The Skylab Metabolic Rate Experiments: How We Conducted the M-171 Biomedical Project

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During the Mercury, Gemini, and Apollo Programs, only limited measurements of astronaut physiological responses were possible. Medical measurements made during the early flights demonstrated that man could withstand the acceleration periods of launch and entry, and that he could begin adaptation to the microgravity environment while still performing necessary tasks.[4,6] Restricted internal volumes of the spacecraft and the operational complexities of those missions essentially precluded the conduct of in-depth measurements to gather in-flight data on physiological changes. In the earlier programs, the decisions to proceed with longer, more complex missions were largely based upon positive data from successive postflight medical evaluations. Extensive biomedical measurements had to await the advent of larger spacecraft with longer stay times in space. Skylab presented this opportunity.

Development of medical experiments for Skylab was based upon the important philosophical decision to structure the experimental program along classical lines of medical research. This resulted in grouping related studies together to understand their contribution to the response of major body systems during long duration microgravity exposure. Furthermore, this approach determined that investigators selected for the Skylab Program would be chosen from NASA's then current biomedical investigators. These individuals were already knowledgeable about human responses to spaceflight. They understood that highly integrated studies with appropriate hardware and procedures would be required to meet program objectives. This approach was important given the compressed schedule necessary to meet flight requirements as Skylab was being developed concurrently with the completion of the final Apollo missions.

Potential Skylab astronauts were informed before their selection that these were high priority biomedical research missions and they would be required to participate fully in the selected experiments. Any astronaut who did not want to accept this requirement would not be considered for selection. These operational studies were deemed critical to determining if humans could withstand extended duration spaceflight.

It should be noted that participation in NASA-supported in-flight biomedical investigations subsequent to Skylab was open to the general scientific community. Final selection of experiments was based upon scientific quality as judged by peer review panels, with consideration of NASA program priorities.

Dr. John Rummel (Co-Principal Investigator M-171) joined the Environmental Physiology Laboratory (EPL) in 1966. An early assignment by the M-171 Principal Investigator, Mr. Ed Michel, was to evaluate a proposed flight metabolic analyzer that was to be flown on the ill-fated Apollo 1 mission. Two proposed experiments were designated MO19 (metabolic rate) and MO20 (pulmonary function). Crew Systems Division (CSD) was responsible for hardware development. The hardware manufacturer was Melpar. Their proposed gas chromatograph would function only at the 5 psia oxygen cabin pressure for Apollo, which prohibited evaluation in the EPL. There was no validation of function or procedures for this unit prior to the delivery of a training unit scheduled for September 1966 as flight hardware fabrication had already begun. This established a bad precedent that would not be permitted for M-171. Repeated efforts by the manufacturer and CSD personnel failed to produce a functional unit. The Johnson Space Center Biomedical Research Office (BRO) finally recommended that the effort be dropped from further consideration.

Requirements for measuring metabolic rate in flight (MO50) were incorporated into planning for the Apollo Applications Program (AAP), which subsequently became the Skylab Program. During this period, fitness experiments were conducted at Harding College to compare treadmill vs. cycle ergometer exercisers for use in MO50. Cycle ergometry was ultimately selected as the preferred exercise device since the actual metabolic workload was easier to control and measure as compared with exercise on a treadmill, particularly in a weightless environment.

In December 1968 the designation for the MO50 experiment was changed to M-171. During this period CSD initiated the procurement of two prototype flight metabolic

This feature is coordinated and edited by Mark Campbell, M.D. It is not peer reviewed. The AsMA History and Archives Committee sponsors the Focus as a forum to introduce and discuss a variety of topics involving all aspects of aerospace medicine history. Please send your submissions and comments via email to: mcamp@1starnet.com.

DOI: https://doi.org/10.3357/amhp.6009.2022

analyzers. A third prototype was provided by the Marshall Spaceflight Center (MSFC):

1) Perkin-Elmer—This prototype unit combined a 14-L mechanical spirometer with discrete oxygen and carbon dioxide sensors. It was a large, complex device spread over a laboratory tabletop; it did not work well and would have been very difficult to reduce to reliable spaceflight equipment.
2) Beckman Instruments—This clever device employed a flow cell with 623 parallel tubes and a quadrupole mass spectrometer together with an early digital computer. Krypton and Xenon noble gases were injected into opposite ends of the flow cell to enable the calculation of inspired/expired volumes by dilution.[9]
3) MSFC developed a prototype system that used a compact Perkin-Elmer mass spectrometer for gas analysis and a modular analog computer together with inspiration and exhalation spirometers.

