PHYSIOLOGICAL PROBLEMS IN SPACE EXPLORATION

Edited by

JAMES D. HARDY, PH.D.

Director, John B. Pierce Foundation Laboratory
Professor of Physiology, Yale University Medical School
New Haven, Connecticut

Formerly
Director of Research
U. S. Naval Aviation Medical Acceleration Laboratory
Johnsville, Pennsylvania

CHARLES C THOMAS • PUBLISHER
Springfield • Illinois • U.S.A.

Published and Distributed Throughout the World by
CHARLES C THOMAS • PUBLISHER
BANNERSTONE HOUSE
301-327 East Lawrence Avenue, Springfield, Illinois, U.S.A.
NATCHEZ PLANTATION HOUSE
735 North Atlantic Boulevard, Fort Lauderdale, Florida, U.S.A.

Library of Congress Catalog Card Number: 63-19579

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Printed in the United States of America
M-1

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Publication Number 561
AMERICAN LECTURE SERIES®

A Monograph in
The BANNERSTONE DIVISION *of*
AMERICAN LECTURES IN PHYSIOLOGY

CONTRIBUTORS

JOHN R. BROBECK, M.D.: *Professor of Physiology*
School of Medicine, University of Pennsylvania,
Philadelphia, Pennsylvania.

JOHN LOTT BROWN, PH.D.: *Associate Professor of Physiology,*
School of Medicine, University of Pennsylvania,
Philadelphia, Pennsylvania.

RANDALL M. CHAMBERS, PH.D.: *Head, Human Factors Division,*
Aviation Medical Acceleration Laboratory,
U. S. Naval Air Development Center,
Johnsville, Pennsylvania.

CARL C. CLARK, PH.D.: *Manager, Life Sciences Department,*
Martin Company,
Baltimore, Maryland.

FRANZ HALBERG, M.D.: *Professor of Pathology,*
Medical School, University of Minnesota,
Minneapolis, Minnesota.

JAMES D. HARDY, PH.D.: *Director, John B. Pierce Foundation Laboratory,*
and Professor of Physiology,
Yale University School of Medicine,
New Haven, Connecticut.

EDWIN HENDLER, PH.D.: *Manager, Life Sciences Research Group,*
Aerospace Crew Equipment Laboratory,
U. S. Naval Air Engineering Center,
Philadelphia, Pennsylvania.

FOREWORD

The physiological problems which have challenged students and investigators in their attempts to adapt man for space explorations have been those associated with environmental extremes. The high vacuum of inter-stellar and inter-planetary space, marked alterations in acceleration due to high velocities of space craft, inter-stellar dust and atomic nuclei, extremes of heat and cold, and long periods of loneliness in a limited space, are factors which mean stress to the astronaut. Thus, in a real sense space physiology is the physiology of stress. For this reason there has been from the beginning of the space adventure a deepseated conflict between those who have maintained that engineering skills should be strained to provide the same environment for the astronaut in space as he has on Earth and those who would extend man's capabilities for survival by physiological means. In the first instance, therefore, there is no space physiology, only space engineering of the environment. However, the long experience in aviation medicine and physiology has shown that danger and death lie in this direction and unless physiologists and psychologists can provide the data which show the safe and the dangerous limits for human performance and survival, the engineering profession will proceed with designs of aircraft and spacecraft based on their own best guesses. The good fortune which has attended the few space flights to date are examples of the great benefits which have been derived from the somewhat painful but beneficent cooperation between engineering and biological scientists. Space travel is still a most dangerous venture and thus many problems remain to be solved. Rescue operations in space and emergency escape are not practical during most of a space voyage at present. However, progress in space biology up to date is such as to encourage us to approach this and other challenges with optimism. It is the intent of this volume to present background information and our state of knowledge in the several aspects of space psychophysiology for the use of students and the interested general reader.

