THE SPACE ENVIRONMENT AND ITS IMPLICATION ON MANNED FLIGHT OPERATIONS

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INTRODUCTION

The characteristics of the space environment are only partly known today and, consequently, their implications on man's performance capability when exposed to the conditions of space are not fully understood. Strughold has classified some of the effects of the space environment with regard to the physiology of man (ref. 17). One of these classifications describing the functional borders of the terrestrial atmosphere is shown in table 1. According to this classification, the vital partial pressure of oxygen is lost at about 15 km, causing anoxia and death of the unprotected individual within a period of about ten seconds. Loss of sufficient air pressure, which necessitates the pressurization of the vehicle, occurs at an altitude of about 20 km, and that means that heights in between 25 and 30 km must be considered as the final functional border for the biological and physiological functions of mammalian life.

At an altitude of about 37 km, the radiation climate in space begins. This is represented by the full range and intensity of cosmic radiation, ultraviolet solar radiation, and the various types of trapped radiation (the so-called Van Allen Belts) which become effective at various distances from the surface of the Earth. I must add here that Strughold's table has been revised several times during the last ten years, and that this version is still not complete with respect to our latest information on some of the factors of the upper atmosphere, the stratosphere, the ionosphere, and of the various regions of cislunar and outer space. Data are made available through space probes and satellites, providing an almost continuous flux of new information.

In accordance with table 1, the range between 100 km and 500 km is characterized by a very gradual thin-out of the atmosphere, which produces considerable changes of the mechanical conditions on the fringe of space. By and large, it can be assumed that the space environment becomes more unfriendly and hostile with increasing distances from Earth, although there are some indications that conditions may become somewhat more favorable after the penetration of the outer Van Allen Belt. However, the effects of solar proton events beyond this belt may again limit the validity of my last statement.

MAIN PROBLEM AREAS

The problems which space imposes on man can be approached in various ways. One avenue of approach is to consider space as an area, or

TABLE 1

MAIN CHARACTERISTICS OF ATMOSPHERIC AND SPACE ENVIRONMENT AS RELATED TO HUMAN SPACE FLIGHT*

Lack of O_2 - partial pressure (Anoxia)	15 km
Vaporization of body fluids due to insufficient air pressure (Space ebullism)	20 km
Low air density necessitates use of sealed cabin	24 km
Penetration limit of primary cosmic rays	40 km
Ultraviolet of solar radiation (Full range and intensity)	45 km
No support from air (Endpoint of aerodynamics)	50 km
No transmission of sound (Silence of space)	100 km
No scattering of light (Darkness of space)	100 km
Penetration of macro-meteorites	120 km
No mechanical effect from exosphere (Endpoint of thermodynamics)	300 km
Inner radiation belt (Protons and Bremsstrahlung)	1,000 - 5,000 km
Outer radiation belt (Electrons)	12,000 - 18,000 km
Equilibrium of terrestrial and lunar gravispheres	340,000 km
Mean distance of Moon	384,400 km
Terrestrial satellite gravisphere	500,000 km

*All figures given in this table are approximations.

means, or tool for research. The space factors which must be considered in this regard are listed in table 2. This table was originally prepared to delineate the research areas of space biology; that is, the investigation of the effects of the space environment on the lower part of the phylogenetic spectrum, particularly on the biological components of lower organisms such as cells, tissue, micro-organisms, plants, and small animals. The space factors listed in table 2 are reduced oxygen, reduced atmospheric pressure, composition of atmospheres, extreme temperatures, radiation and magnetism, gravitation and weightlessness, and exotic environments.

TABLE 2

RESEARCH AREAS

1. MOLECULAR BIOLOGY

Origin of life
Primordial molecules
Cytochemistry
Heredity

2. SPACE FACTORS

Reduced oxygen tension
Reduced atmospheric pressure
Composition of atmospheres
Extreme temperatures
Radiation and magnetism
Gravitation and weightlessness
Exotic environments

3. CELLULAR ENVIRONMENTAL BIOLOGY

Fertilization
Cell division
Embryogenesis
Growth
Metabolism
Biological clocks and rhythms
Geotropism

4. SEARCH FOR EXTRATERRESTRIAL LIFE

Chromatography
Telescopic observations
Radio-photography
Spectroscopy - U. V., I. R. - Visible
Prebiological chemistry
Physical & chemical analyses
Microscopy

5. COSMOLOGY

History of the planetary system
Structure of the universe

It is only natural that the efforts to investigate and understand the effects of the space environment on biological matter of all parts of the spectrum includes such areas as molecular and cellular biology as well as the problem of the origin of life and the search for it in the universe. It is believed that information on these problems will not only help to clarify some of the unsolved effects of the space environment on higher organisms such as man, but also to understand some of the cosmological problems involved.

