAs were completed in zero-G during four of the Apollo missions. There were 14 lunar surface EVAs that ranged from 46 minutes to 7 hours, 37 minutes,[4] with an average duration of 5.8 hours..[17] Table 2 summarizes a few of the details for the lunar surface EVAs.[15]

**Table 2. Summary of Metabolic Expenditures for Apollo Lunar Surface Extravehicular Activity**

| Apollo Mission | EVA | Crewman[a] | Total for all activities | | EVA duration, hr |
|---|---|---|---|---|---|
| | | | kJ/hr | Btu/hr | |
| 11 | 1 | CDR | 949 | 900 | 2.43 |
| | | LMP | 1267 | 1200 | |
| 12 | 1 | CDR | 1028 | 975 | 3.9 |
| | | LMP | 1054 | 1000 | |
| | 2 | CDR | 922 | 875 | 3.78 |
| | | LMP | 1054 | 1000 | |
| 14 | 1 | CDR | 843 | 800 | 4.8 |
| | | LMP | 980 | 930 | |
| | 2 | CDR | 959 | 910 | 3.58 |
| | | LMP | 1054 | 1000 | |
| 15 | 1 | CDR | 1159 | 1100 | 6.53 |
| | | LMP | 1033 | 980 | |
| | 2 | CDR | 1054 | 1000 | 7.22 |
| | | LMP | 854 | 810 | |
| | 3 | CDR | 1086 | 1030 | 4.83 |
| | | LMP | 854 | 810 | |
| 16 | 1 | CDR | 917 | 870 | 7.18 |
| | | LMP | 1065 | 1010 | |
| | 2 | CDR | 822 | 780 | 7.38 |
| | | LMP | 874 | 830 | |
| | 3 | CDR | 854 | 810 | 5.67 |
| | | LMP | 864 | 820 | |
| 17 | 1 | CDR | 1150 | 1090 | 7.2 |
| | | LMP | 1139 | 1080 | |
| | 2 | CDR | 864 | 820 | 7.62 |
| | | LMP | 874 | 830 | |
| | 3 | CDR | 980 | 930 | 7.25 |
| | | LMP | 990 | 940 | |
| Mean | | | 980 | 930 | |
| Total time, hr | | | 158.76 | | |

[a]CDR = Commander; LMP = Lunar Module Pilot

The suit was designed for launch and reentry from both the Earth and the moon, microgravity EVA, and lunar surface EVA. The suit was not worn during transit from the Earth to the moon and back, rather in-flight coveralls were provided for crew comfort during this part of the mission. Figure 8 shows a picture of the Apollo lunar surface EVA suit.

**Figure 8. Apollo space suit.**

Real-time data available during lunar surface EVA included voice data, ECG, oxygen bottle pressure, liquid cooling garment (LCG) water inlet and outlet temperatures, and inlet temperature of the ventilation gas entering the space suit. Water usage was available after most of the EVAs to provide a measure of the total heat lost from the suit; however, this information was not provided during EVA.[13]

Three independent methods were used to estimate real-time metabolic rates during the lunar surface EVAs:

1) The relationship between heart rate (provided by the ECG signal) and metabolic rate, correlated with pre-flight bicycle ergometer tests
2) The relationship between consumption of oxygen from the life support system and metabolic rate, with a correction for assumed suit leakage rate
3) The relationship between the inlet and outlet water temperatures of the LCG, with an assumed flow rate. This provided a modified direct calometric approach for energy measurement.

As each of these methods was inaccurate on its own, these values were integrated real-time to estimate the metabolic rate of each CM.[13, 15] Post-EVA, the remaining feedwater was also used to determine the energy expended during the EVA.

*1. Items of Note During the Apollo Lunar Surface Extravehicular Activities*

Overall exertion was fairly moderate during the Apollo lunar surface EVAs (Table 3); however, there were a few instances when it was excessive, causing fatigue and elevated heart rates. During the second EVA of Apollo 14, the astronauts used a two-wheeled, two-legged rickshaw to travel to Cone Crater. After 2 hours and 10 minutes into the EVA, they were 50 minutes behind schedule due to difficulties identifying the crater location. The task was abandoned as the astronauts were seriously fatigued and had elevated heart rates (150 bpm for Alan Shepard and 128 bpm for Edgar Mitchell). Apollo 15 was the first mission to use the Lunar Roving Vehicle (LRV). Changes to the suit and life support systems allowed EVA time to extend from 4 to 5 hours to 7 to 8 hours without the need to recharge consumables. This was the first mission to include noted physiological difficulty, as flight doctors observed that the EVA CMs experienced irregular heartbeats while on the lunar surface, and this irregularity continued during transit back to Earth. The cause was uncertain, but potassium levels and workload could have had an effect. In addition, it was later determined that one of the CMs may have had a preexisting undetected coronary artery disease. Apollo 16 included an improved drill for deep core samples based on lessons learned from challenges experienced when drilling during Apollo 15. Additionally, work/rest schedules were improved. No irregular heartbeats were recorded, and the Apollo 16 crew did not experience any physiological issues.[14]

