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BIOMEDICAL REQUIREMENTS FOR SPACE CABIN ENVIRONMENTS

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Introduction

In this paper I plan to discuss the physiological needs of space crews that must be provided for by the life support systems of space craft. I will make no effort to define how the space crew's physiological needs will be met. This is a task for the designers of life support systems, one involving all of the scientific disciplines and a subject far too broad and technical for me, as a physician, to attempt. I can only hope to present the more urgent physiological requirements of space crews for which provision must be made when man travels in space.

I have divided these physiological requirements into several categories, each of which will be discussed independently. Listed in order of decreasing priority, the space crew will require

1. A livable atmosphere.
2. Food and water.
3. Radiation protection.
4. Provision for personal hygiene.
5. Provision for control of fatigue.
6. Protection from the effects of weightlessness.

For even the shortest space mission, the first of these, a livable atmosphere, is absolutely essential. The others assume increasing importance with increased length and complexity of the space mission.

A Livable Atmosphere. The ideal atmosphere would be that which exists in an air-conditioned building at sea level in which the individual can select the most comfortable temperature and humidity to suit himself. However, with proper clothing and some acclimatization, man can adapt himself to rather extreme atmospheric conditions. Man can, and does, live in the desert, the jungle and the arctic. He can live at sea level or at altitudes of two to three miles above sea level, yet there are uninhabitable areas on earth as a result of temperature and altitude extremes to which man is unable to adapt. Somewhere between the extremes of temperature, humidity and atmospheric pressure that exist in the desert, jungle or mountains, and that of the air-conditioned sea level building, we will find the conditions in our space cabin. Our problem is to determine the most ideal atmosphere for the space cabin.

The ideal atmosphere for man on earth is not necessarily the best atmosphere for use in space cabins. I would suggest we look first at the minimum requirements a space cabin atmosphere must provide for, if man is to survive in space, and then see what can be added to this minimum atmosphere to improve upon it.

The single most important function of man's atmosphere is the provision of oxygen for respiration. For oxygen to be useful to man it must be of sufficient partial pressure when it reaches the alveoli of the lungs so that it is picked up by hemoglobin and circulated to body tissues. It is desirable that hemoglobin be 100 per cent saturated with oxygen as the blood circulates through the capillaries of the lungs. The minimum partial pressure of oxygen required in the alveoli of the lungs to provide for 100 per cent saturation of hemoglobin is approximately 100 mm of mercury, Two other constituents are always present in alveolar gas: water vapor and carbon dioxide. For this reason, breathing 100 per cent oxygen at 100 mm of mercury, pressure will not provide for 100 per cent saturation of hemoglobin with oxygen. Normally, depending upon the atmosphere breathed, between 30 and 40 mm of carbon dioxide is always present in the alveoli and 47 mm of water vapor, the vapor pressure of water at body temperature. The partial pressure of carbon dioxide and water vapor in the alveoli is normally about 87 mm of mercury. Therefore, to provide a partial pressure of oxygen of 100 mm of mercury in the alveoli, the total pressure must be 187 mm in the alveoli and, thus, 100 per cent oxygen at 187 mm of pressure must be inhaled to provide for 100 per cent saturation of hemoglobin. This is roughly the environment to which todays crews are exposed when wearing full pressure suits, a 100 per cent oxygen environment at 3.5 psi or 183 mm of mercury.

At this point it might be best, from the standpoint of clarity, to change units. Conventionally, when discussing respired gases. the partial pressures of gases are measured in mm of mercury. When discussing cabin pressures, the most commonly used unit is pounds per square inch.

As just mentioned, the minimum atmosphere that can be used which will maintain space crews' oxygenation at 100 per cent is 3.5 psi, the pressure used in todays pressure suits. In order to provide a margin of safety in the event of a cabin leak or puncture, todays space craft, Mercury and Gemini, were designed to operate at 5 psi. For the shorter space missions, the use of 100 per cent oxygen at 5 psi has proven quite satisfactory.