It must be mentioned in this connection that the space factors already mentioned must also be evaluated with regard to their significance in the biomedical area, and with regard to their implications on the behavior and performance of man.

Proceeding from the biological level to medical and behavioral problems leads more or less directly to the other approach of space exploration; namely, the use of extraterrestrial space as a theatre of operations. The main problem areas for an operational analysis of the space environment are outlined in table 3. They imply the intention of man to enter space by means of suitable vehicles and protective devices and to operate in this environment for certain purposes and objectives. In order to do so effectively, the critical problem areas for an operations analysis must be explored, and the requirements for man's performance under the conditions anticipated or found must be established.

TABLE 3

FLIGHT MEDICINE AND BIOLOGY:
SPACE BIOTECHNOLOGY

SPACE FLIGHT OPERATIONS ANALYSIS: PROBLEM AREAS	SPACE SYSTEMS DEVELOPMENT: TASK AREAS
1. Biomedical analysis	1. Life support systems
2. Hardware and machine analysis	2. Control systems
3. Man-machine interaction	3. Communication systems
4. Man-machine system support	4. Space flight support
5. Vehicle system analysis	5. Manned vehicles and biosatellites

This, then, leads to questions about the physiological and psychological effects of the space factors, how the existing hypotheses can be verified, and what can be done in order to maintain man's capability to perform the anticipated tasks. Our present knowledge on some of the major effects of the space environment will be briefly summarized. It may be stated in this conjunction that these effects are of considerable importance for the evaluation of human factors associated with remote control of space systems.

LACK OF OXYGEN, ATMOSPHERIC PRESSURE, AND THE VACUUM

The problems associated with the gradual decrease of oxygen and pressure within the atmosphere belong to the classical subject of aviation medicine, and must not be repeated here. Most of them have been solved in a practical way by means of protecting devices and life support systems, which are also applicable to advanced space craft (ref. 12). However, some difficulties are brought forth by the size and weight of such systems, the demand for a very high degree of reliability, and the requirements for continuous operation over long periods of time.

While the demand for a "shirt-sleeve environment" in manned space craft constitutes one extreme in the program for an optimization of life support systems, the characteristics of the hard vacuum in space and the hazards of radiation and meteoric penetration may impose severe limitations on the actual living conditions so that man's tolerance limits must be considered as the other extreme of the scale (ref. 7).

It should also be pointed out that we need further information about the behavior of materials in the vacuum and under extreme temperature conditions. These may range from -425° F. of liquid helium to 8000° F. of exotic chemical exhausts. Various parts of the space craft as well as personal and protective equipment will be submitted to high mechanical stresses due to changing pressure and temperature.

RADIATION

It has already been pointed out that the radiation hazards in space may decisively affect the design of space craft, their trajectories, and the realization of space travel. At present, radiation hazards are anticipated during extended flight missions. This, in turn, is one of the main factors which stimulate the development of remote-handling devices.

At the present state of knowledge, we can assume that materials used in space vehicle construction and for some of the processes in probing outer space, such as metals, some organic compounds, and chemicals, are not adversely affected by space radiation. Space craft recovered after orbital flights and high trajectories have not shown any deterioration due to solar or ionizing radiation. The actual adverse, and even destroying, effect seems to concern exclusively living matter. If the calculations of Schaefer (ref. 15), Tobias (ref. 13), and Winkler (ref. 13) on the radiation doses associated with solar proton events are correct, the picture is not very favorable for man's flight into space. For protection, various kinds and amounts of shielding have been suggested, the discussion of which goes beyond the scope of the present paper.

WEIGHTLESSNESS

The effects of weightlessness have been investigated at various levels of biological sophistication and by various means. Men have been exposed to the zero-G condition for periods up to about one minute, and animals and organic specimens of lower order were studied in biosatellites for periods of several days. The results of these experiments have been summarized by this author and others in several publications. No pathologic effects due to weightlessness alone have been found in the specimens used. However, there were some alarming episodes of motion sickness reported by human subjects, particularly during or after dynamic exposure within the aircraft. The effects of prolonged states of weightlessness are hypothetical at this moment, and more research has to be done on the physiology and performance of man exposed to weightless periods of days or weeks (ref. 1, 2, 6).