These three prototypes were evaluated in a similar manner by EPL personnel under guidance from Dr. Rummel. Results of these evaluations were presented to the Skylab Program Manager, Kenny Kleinknecht. While Dr. Rummel's recommendation was to select the Beckman Instruments concept, Mr. Kleinknecht decided to proceed with the MSFC design. Mr. Kleinknecht made a side comment that "MSFC successfully designed and built the Saturn V rocket; surely they can build a simple metabolic analyzer and its associated hardware."

Once the decision had been made that MFSC would develop the biomedical hardware for the Skylab M-171 experiment, a support team was appointed. Robert Schwinghammer was the lead and Olin K. Duren was designated as Project Manager, assisted by Cortes Perry.

NASA Johnson Space Center's activities were led by Dr. Rummel. Chuck Sawin was appointed to lead the hardware evaluation during its development at MSFC to assure sufficient accuracy to meet experiment requirements. Melvin Buderer integrated cardiac output determinations[1,2] with the rest of the experiment evaluations and served as a member of the test team during pre- and postflight activities.

A key aspect of verifying the accuracy of the metabolic analyzer was to compare its measurements with those from the Douglas bag/microscholander technique, which was the laboratory standard for such measurements. Douglas bag measurements were performed by EPL technicians Robert Heyer and Herman Sharma. John Lem was appointed the lead engineer for all aspects of the M-171 hardware development.

Monitoring hardware development required frequent travel to MSFC. The Manned Spacecraft Center used a NASA Lockheed Electra propjet for roundtrips to MSFC most weekdays during the key development period. Typically, it was possible to leave Ellington Field early in the morning, fly to the Army Redstone Arsenal (location of MSFC), work a normal day, and return home later that evening.

Mr. Duren had a wry sense of humor that showed itself on several occasions. Mr. Schwinghammer was less than open when questioned about development issues. On one occasion during a visit to MSFC, Dr. Rummel requested that we see the work being done on the critical rolling seal spirometers (we were touring the MSFC machine shop at that time). Mr. Schwinghammer looked around at the ongoing activities and said that unfortunately we would not be able to see the spirometers at that time because they weren't being worked on. After lunch, Mr. Duren revealed that the real reason was the spirometers were in fact being fabricated at an offsite, commercial machine shop!

On another occasion, just before the metabolic analyzer was to be shipped to the Johnson Space Center, we performed an integrated test in the MSFC laboratory where Chuck Sawin rode the M-171 ergometer at fixed workloads of 100 and 150 W. We compared the metabolic analyzer readouts with established values for human performance at those workloads. The metabolic analyzer readouts were nowhere near expected values. After lunch, we gathered in Mr. Duren's office to reexamine the morning's test results. All calculations within the metabolic analyzer were performed via step-by-step implementation of the physiological equations for computing oxygen consumption, carbon dioxide production, and minute ventilation. Each mathematical step was performed by a discrete Burr-Brown analog module. Each module had a potential computational error of ± 25 mV. While we were reviewing the equation schematics on a large wallboard, Mr. Duren suggested he knew the answer to our predicament. He proclaimed that we needed "another couple of summers." We all turned to the schematics and examined each instance where a summing amplifier was used. At that point, Mr. Duren said, "You don't understand. We may need the summers of 1972–73!"

Fortunately, the potential module computational errors appeared to cancel each other out. The essential problem was the analog triggering circuit that determined the point at which the exhalation spirometer exhaust valve should open. The triggering amplifier required adjustment to be less sensitive, allowing the collection of full expirations from the subject. Once corrected, system performance was reliable. The preferred mode of operation used only the expiration spirometer volume ("Mode 2"). Inhalation volume was calculated from exhalation volume and the ratio of measured inspired and expired nitrogen concentrations.

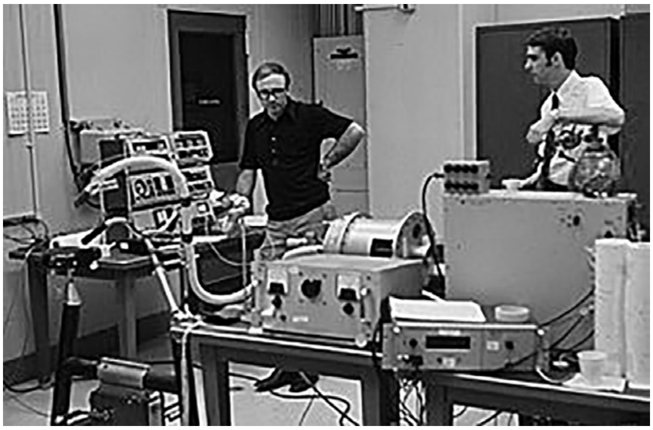

Fig. 1. Setup for evaluation of M-171 prototype in EPL (Dr. Rummel and Dr. Buderer).

