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FACTORS AFFECTING THE THERMAL EQUILIBRIUM OF A SUBJECT IN THE APOLLO EXTRA-VEHICULAR MOBILITY UNIT

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Summary

The development program for the Space Suit System to be used in Project Apollo is approaching the end of its second year. With the first prototype units delivered and tested, reassessment of the basic input assumptions, conceptual approaches, and system objectives can now be undertaken. System performance test data justified many of the untired concepts utilized in the first prototype equipment. Nevertheless, the evaluation revealed several problem areas which required more refined technical approaches and, in some cases, extension of current state of the art knowledge.

The pressure suit, the Portable Life Support System, and the accompanying accessory garments used for meteoroid and thermal protection together comprise what is known as the Extra-vehicular Mobility Unit (EMU).

Soon after the start of system testing, it was found that the latent water loss of the test subjects was excessive. For a subject working at 400 kcal/hr, there were latent loads experienced of greater than 300 kcal/hr. This caused a water loss rate of more than 1 lb/hr. If this rate were continued for four hours, the resultant water loss is physiologically marginal for many healthy subjects. For this reason a system which dissipates a large portion of the metabolic load sensibly is desired. Because much less power is required to pump liquid than air, a liquid cooling system was adopted. Preliminary work in this area was performed on flight suits by the Royal Aircraft Establishment at Farnborough. Before this principle was adapted for the subject program, a reappraisal of the design point mission culminated in the selection of 400 kcal/hr as an average continuous metabolic load. The peak metabolic load (at which the system can maintain the subject in thermal equilibrium) was established at 500 kcal/hr. This compares to the 400/235 kcal/hr selected for the gas-cooled space suit system.

Recent physiological research has generated data on extremes of subject comfort levels as a function of metabolic load and mean skin temperature. A curve can be plotted to show the extremes of comfort levels represented by the onset of sweating and the occurrence of shivering. The liquid cooling system is designed to maintain the subject at a mean temperature for extremes of metabolic activity. Because a subject will not be working at peak metabolic loads throughout the entire mission, some thought had to be given to providing regulation of cooling garment inlet temperature. If this regulation were not provided, subcooling would result for a subject resting in a shaded area on the lunar surface. This regulation was provided by incorporating a heat exchanger bypass loop. A flow control diverter valve was to
provide a predetermined flow split based upon mission requirements. Flow control concepts utilizing both automatic and manual control systems are being studied. While an automatic system possesses a greater complexity and substantially greater weight, it was found during manned space flight to date that manual flow control resulted in excessive regulation on the part of the astronauts.

During extra-vehicular operation when the Liquid Cooling Garment is utilized, the Portable Life Support System gas loop removes a small portion of the metabolic load sensibly. In addition, the gas loop also performs the functions of oxygen supply, suit pressurization, contaminant control, humidity control, and carbon dioxide helmet purging. In order to maintain the CO₂ partial pressure within physiological limitations for the Apollo design mission, it was necessary to select a minimum helmet inlet volumetric flow which would accomplish CO₂ partial pressure purging commensurate with minimum system weight and power requirements. Manned suit testing indicated that for metabolic loads of 400 kcal/hr, a minimum helmet inlet volumetric flow of 5 cfm was necessary to maintain CO₂ partial pressure purging requirements. For the peak loads encountered during a typical Apollo extra-vehicular mission, a design point helmet inlet flow of 6 cfm was selected to maintain CO₂ concentration below marginal levels. During the manned testing at Hamilton Standard, a technique was developed for determining whether or not the alveolar CO₂ partial pressure was within physiological limitations.3

The oxygen flow rate set by CO₂ purging requirement also serves to remove the latent heat loads associated with respiration during extra-vehicular operation. Moreover, the gas loop acts as a partial back-up thermal transport system in the event of a liquid loop failure.

An index of the performance realizable from the thermal transport system is the degree to which it can absorb metabolic heat. For a given metabolic load the ratio of metabolic heat to total system heat increases as the sum of component-generated heat plus inward heat leak is reduced. Consequently, a means of minimizing environmental (inward) heat leak must be achieved. Several methods to control heat leak into or out of the Pressure Garment Assembly (PGA) have been studied. The primary thermal regulatory garment is an external thermal garment (ETG) composed of several layers of aluminized mylar. This "superinsulation" provides a highly effective radiation barrier in a vacuum environment. A different means of passive thermal control must be provided for the helmet visor. The approach to solving the problems associated with providing maximum visibility for both light and dark side operation while providing temperature control, minimum heat leak (in or out) and attenuation of eye-damaging radiation is based upon the use of selective optical coatings.