The levels of sophistication of weightless experiments are shown in table 4. Possible remedies, such as artificial gravitation and physical exercise in space craft, are being considered (ref. 8). However, this may create new problems of stabilization, navigation, and control of the space systems concerned.

SENSORY DEVIATIONS

From our present knowledge about sensory requirements in human beings and the effect of the space environment, it can be assumed that some of our senses necessary for perception and orientation may be adversely affected. There is enough reason to believe that the sound of an exploding meteor may not be perceived, that visual perception will be impaired by glare, and that the up-and-down orientation due to gravitational cues will be lost.

The amount of sensory deviations in space is not quantitatively known at the present time. By extrapolating from experiences with high-flying aircraft and balloons, it is improbable, however, that man's performance capability will be critically affected (ref. 16). There is reason to conclude that technical means can be used to substitute or compensate for the type of sensory deviations which may be brought about by the space environment. Radar, goggles, indicators, and restraining devices will most probably suffice to maintain or restore man's sensory abilities (ref. 14).

CONFINEMENT AND ISOLATION

Confinement and isolation are the main psychological factors which will be encountered at least during the early state of manned space flight. Particular

TABLE 4

LEVELS OF SOPHISTICATION OF WEIGHTLESS EXPERIMENTATION

CLASSIFICATION	DURATION	VEHICLE	NATURE OF EXPERIMENT
Brief Exposure	2 minutes	Free-fall, Subgravity Tower, Jet Aircraft	Exploratory studies of neuromuscular, ocular, cardiovascular, gross-motor, and respiratory functions with regard to tolerance, selection, and task performance
Extra-Atmospheric Ballistic	10 minutes	Satelloids, Research Rockets, IRBM, ICBM	Includes above but potentially "purer" type exposure
Brief Satellite	Hours	Rocket	Includes all above plus complicated motor performance, cardiovascular stability, respiratory gas exterior control, and liquid-gas interior control
Prolonged Satellite	Days	Rocket	Includes all above plus psychologic studies, sleep-work cycles and efficiency, nutrition excretory waste control, etc.
Semi-Permanent	Weeks or Months	Rocket	Same as above plus muscle atrophy changes in tissue turgor, long duration problems of re-adaptation to norm after re-entry, plant geotropism, skeletal growth, etc.

reference is made to Project MERCURY and its possible extension into orbital flights of longer durations than originally planned. In this type of space craft, the astronaut is severely restricted and alone. Similar conditions will prevail in space craft of the X-15 and DYNA-SOAR type.

Many of the effects of confinement and isolation on the psychophysiological behavior of men are already known or are under study at the present time. While both factors may produce degrading effects on the well-being and performance of the astronaut, they may very well be mitigated by the use of second generation space craft. The "break-off phenomenon" as described by Clark and Graybiel (ref. 3) does not seem to be a serious problem. Thus, confinement and isolation as space factors may be of secondary importance only, if communication can be maintained between the craft and the ground and if larger-sized vehicles are available which can accommodate a highly motivated, competent, and well-trained crew.

The "isolation syndrome," consisting of hypnagogic imagery and related symptoms, is a complex stress phenomenon which seems to be predictable in terms of response rather than of causative factors and practical implications (ref. 4 & 20).

COMBINED STRESSES

At the present time, the theories about the effects of the combined stresses of the space environment on man are more speculative than based on facts. However, the assumption of accumulative effects and a possible non-linearity seem justified (ref. 18)

If we consider that there are interactions between the biochemical, physical, physiological, and psychological parameters involved, it is logical to assume, for instance, that sensory deviations may be enhanced in an individual confined, isolated, and restricted in motility in the space environment. Minor physiological disturbances may be aggravated during enforced encumbrance, weightlessness, and exposure to ionizing radiation. Therefore, it is necessary that the various factors of the space environment are studied with respect to the combined stresses which they impose on man.

Table 5 (ref. 5) shows a summary of the biophysical and logistic parameters of a satellite environment designed to accommodate a crew of one or three for periods of one or three days (ref. 5). It appears that a weight of about 33 kg would be sufficient to accommodate one man for a period of about 24 hours. The load of the stress can be considerably decreased by providing better protection, more supplies, and a higher degree of comfort to the astronaut (ref. 19).