JAMES D. HARDY, PH.D., *Editor*

New Haven, Connecticut

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TEMPERATURE PROBLEMS IN SPACE TRAVEL

James D. Hardy, Ph.D.

Man and his progenitors have been born and had their being under the protective envelope of the Earth's atmosphere and near the stabilizing influences of the great water masses—lakes, rivers and oceans. These many protections are apparent to us when we study with great telescopes the harsh and scarred surface of our nearest cellestial neighbor, the Moon, and make plans to explore this landscape in person. Without an atmosphere and with no liquid water surfaces, an astronaut will be exposed to the full radiation from the sun during the lunar day and to the extreme cold of outer space during the night. As we look beyond the moon towards our nearest planetary neighbors, Venus and Mars, and possibly Jupiter and Mercury, with an idea of sending manned expeditions to study their surfaces at close hand, the thermal threats (which set the final limits to the existence of all life) are major problems in the planning. In many areas our information concerning the planets is insufficient to evaluate the extent of the dangers from excessive heat or cold and it will be necessary to send instrumented probes to study conditions before a man actually ventures into the face of the fiery blasts of solar radiation or the silent deep spaces where the cold is such that the molecular motions are almost ceased. It is thus the purpose of this chapter to examine the thermal environment of interest to the astronaut and to describe the physiological limitations of man and his temperature regulatory capacities. It is not enough to say that man will have to be protected in space because, although this is unquestioned, it is necessary to determine for a particular mission how much and for how long. Weight is of overriding importance in space travel and protective equipment will be limited.

THERMAL ENVIRONMENTS IN SPACE

The Earth: The extremes of temperature on the Earth's surface are included in the range of +50° and −75°C, and with proper dress man has found it possible to live for extended periods in regions in which such temperatures are occasionally recorded. However, large land areas have average yearly temperatures near +20°C with seasonal means of +10° and +30°C. Day to night variations of temperature in most localities may be less than temperature changes due to the local weather, thus indicating the great stability of temperature provided by the influences of the atmosphere and the large water areas. The sun's radiation which reaches the Earth's surface (see Figure 1) is filtered by atmospheric absorption of the infrared radiation (beyond 3μ) and the ultraviolet and x-radiation. The visible and near

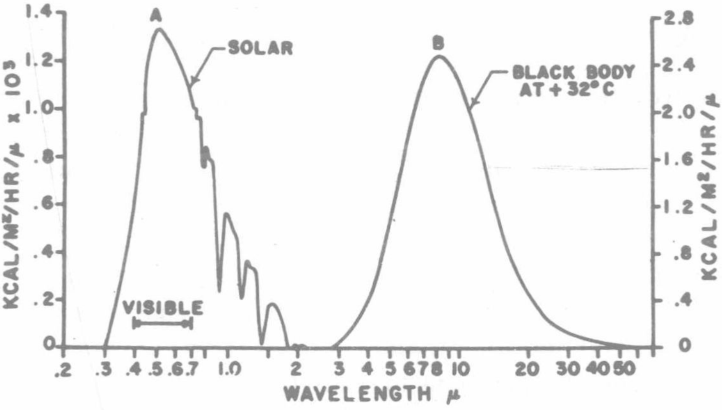

Fig. 1. Solar Radiation Spectrum A; Low Temperature Radiator, B.

infrared radiation which is absorbed at the Earth's surface is converted largely into heat and a part of this heat is re-radiated back to space as infrared radiation with a maximum near 10μ. However, as the water vapor and CO_2 in the atmosphere absorb strongly in the far infrared, most of this heat is retained during the night when sun is not shining This "greenhouse" effect tends to prevent large temperature swings from day to night except in very arid regions or at high altitude where water vapor content of the air is reduced. The effects of cloud layers in reducing radiation heat loss are seen in Figure 2. The radiant temperature (equivalent black body temperature) of the Earth's surface, the clouds and the sky were measured with a radiometer as the aircraft climbed to 40,000 ft. The dry bulb temperature recorded by radio sonde balloon is shown for comparison. In general the thermal