It is the intent of this paper to summarize the above mentioned problem areas associated with maintaining the physiological well being and "subjective comfort" of space explorers, along with the technical approaches that are being taken to solve them.

Selection of a Thermal Concept

The objective of a life support system designed to operate in the extremes of the lunar environment is to provide mobility and visibility along with the necessary functions required for life support. Important among the required life support functions is thermal control.

In order to maintain a subject in thermal equilibrium, the heat generated by the metabolic process must be dissipated to the surrounding environment. When ambient conditions act to affect the transfer of metabolic loads, heat is transferred between the outer surface of the skin and the deep areas of the body by tissue conductance and by the circulating flow of the blood. This causes the skin temperature to increase
or decrease at a rate proportional to the ambient temperature level. In the design of a closed anthropomorphic system such as a space suit, a means must be provided to maintain skin temperatures within acceptable physiological tolerances for varied work loads and environmental conditions.

Initial studies made shortly after receipt of the contract to develop a life support system for Project Apollo established an average metabolic load of 235 kcal/hr with peak loads of 400 kcal/hr. Extensive trade-off studies to select an optimum system resulted in the selection of a closed ventilation loop system with circulation provided by a battery powered fan. Thermal control was accomplished principally by evaporative cooling of the body to the circulating oxygen stream with a small portion of heat removed by the sensible capacity of the gas stream. (Fig. 1) The system was designed to remove the total eccrine and apocrine sweat loss (sensible loss) as well as the insensible water loss (latent respiration plus water lost through skin diffusion) occurring at the design point metabolic loads. Although it was desirable to select a volumetric flow rate sufficient to maintain the subject at a "no sweat" condition, weight penalties associated with increased fan size and power requirements were found to be prohibitive. The flow rate was therefore selected to be the minimum necessary to achieve thermal equilibrium and to maintain carbon dioxide purging requirements.

Soon after development testing began on the prototype system, it was found that subjects incurred a water loss of greater than 1 lb/hr during a four hour test at average metabolic loads of 235 kcal/hr. This imposes a severe physiological stress on the subject since excessive sweat loss leads to a sodium depletion causing an increased excretion of water by the kidney and a further decrease of extracellular body fluid. Eventually there is a possibility of a lowered cardiac output and a peripheral circulatory failure. From a mission standpoint, excessive subject water loss would severely reduce the possibility of a back to back mission capability.

At this point in the development program a means for achieving subject thermal equilibrium without imposing physiological stress was sought. Preliminary work done at the Royal Aircraft Establishment on liquid cooling was closely examined. The concept of liquid cooling was advantageous in that it relied upon sensible cooling brought about by circulating a fluid through tubing in contact with the skin surface. Furthermore, a liquid heat transport system offered the advantage of increased heat load or mission duration for a given system weight through a decrease in power consumption over a gas system.

In early 1961, a development program was initiated to evaluate the feasibility of utilizing the concept of liquid cooling for the Apollo Extra-Vehicular Mobility Unit (EMU). Construction of a prototype liquid cooling garment designed to be worn under the Pressure Garment Assembly (PGA) was begun. The tube length distribution was made proportional to the body mass distribution so as to provide a local cooling capability approximately proportional to the equivalent rate of heat generation. Uniform flow distribution throughout the garment was assured through the use of equal length heat transfer tubes. The supporting structure for the tubing distribution was a full length union suit constructed of open mesh fabric. Cooling tubes were not extended over the hands, feet or head due to the difficulty in providing this distribution. Cooling of these areas relied upon blood circulation. Flow distribution was established as a supply to the extremities with a return from the waist.