HUMAN PERFORMANCE IN SPACE

If space is to be used effectively as a theatre of operations, an appropriate set of requirements must be established. Methods for the assessment

TABLE 5

BIOPHYSICAL AND LOGISTIC PARAMETERS OF SATELLITE VEHICLE ENVIRONMENT

Factors	Characteristics			Weight		Remarks
	Normal	Tolerance Limits	Tolerable Stress (72 hours flight)	Per man per day	3 men 3 days	
Cabin pressure	760 mm Hg	187 mm Hg	236 mm Hg	10 kg	30 kg	Weight of protective suit
Partial 0_2 pressure	160 mm Hg	39 mm Hg	100 mm Hg			
$p0_2$ alveolar	107 mm Hg	30 mm Hg	100 mm Hg			At 100% 0_2
0_2 consumption	603 1*	360 1*	500 1*	0.8 kg	7.2 kg	*Per day
CO_2 concentration	<1%	4.3%	<1%	2 kg	20 kg	Weight of CO_2 absorbent
Temperature	22° C	−40° C* +200° C	0-30° C			*Tolerance with protective clothing
Humidity	50% r. h.	<100% r. h.	<70% r. h.	2.5 kg*	22.5 kg*	Anhydrone
Acceleration	1 g	>12 g	8 g			Depending upon duration
Deceleration		80 g/sec	80 g/sec			Re-entry t = <0.5 sec
Noise	30-40 db	150 db	<130 db			
Dry food	2,800 cal	80 cal	1,800 cal	0.5 kg	4.5 kg	
Water	2.2 1	0.2 1	2 1	2 kg	18 kg	
Lighting	30-300 NIT	0.1 NIT	>30 NIT			
Radiation	0.1 mrep/d	43 mrep/d	<43 mrep/d			
Personal equipment				5 kg	15 kg	Clothing, underwear hygiene, etc.
Technical equipment (containers, blowers, ducts, etc.)				10 kg	20 kg	
Total				32.8 kg	137.2 kg	

of the environmental effects, task performances, and stresses must be based on the main task areas of the astronaut (ref. 11). They comprise the following objectives and parameters:

1. Control. It has been pointed out that the astronaut must be able to pilot a high-performance vehicle through the atmosphere during liftoff; monitor it during free flight; initiate return and control it during re-entry and landing. During a ballistic shot, and also in the standard MERCURY flight profile, the flight operation is almost entirely automatic or monitored from the ground, and the astronaut has only an option to control the craft during certain maneuvers. In future space craft, control functions will most probably be divided into remote control from the ground, direct control on board, and remote control for handling procedures from and outside the space vehicle. The designation of responsibility for the various types of activity will depend upon the characteristic of the task, the environmental conditions, and the capability of the operator under the various conditions (ref. 9).

2. Communication. Space communications encompass the problems connected with one of the basic needs of man in any type of environment: namely, to be informed about the conditions he is in, and to inform his fellow man about his own situation and the needs associated with it. Experience with space probes has shown so far that technically a two-way speech communication is feasible for lunar distances. With increasing distances and speed, motions such as the rotation of the Earth and other planets and the movements of satellite and space vehicles pose some problems of coverage of area and range, beaming, signal-to-noise ratio, and signal characteristics, which may affect the ability to communicate in space.

3. Observation. The occupant of a space craft is expected to collect and interpret information concerning the operation of his vehicle, the characteristics of his engineered environment, his performance capability and subjective experiences, and the space environment in which he operates. At least for the first part of space explorations, man will be the main recorder and transmitter for such data because of his perceptive, interpretative, and discriminative abilities. Although the "bandwidth" for perceiving and transmitting is very restricted, his "resolution capacity" is high, particularly if he is in close contact with the processes and phenomena concerned.

4. Monitoring. Even in case of automatic and semi-automatic space systems, man is supposed to perform as an inspector and troubleshooter. His effectiveness will depend mainly on the complexity of the system, his technical abilities, and the accessibility of components and parts which may fail during a space flight. At present, the possibility of replacement of faulty parts or repair activities seems to be slim.

5. Decision-making. Man's major function during manned flight operations will be that of decision-making. Although progressively sophisticated electronic equipment and computers will be available, man's intellectual superiority as decision-maker will remain unchallenged at least for the next 20-30 years. This capability appears to be particularly effective in his role as pilot of a space craft.

6. Programming and Planning. All space missions will be very carefully planned in advance. However, there will be many new and unpredictable situations in space operations. Man's flexibility, adaptability, and intuitive intelligence enables him to re-program if the situation so requires (ref. 10).