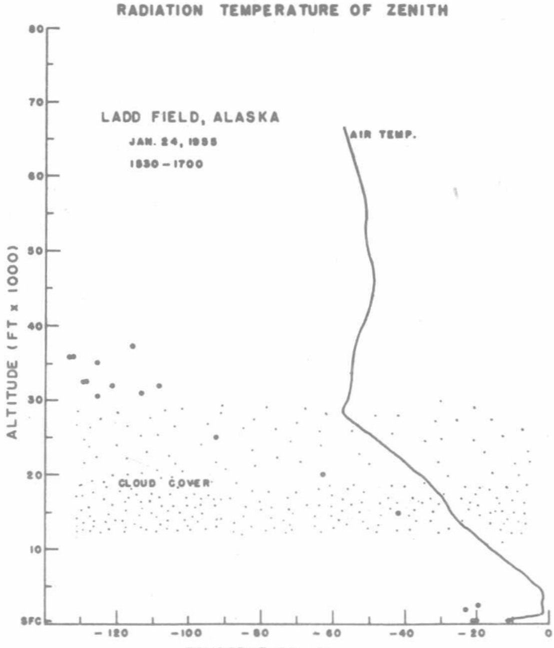

Fig. 2. Sky and Cloud Temperatures at Altitude (•).

environment on the Earth is characterized by the water vapor and winds, although in very arid areas such as dry deserts, radiations from the sun and to the sky become important and give one an impression of what it may be like without the protection of the Earth's atmosphere. For example, the climate of San Francisco may be compared to that of Death Valley, or Oslo with Fairbanks.

Space: It has been estimated that the temperature of interstellar dust and hydrogen in equilibrium with the dilute interstellar radiation is of the order of 100°K.[1] Knowledge of this temperature is not complete and temperature lower than this estimated value is possible. In space near the Earth, the sun's radiation is the important heat source. The sun has an irradiance of 2.00 gm cal/sec/cm^2 outside the Earth's atmosphere,[1a] and this intense radiant-heat falling on the skin is about that which will stimulate pain sensation.[2] Thus, even if it were not for the requirement to protect man from the effects of the high vacuum of the space environment, the radiant heat load would necessitate protection. The radiant heat load will be almost twice this great outside of the Venusian atmosphere and near the planet Mercury about seven times as great as that near the Earth. Thermal radiation from the sun in the neighborhood of Mercury falling on the unprotected skin would cause a skin burn in

TABLE I

Planet	Mean Distance from Sun (millions of miles)	Heat Load	
		Kgcal/m^2/hr	Basal Metabolic Rates*
Mercury	36	7950	199
Venus	67	2280	57
Earth	93	1190	30
Earth's surface	—	0–956**	24
Mars	142	510	13
Jupiter	483	42	1

* BMR = 40 kgcal/m^2/hr (figures have been rounded to nearest whole number).
** Death Valley during August.

less than a minute. The magnitude of the radiant heat load for the nearby planets in terms of the energy received on a totally absorbing surface normal to the sun's rays is given in Table I.

It is seen that shading or cooling will have to be provided for the astronaut in the space environment near the Earth or Moon and that this problem will be greater as one goes nearer the sun. Of course, the astronaut will be surrounded by the very low radiant temperature of outer space and thus there is a heat sink into which he can pour a great deal of the heat that he absorbs.

Moon: The surface temperature of the moon on the dark side has been estimated at −125°C and on the sunny side at +100°C. This latter temperature together with the direct and reflected radiation from the sun will pose a heat problem of major but not impossible proportions. The moon has no water surfaces or atmosphere and thus the radiation to the sky from the moon will assist in the heat loss problem but there will be no cooling by convection currents of air and temperature changes will occur very rapidly with changes in sunlight.