The development effort at Hamilton Standard demonstrated that prevention of sweating occurred for subjects working at metabolic rates in excess of 500 kcal/hr with over 500 kcal/hr transferred directly to the cooling water. During testing, limiting comfort levels were established as the onset of sweating and the onset of
shivering. It was also found that the threshold (sweating and shivering) temperatures for a given metabolic load are a direct function of the mean skin temperature. (Fig. 2)

A reappraisal of the design point metabolic loads was necessary before the principle of liquid cooling was utilized in the space suit program. Recent testing both at Hamilton Standard and NASA brought to light new estimates of metabolic loads levels for the Apollo extra-vehicular mission; based in part on the effect of suit encumbrance and reduced gravitational force upon metabolic loads. An average continuous metabolic load for a three hour lunar surface mission was established as 400 kcal/hr with peak allowable loads of 500 kcal/hr.

Designing a Liquid Transport System

The concept of liquid cooling was adopted through the incorporation of a closed liquid loop between the PLSS and Liquid Cooling Garment. Circulation was provided by a battery powered pump assembly. A heat exchanger was placed in the loop to dissipate the total thermal load consisting of metabolic heat, heat generated by the various components, and environmental heat leak.

Although cooling garment testing revealed no areas of discomfort over a wide range of metabolic loads for full flow conditions, examination of mission environment indicated a need for regulation of garment inlet temperatures. Testing was done with the subject insulated from the surrounding environment to minimize inward or outward heat leak. However, when the combined effects of direct solar radiation, solar albedo, and lunar emission upon a subject working in a lunar environment were considered, it became evident that some amount of heat leakage (to and from the environment) would occur. For the case of a subject working at minimum metabolic loads and radiating to a cold environment, skin temperatures would quickly fall. To avoid falling below the low temperature comfort level and to avoid eventual subcooling, a means of flow control was considered necessary.

One of the simplest methods of achieving regulation of cooling garment inlet temperatures was to incorporate a heat exchanger bypass loop. In this way a constant pump speed and liquid flow rate could be used for all operational modes. A flow control valve was utilized to regulate the flow split to the cooling garment to maintain a mean temperature level between the threshold levels for all mission requirements. Both automatic and manual flow control concepts have been investigated. Manual flow control possesses the advantages of minimum weight and complexity but results in an added control that could give rise to constant overcompensation by a stressed subject in a lunar environment. Automatic flow control concepts controlled by various types of actuating signals such as cooling garment temperature differential, skin temperature, heart beat, oxygen consumption, respiratory moisture production, deep body temperature and incipient perspiration have been investigated. The transient response attainable with these concepts must be compared on a subjective basis before the system which provides maximum thermal comfort can be selected. The sequence of tasks anticipated during a typical three hour Apollo extra-vehicular mission have been combined to produce typical metabolic load profiles. (Fig. 3) The continual variation of metabolic loads and the variation in external environment that will be encountered as the subject moves from lighted to shaded areas of the lunar surface in the accomplishment of these tasks may well necessitate an automatic thermal control system. At this time, however, a manual control approach is being pursued because of the lower weight and superior reliability.

Design of a Back-up Thermal System

In addition to providing the functions of oxygen supply and suit pressurization, a closed oxygen loop was used to provide those remaining life support functions
necessary for maintaining the comfort and physiological well being of the subject. In a closed system which recirculates breathing oxygen, it is necessary to remove those contaminants which, if recirculated, would endanger the subject. One of the gases which must be removed from the oxygen stream is the carbon dioxide generated by the subject. At an average metabolic load of 400 kcal/hr, there is approximately 0.31 lb/hr of CO₂ generated. A contaminant control system is utilized to maintain the carbon dioxide partial pressure level within safe tolerances for a three hour mission, and also to remove odors and trace contaminants. The carbon dioxide is absorbed by passing the CO₂-laden oxygen stream through a lithium hydroxide bed where the CO₂ reacts with the LiOH to produce lithium carbonate and water. A considerable amount of heat is generated by the reaction which must be removed from the stream before the flow is returned to the suit. Temperature regulation within the O₂ loop is achieved by the common liquid-gas loop heat sink. In the original gas system previously described, the heat sink was in the form of a water boiler. However, it has been determined that this component could be made more reliable if the expendable water were allowed to freeze. An ice "sublimator" has been developed which depends upon the sublimation of ice from a porous plate to remove heat from the closed recirculating loops. As ice sublimes from the plate, additional water is automatically supplied from a pressurized water reservoir. The rate of water supply is a function of the rate of sublimation which, in turn, depends upon the system. The maximum heat rejection rate of the sublimator is 750 kcal/hr which includes metabolic loads, external leakage, and heat loads added by the various components.