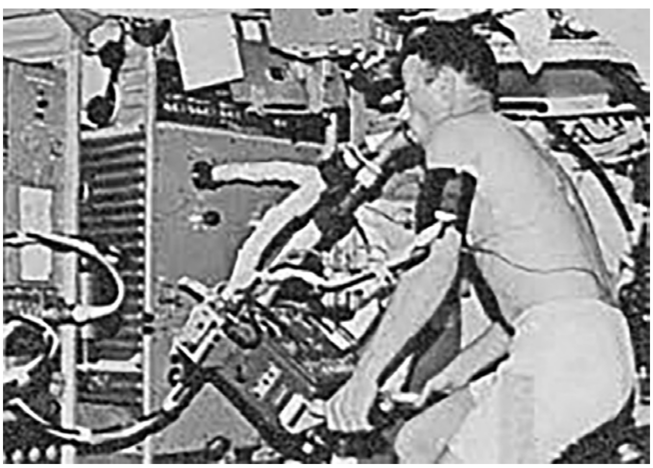

Fig. 2. Skylab in-flight experiment hardware configuration during an astronaut test.

Metabolic analyzer calibration was detailed in our prior paper on SMEAT.[8]

Detailed preflight laboratory evaluation of the Metabolic Analyzer was performed in the EPL (**Fig. 1**). A subject performed steady-state workload cycle ergometer exercise while alternating between breathing into the metabolic analyzer or Douglas bags.

The in-flight equipment required to perform M-171 included: the metabolic analyzer and cycle ergometer, the M093 vectorcardiogram subsystem, the experiment support subsystem, and blood pressure device (**Fig. 2**). A U.S. Patent (3,799,149) for the M-171 metabolic analyzer was awarded to Dr. John Rummel and Mr. Cortes Perry in March 1974. The patent was an indicator of the complexity and uniqueness of the M-171 metabolic analyzer.

The primary objective of M-171 was to determine whether man's metabolic effectiveness while performing mechanical work was progressively altered during exposure to the space environment. The secondary objective was to determine the suitability of the bicycle ergometer as an in-flight personal exerciser as the personal exercise equipment was to be a major cardiovascular system countermeasure. The ergometer was an electromechanical bicycle type exercise device. A restraint system consisting of a shoulder and waist harness and foot restraints was developed. The upper torso harness was ineffective and quickly discarded by the Skylab 2 crew. The foot restraints (triangular shoe cleats that locked into the pedals) were highly effective. The crew recommended the addition of wrap-around handlebars, which were added for Skylab 3. The ergometer was used in the workload control mode and workload was independent of pedal speed within the range of 50 to 80 c/m.

A three-step workload protocol (5 min per step) that approximated 25%, 50%, and 75% aerobic capacity was established for each individual crewman preflight. Skylab 4 crewmen had eight preflight tests, six spaced at approximately monthly intervals prior to launch. The remaining two were at 15 and 5 d before launch. The first six baseline tests were conducted by the crew themselves in the one-g trainer facility. The last two were conducted in the Skylab Mobile Laboratory (SML) by the Co-Principal Investigator's team. This laboratory was dedicated to M-171 and outfitted with a complete set of experiment hardware.

The final preflight exercise test for each crew was performed at Kennedy Space Center 3 d before launch. Immediately following the last test, all equipment had to be disassembled and carefully packed for shipment. At that time, the shipping crates (approximately 35 units) containing the equipment were transported to Melbourne, FL, USA, and loaded onto a commercial aircraft. Thus began a series of three to four commercial flights to reach the pickup location for transport to the primary recovery ship. This journey typically required more than 24 h. The longest such trip was to Pago Pago, American Samoa. Depending on the specific U.S. Navy aircraft carrier designated as the primary recovery ship, either helicopters or twin-engine aircraft flew the equipment and team members to the ship. We were "on station" when each crew launched from Kennedy Space Center, FL, USA. We then had the duration of the specific Apollo mission to set up and check out our equipment.