The Planets: In the foreseeable future the Earth Astronaut will not penetrate further than the planets Mars and Venus. The temperature on Venus has been reported as near 800°C based on measurements in the radio-frequency spectrum. If this should turn out to be the case, manned exploration of the planet's surface will be most difficult because of the heat. Manned expeditions to Mercury are probably excluded because of heat loads. The Martian icecaps which change with the season may be of carbon dioxide (−78°C) and crystals of CO_2 may be responsible for the bluish haze which is sometimes observed. Mars appears to have no oceans and to be subject to violent dust storms. The thermal problem of the astronaut exploring Mars may be one of supplying heat rather than losing heat.

HEAT TRANSFER

The human body exchanges heat with the environment through four main channels, i.e., radiation, conduction, convection and vaporization, and in the micro-climate of the body surface these thermal exchange channels will continue to operate in space. The general equation of heat transfer can be written as the algebraic sum of the factors involved.[3]

$$H_L = H_R + H_C + H_D + H_V \tag{1}$$

in which

H_L = heat loss or gain
H_R = radiant heat loss
H_C = convective heat loss
H_D = conductive heat loss
H_V = evaporative heat loss

Depending upon the direction of heat flow, the quantities may be either positive or negative but are generally considered to be positive when the transfer of heat is from the body surface into the environment. As man must live in thermal equilibrium with his environment (except for small short-term transients which must be adjusted for) the heat balance equation can be stated as:

$$H_p - H_L = S \tag{2}$$

in which

H_p = heat production within the body
S = body heat storage (positive when body is gaining heat)

Heat balance requires that $S = 0$ over any extended period although under extreme physiological conditions body heat storage can fluctuate ±300 kcal in a 70 kg man.

Heat production in man may be estimated most easily by measurement of the oyxgen consumption although CO_2 production is also sometimes used. The generalized equation for heat production can be written from a consideration of the food which man burns, as follows:

$$\left.\begin{array}{l}\text{Carbohydrate}\\ \text{Protein}\\ \text{Fat}\end{array}\right\} + O_2 \rightarrow CO_2 + H_2O + \text{Heat} + \text{Work} \tag{3}$$

At rest, the heat produced can be taken to be 40 ± 4 kgcal/m^2/hr for normal man and 33 ± 3 kgcal/m^2/hr for the normal woman. Thus, for the 70 kg man of 1.9 m^2 body surface area, the daily resting heat production will be 1824 kcal. The maximum heat production of which a man is capable depends on the degree of athletic training but is roughly twenty times the resting level for short periods of time (5–10 min); work at the rate of three to five times the resting metabolism can be performed for many hours without difficulty. The space environment may affect the amount of useful work which a man can do because of alterations in temperature, gravitational field, clothing restrictions, etc., but the associated heat loads must be eliminated from the body surface as they occur to prevent excessive body heat storage. The physiological factors which limit thermal exposure are discussed later in this chapter, the subject of body heat production being introduced at this point to indicate its importance in heat transfer problems.

RADIATION OF HEAT

By radiation in this sense is meant the exchange of thermal energy between objects in the form of electromagnetic energy and this process depends quantitatively only upon the temperature of the various exchanging objects and their abilities to absorb or radiate. The flow of heat by radiation does not require the presence of an intervening medium between the radiators and receivers and thus heat will pass by the process of radiation from a hot object to a cooler one through a vacuum. Two objects in equilibrium as regards the radiation transfer of heat can be said to be at the same temperature; in many respects temperature can be thought of as the property of matter which determines the direction of heat flow. Inasmuch as the radiant transfer of heat takes place through a vacuum, it is this mode of heat loss and heat gain which will be of greatest importance in the space environment and on the surfaces of the moon or other celestial objects having little or no atmosphere. The problem of maintaining a proper thermal environment for the astronaut in space will, to a great degree, revolve about the manipulation of the heat gains and losses by radiation.

Figure 1 shows the relative positions in the electromagnetic spectrum of the sun's radiation and the radiation from the hu-