Humidity control is accomplished by maintaining suit inlet flow saturated at the sublimator exit temperature. Excess water is removed by a water separator.

In addition to supplying oxygen for metabolic needs and for suit pressurization, the oxygen loop must perform purging of CO₂ from the oro-nasal area. The volumetric flow necessary to accomplish CO₂ purging plays a substantial role in sizing the system since it establishes the minimum allowable helmet flow requirement. During manned testing at Hamilton Standard, a procedure was developed for evaluating alveolar CO₂ partial pressure as a function of metabolic activity. Experimental data obtained on the relationship between ventilation flow rate, CO₂ production rate, and helmet CO₂ partial pressure established a minimum helmet inlet flow of 5 cfm necessary to maintain safe tolerable CO₂ partial pressure within physiological tolerances. Of this amount, approximately 1.5 cfm is passed over the top and back of the head for cooling purposes.

The oxygen stream has sufficient capacity to normally remove those heat loads associated with subject respiration during extra-vehicular operation. However, in the event of a liquid loop failure, the oxygen stream can serve as a partial back-up to remove a maximum of 150 kcal/hr at design flow conditions. During intra-vehicular use in both the CM and LEM, liquid cooling is not utilized. Therefore, the PDA ventilation system must also be designed to allow the subject to achieve thermal equilibrium during the extended periods of intra-vehicular flight. Although intra-vehicular thermal control relies upon latent removal of heat, significant physiological stress is not anticipated due to the lower intra-vehicular metabolic load levels.

Control of the External Environment

As man ventures away from his spacecraft to explore the lunar surface, he will be exposed to a hostile thermal environment consisting of temperatures ranging from -290°F to +260°F, damaging ultraviolet radiation, intense visible energy, and a significant amount of infra-red radiation view factors. In order to maintain an acceptable temperature level within the suit, the subject must be effectively insulated from this environment. A minimum interchange of energy between internal and external environments insures maximum effectiveness of the life support system. If it was established that the mission would occur during lunar dark side conditions, an outward heat leak would be helpful in reducing the required capacity of the PLSS heat sink. However,
because the system must be designed to operate during both lunar day and night, with the subject working hard and resting, an adiabatic suit boundary is desirable. Such an insulation barrier is not attainable without a significant cost in weight. If the insulation weight necessary to insulate the suit is traded against the heat sink capacity required to dissipate inward leak, an "optimum" heat leak can be found. This occurs in the vicinity of 50 kcal/hr. The insulation required to maintain this inward heat leak, allows an outward leak of approximately 70 kcal/hr. Control of environmental heat leak is an essential factor in maintaining the thermal equilibrium of a suited subject. As a result of an investigation of many insulating materials, it was found that passive thermal control could be best achieved by utilizing a thermal coverall composed of multiple layers aluminized mylar which offers a series of reflective barriers to thermal radiation. Although superinsulation is one of the most effective insulations presently known, it possesses some disadvantages. A vacuum of $10^{-4}$ mm of mercury or less must be provided to maintain its insulating properties, since its effectiveness falls off rapidly when this value is exceeded. Venting of the layers of the thermal coverall provides the necessary vacuum conditions. Analysis has shown that relatively few vent holes are required to prevent ballooning of the thermal garment following a cabin depressurization with a steady state pressure well below the maximum allowable valve reached within one minute. Local rates of high heat flux are another problem resulting from compression of the insulation layers. The effects of compression are currently being studied but it is felt that judicious design can minimize this problem area. A white dacron outer layer has been used for the thermal coverall to provide a high emittance at far infra-red wave lengths while providing a low solar absorptivity to minimize garment surface temperatures.

Another area where passive thermal control must be provided is that of the helmet visor. Design objectives for an extra-vehicular visor are maximum visibility during both lunar light and dark side operation commensurate with minimum heat leak, maximum attenuation of ultraviolet radiation, reduced transmission of visible and near infra-red energy, provision of meteoroid protection, and maintenance of temperature levels. Temperature extremes are set by the material limitations of the visor on the high end and that necessary to prevent visor fogging and frosting at the low end. Maintaining the internal visor temperature above the local dewpoint of the oxygen stream is necessary to reduce the possibility of fogging and frosting.