CONCLUSIONS

Two avenues of approach have been outlined which will ultimately lead to the exploration of space. They aim at the investigation of the characteristics of the space environment and of their biological effects. Ground-based laboratory experiments and actual space probes by rockets and satellites will help to increase our knowledge. In addition, actual manned space operations in vehicles already available or under construction are planned to test man's capabilities in the space theatre of operations. This latter approach is Project MERCURY.

As our space vehicle capability increases, the environment of terrestrial and interplanetary space will be consequently explored and understood. This knowledge will be advanced best by bringing research data back from actual flights. It may require a rather different engineering concept with regard to materials, tools, and procedures adequate in space. This concept may have to be based more heavily on the characteristics of the space environment and the vehicle system than on the physiologic and psychologic (sensomotor) capabilities of the operator.

BIBLIOGRAPHY

1. von Beckh, H., "Weightlessness and space flight," Astronautics 4:26-27, 84 and 86, 1959.

2. Burch, G. E., and Gerathewohl, S. J., "Some observations on heart rate and cardiodynamics during weightlessness," Aerospace Medicine 31:661-669 (1960).

3. Clark, B., and Graybiel, A., "The break-off phenomenon: A feeling of separation from the earth experienced by pilots at high altitude," Journal of Aviation Medicine 28:121-126 (1957).

4. Freedman, S. J., and Greenblatt, M., Studies in human isolation, WADC Technical Report 59-266, Wright-Patterson Air Force Base, Ohio, September 1959.

5. Gerathewohl, S. J., and Steinkamp, G. R., "Human factors requirements for putting a man in orbit," Astronautica Acta 5:73-84 (1959).

6. Gerathewohl, S. J., and Ward, J. E., "Psychophysiologic and medical studies of weightlessness," 2nd Inter. Symposium on the Physics and Medicine of the Upper Atmosphere and Space, San Antonio, Texas, 10-12 November 1958.

7. Lambertsen, C. J., "A philosophy of extremes for the gaseous environment of manned, closed ecological systems," IAS Proceedings of the Manned Space Station Symposium, 20-22 April 1960.

8. Mayo, A. M., "Requirements for artificial gravity during prolonged space flight — impact on vehicular design and operation," 7th Annual Meeting, American Astronautical Society, Dallas, Texas, 16-18 January 1961.

9. Mayo, A. M., "The Space Man-Machine System," American Management Association, Briefing Session No. 7209-01, New York, N. Y., 5-7 October 1960.

10. Mayo, A. M., "Outlook for Manned Space Vehicles," ARS Symposium, Washington, D. C., 21 February 1961.

11. McKenzie, R. E., Hartman, B. O., and Welch, B. E., "Observations in the SAM two-man space cabin simulator. III System Operator Performance Factors," 32nd Annual Meeting, Aerospace Medical Association, Chicago, Illinois, 24-27 April 1961.

12. Morgan, E. E., and Welch, B. E., "Observations in the SAM two-man space cabin simulator. II Biomedical Aspects," 32nd Annual Meeting, Aerospace Medical Association, Chicago, Illinois, 24-27 April 1961.

13. Proceedings of Conference on Radiation Problems (Ed. by G. J. Jacobs), National Aeronautics and Space Administration Technical Note D-588, December 1960.

14. Rose, H. D., "Perception and Reaction Times," Physics and Medicine of the Atmosphere and Space (Ed. by O. O. Benson and H. Strughold), John Wiley & Sons, Inc., 1960.

15. Schaefer, H. J., "Proton radiation hazards in space," Astronautics 6:39, 62-67 (1961).

16. Simons, D. G., Man High (with Don A. Schance), Doubleday, New York, N. Y., 1960.

17. Strughold, H., "Biophysics of the Space Environment," Lectures in Aerospace Medicine, School of Aviation Medicine, USAF Aerospace Medical Center, Brooks Air Force Base, Texas, 11-15 January, 1960.

18. Voas, R. B., "Project Mercury simulations involving acceleration," NRC-Armed Forces Committee on Bioastronautics, Panel on Acceleration Stress, Palo Alto, California, 6-10 March 1961.

19. Welch, B. E., and Morgan, T. E., "Observations in the SAM two-man space cabin simulator. I Logistic Aspects," 32nd Annual Meeting, Aerospace Medical Association, Chicago, Illinois, 24-27 April 1961.

20. Wheaton, J. L., "Fact and fancy in sensory deprivation studies," USAF School of Aviation Medicine, Brooks AFB, Texas, Reviews 5-59, August 1959.