*2. Apollo Zero-G Extravehicular Activities*

Four zero-G EVAs were performed from the Command Module on Apollo 9, 15, 16, and 17, primarily to retrieve film canisters. During the zero-g EVA, one CM stood in the hatch and managed the umbilical, while the second CM went outside of the vehicle to retrieve the film canisters. Liquid cooling was not provided, and the gas cooling system could not sustain prolonged work rates greater than 1050 kJ/hr (995 Btu/hr); therefore, these EVAs were short duration, averaging 63 minutes. Heart rate data were the only data available to monitor exertion for these EVAs. Table 3 shows the average metabolic rate for each of the Apollo zero-G EVAs. The metabolic rates shown are considered maximum values because metabolic rate estimates derived from heart rate tended to provide higher values. Despite the cooling limitation, the CMs did not overheat, and voice communications indicated that operations were not physically challenging. The low metabolic rates were attributed to having good restraint systems, extensive training in the neutral buoyancy facility, and the short EVA duration.[13]

**Table 3. Summary of Metabolic Expenditures for Apollo Zero-G Extravehicular Activity**

| Mission # | Crewman | Metabolic Rate (kJ/hr) | Metabolic Rate (Btu/hr) | Duration (min) |
|---|---|---|---|---|
| **9** | LMP | 634 | 600.92 | 59 |
| **15** | CMP | < 992 | 940.24 | 40 |
| | LMP* | < 486 | 460.64 | 40 |
| **16** | CMP | <2108 | 1998.00 | 85 |
| | LMP* | ** | ** | 85 |
| **17** | CMP | <1267 | 1200.89 | 67 |
| | LMP* | <602 | 570.59 | 67 |
| **Total** | | | | 443 |

*Standup EVA
**Not measured
LMP = Lunar Module Pilot; CMP = Command Module Pilot

*3. Apollo Lessons Learned*

The Apollo lunar surface and zero-G EVAs were extremely successful. Similar to Gemini, data from each mission became the best indicators of energy expenditure required for subsequent missions. NASA learned about space suit and life support design requirements for use in both microgravity and on a reduced-gravity surface, conducting operations at a distance beyond low Earth orbit, and how humans respond physiologically to living and working in an extreme environment like that of the moon.

Based on lessons learned from the Gemini EVAs, pre-flight predictions anticipated high energy expenditure on the surface of the moon; however, the metabolic rates were lower than predicted.[13] Average metabolic rates ranged from 822 kJ/hr (780 Btu/hr) to 1267 kJ/hr (1200 Btu/hr),[15] with an overall average of 979.2 kJ/hr (928.1 Btu/hr).[18] The highest average metabolic rate (1267 kJ/hr, 1200 Btu/hr) during an EVA was experienced by the Lunar Module Pilot (LMP) on Apollo 11 during a locomotion evaluation for which he had to be very active. The LMP encountered the highest discrete metabolic rates during transport of the Apollo Lunar Surface Experiments Package pallet, Lunar Module (LM) ingress with lunar samples, and drilling and removal of drill bits. Overhead activities such as vehicle egress, offloading and setup of equipment around the LM, vehicle ingress, and stowage of the lunar samples required the highest energy consumption.[13]

The lowest observed metabolic rate (414 kJ/hr, 392.4 Btu/hr) occurred during LRV operations,[18] and is lower than that of riding in an automobile on Earth (~502 kJ/hr, ~392 Btu/hr).[2] The lower metabolic rates encountered during use of the LRV contributed to the success of the Apollo 15-17 missions, as the reduced metabolic rates led to reduced life support consumables usage, and less CM fatigue during these extended EVAs.[13] Low metabolic rates were also observed during photography and periods when the astronauts paused to observe and provide descriptions.

It is interesting to note that while the lunar surface EVA metabolic rate was lower than predicted, heart rates were higher than predicted. However, increased heart rates were also observed during rest periods, so it was anticipated that elevated heart rates were due to deconditioning during the 3-day translunar coast period of weightlessness.[15] This observation gave further weight to the argument that heart rate alone should not be a predictor of energy expenditure during EVAs.

## IV. Summary and Conclusions

The human body has evolved in Earth's atmosphere and gravity environment, and a large part of our exploration efforts beyond Earth include monitoring how the human body responds to the extreme environments encountered during space flight. Understanding how EVA activities affect CM energy expenditure is important, as this information provides details on crew health, determines the EVA duration as life support consumables are depleted, and affects EVA hardware design and operations planning.

Measuring metabolic rate on Earth via open-circuit spirometry is the current standard used in exercise physiology, but it is impractical during EVAs due to the equipment and data processing required. Various methods were used during the Mercury, Gemini, and Apollo Programs to monitor the physical condition of CMs and values for metabolic rate were estimated, but it is understood that these values likely contain error and can only be used as an indication of energy expenditure, not actual metabolic rate data. Further research of the metabolic rate monitoring methods and data during EVAs for the Apollo Skylab, Space Shuttle, and International Space Station Programs is essential to understand the full spectrum of information throughout EVA history. As space exploration moves toward new destinations, the necessity of assessing true CM metabolic rate real-time will continue to be evaluated, and if deemed necessary, life support systems must be altered to provide this level of data during EVAs.

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