A technique for achieving thermal control utilizing selective optical coatings in a multiple visor system has been adopted. Although the use of selective optical coatings is not new, their application in a system where multiple interacting coatings are vacuum deposited on an irregularly curved surface is without precedent.

Development work on optical coatings has provided sufficient data to warrant consideration of the use of selective coatings in other areas of the EMU where heat transfer problems exist. For example, the radiant transfer of heat between PLSS components and to the inside of the PLSS cover would be advantageous. Several concepts for providing an EMU visor and thermal protection assembly are being evaluated. One approach is to use a visor assembly mechanically attached to a helmet which has integral thermal protection over the remainder of its surface. Other concepts include incorporation of helmet thermal protection on the visor assembly. Development efforts indicate that it is possible to provide a 100 per cent barrier to ultraviolet radiation, a 10 to 20 per cent transmittance of visible energy, and a regulation of infra-red radiation transmittance and emittance to control visor surface temperatures.

**Liquid Loop Optimization**

Once the liquid loop concept had been established, studies were initiated to select an optimum liquid flow rate commensurate with maximum heat rejection capability (at zero sweat rate) and minimum weight. The liquid loop was designed for a heat exchanger exit temperature of $45^\circ$F at full load.
A design ground rule for the Liquid Cooling Garment was to prevent sweating at peak metabolic loads (500 kcal/hr). During cooling garment testing, it was found that the skin temperature below which sweating would not occur at 500 kcal/hr was approximately 80°F. The effect of liquid flow rate upon garment exit temperatures required to maintain the subject in thermal equilibrium at peak loads has been plotted. (Fig. 4) A further curve can be plotted to show the effect of flow rate upon battery and sublimator weight. (Fig. 5) As a result of the liquid loop studies, an optimum flow rate of 4 lb/min was selected. While this flow rate does not necessarily result in a system of the lowest achievable weight, it does culminate in a system of minimum weight commensurate with the prevention of sweating at 500 kcal/hr.

**Conclusion**

It has been shown that realization of thermal control during an Apollo mission is a complex problem. Test subject thermal control must be maintained through a combination of active and passive control over a wide range of ambient conditions. This requirement has necessitated extension of the state of the art in several areas. A specific example is the use of a porous plate sublimator as a heat sink with automatic control of water feed rate as a function of heat load. Design of this component and the water separator are complicated by the fact that they must operate in a zero or a one-sixth gravity field.

Manned testing utilizing liquid cooling has defined thresholds for subject comfort levels. When used in conjunction with an optimized liquid flow, the Liquid Cooling Garment has prevented sweating at peak loads of 500 kcal/hr without the physiological stresses associated with a gas cooled system.

The gas loop has been designed to provide those life support functions necessary to maintain the physiological well being of a subject in lunar surface environments.

Passive thermal control employed as applied to the E T G and on the helmet visor, will provide adequate protection from the lunar thermal environment.

**References**

1. Work done by Dr. J. Billingham at the Royal Aircraft Establishment, Farnborough, England.


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FIGURE 1  GAS COOLED SYSTEM - OXYGEN STREAM THERMAL CAPACITY AS A FUNCTION OF VOLUMETRIC FLOW FOR AN ADIABATIC SUIT WALL
FIGURE 2  THRESHOLD TEMPERATURES AS A FUNCTION OF METABOLIC LOAD AND MEAN SKIN TEMPERATURE
FIGURE 3  METABOLIC LOAD PROFILE FOR A TYPICAL
THREE HOUR APOLLO EXTRA-VEHICULAR MISSION
For Mean Skin Temperature = 80°F

Q Met = 500 kcal/hr
Q Sensible = 466 kcal/hr to water

FIGURE 4  LIQUID COOLING GARMENT TEMPERATURE DISTRIBUTION AS A FUNCTION OF FLOW RATE
FIGURE 5  LIQUID LOOP—BATTERY AND SUBLIMATOR WEIGHT vs FLOW RATE