Typically, our test area was in Officers' Quarters (**Fig. 3**), except for Apollo 14, where testing occurred in the Mobile Quarantine Facility (MQF), which was a modified Airstream trailer. In this case, William Carpentier, the crew flight surgeon, conducted the protocols. Most of our test equipment for Apollo 14 was located outside the MQF on the Hanger Bay deck and interfaced by electronic cabling.

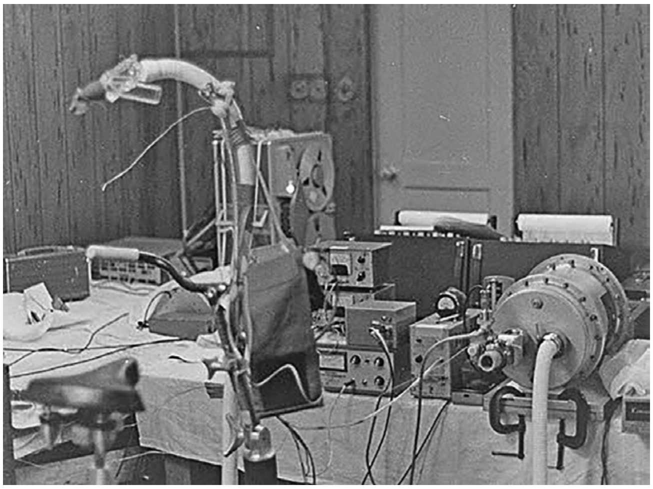

Fig. 3. Postflight test setup in Officers' Quarters.

Fig. 4. Loading Skylab Mobile Laboratories (SMLs) onto U.S. Airforce C5A for transport to North Island Naval Air Station, San Diego, CA, USA.

The advent of the SMLs vastly improved logistics. The SMLs were procured from the DoD, transported to Johnson Space Center, and outfitted for support of specific experiments or activities. After the final preflight test for each mission, SMLs were transported to Ellington Field, where they were loaded onto a C5A (**Fig. 4**) and flown to North Island Naval Air Station. The SMLs were then transferred onto the primary recovery ship. Our equipment array was left mostly assembled and ready for testing in the SML. These SMLs provided a roomier, private, controlled temperature environment for crew testing.

Results of Skylab 2 and Skylab 3 were described in our earlier papers.[3,5,7,11] Skylab 4 was unique both because of its flight duration and the availability of additional exercise equipment on board. First, all subjects maintained similar oxygen consumption at their highest (75% maximum) workload during flight. This reflects consistent mechanical efficiency. Exercise blood pressure measurements were generally consistent for all crewmen through all phases of their mission. It is particularly interesting to review results of voluntary sessions of instrumented personal exercise.[10] Each astronaut performed maximum aerobic cycle ergometer exercise while instrumented with the M-171 equipment. All three crewmen demonstrated higher $\dot{V}o_2$ max at completion of their 84-d mission than they had 4 d before their launch.[10] The Skylab 4 commander on in-flight mission day 79 showed a maximum heart rate of 184 bpm and oxygen consumption of 43 $cc \cdot kg^{-1} \cdot min^{-1}$. The most fit crewman was the SL-4 scientist pilot who reached a workload of 286 W and oxygen consumption of 54 $cc \cdot kg^{-1} \cdot min^{-1}$ on flight day 82.

The daily cycle ergometer personal exercise ranged from 5000 to 8000 (Watt minutes) for each crewman. They also did 100–200 repetitions on the mini-gym. The prototype "treadmill" (a Teflon coated metal plate) was used only by the commander for approximately 10 min each day. It is logical to conclude that the primary exercise device was the cycle ergometer and it clearly supported maintenance of aerobic capacity throughout this long mission.

M-171 was a highly complex set of instrumentation and procedures that required years to develop. Because of the amount of dedicated support, testing, and training employed by the Johnson Space Center, MSFC, and astronaut teams, M-171 was able to complete all of the originally required testing and experiment protocols without missing a single data point throughout three missions using nine crewmembers. A key factor that resulted in the successful implementation of the experiment was the multiple calibration procedures that were built into the hardware systems and crew procedures. This approach provided immediate awareness if there were anomalies in any element of the system at any point in the development process or during flight operations.

Crew participation and assistance in this endeavor was beyond anything we could have imagined. We were able to openly communicate with the medical team and the astronaut crews, and freely discuss medical and physiological results. Today's regulatory environment would probably make it impossible to conduct the Skylab Program as it was conceived and implemented.

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