There are two good reasons for not selecting cabin pressurizations of less than 5 psi. First, as already mentioned, the use of lower pressures would be quite hazardous in the event of an undetected cabin leak or puncture. If a minimum pressure of 3.5 psi were used, for example, and a puncture occurred, the space crew might become hypoxic too rapidly to take corrective action. Another problem with selecting cabin pressures below 5 psi is related to bends. Whenever air crews are pressurized below 5 psi, bends occur quite frequently. However, at pressurization above 5 psi, bends are extremely rare. Pre-breathing, prior to launch, of 100 per cent oxygen for several hours can greatly reduce the incident of bends following depressurization to below 5 psi, but does not completely eliminate this possibility. I feel that both of these factors were important considerations in the solution of a cabin pressure of 5 psi for Mercury and Gemini.

Using a single gas system, that is 100 per cent oxygen, it is impractical to use a pressure of more than 5 psi because of the problem of oxygen toxicity. For prolonged missions there may even be a problem with oxygen toxicity with the 5 psi 100 per cent oxygen system. Low pressure chamber runs with such an atmosphere have indicated there may be some minor problems after exposure of two weeks or more. Low pressure chamber studies have been conducted with the 5 psi 100 per cent oxygen atmosphere by the Air Force, Navy and Republic Aviation.[1] In all of these studies there have been some indications of oxygen toxicity, as manifested by eye irritation, coughing, substernal pain and aural atelectasis. In the Republic Aviation studies, there were some hematological and urinary changes which are requiring further investigation. In the Navy studies, some change in peripheral vision has been noted during night adaptation after subjects were returned to sea level. However, it has not been felt that any of these problems are of sufficient magnitude as to prevent the use of the 5 psi 100 per cent oxygen atmosphere for missions of up to two weeks in length. For longer missions, further study is required to determine the suitability of this atmosphere.

Another serious problem with the use of the 5 psi 100 per cent oxygen atmosphere is the increased fire hazard. Although there have been no fires aboard the Mercury space craft, two fires have occurred in altitude chambers using this atmosphere, one at the Air Force School of Aerospace Medicine and one at the Navy Aircrew Equipment Laboratory. A study at the Naval School of Aviation Medicine has shown that in this atmosphere, paper ignites at a lower temperature and burns approximately six times faster than in our normal sea level atmosphere.[2] It was also found that neoprene coated nylon twill, lightweight nylon and vinyl plastic all ignited in this atmosphere, whereas, with the normal sea level atmosphere, these materials melt but do not ignite.

For prolonged space missions, it appears that, from the point of view of the space crew's well-being, our sea level atmosphere would be best. Such an atmosphere gets around the oxygen toxicity problems and drastically reduces the fire hazard. At the same time, a new hazard is introduced, the problem of bends in the event of loss of cabin pressure. This does not necessarily mean that a sea level atmosphere is still not most desirable from a physiological standpoint. We can get around the bends problem by developing pressure suits that operate at 5 psi or more. Even so, the sea atmosphere is not the most practical. Healthy individuals function very well in cities like Denver, Colorado, where the ambient pressure is about 12 psi. For that matter, many of us have camped in the mountains on hunting and fishing excursions at altitudes of 10, 000 feet where the ambient pressure is down to 10 psi. At this altitude, breathing our normal earth atmosphere, the alveolar partial pressure of oxygen drops to about 61 mm of mercury but, because of the affinity of hemoglobin for oxygen, our arterial oxygen situation remains at about 90 per cent. Such an altitude is tolerated quite well by healthy individuals, the only measurable effect being some loss of dark adaptation by the retina of the eye and, thus, a loss of night vision. A slight enrichment of the atmosphere with oxygen can easily correct this. Such an atmosphere would greatly reduce the likelihood of bends in the event cabin pressure is lost and the 3.5 psi pressure suit must be relied upon. Also, the fire hazard is much lower than with the 5 psi 100 per cent oxygen system. I feel rather safe in predicting that man could function at 100 per cent efficiency for an indefinite period of time in space with a 30 per cent oxygen, 70 per cent nitrogen atmosphere at 10 psi. Probably, an atmosphere of 50 per cent oxygen, 50 per cent nitrogen at 7 psi could be tolerated for an indefinite period of time, but more work needs to be done on such atmospheres in altitude chambers before this can be said with impunity. I think it highly doubtful that the present 5 psi, 100 per cent oxygen system will suffice for prolonged space missions.

For a more detailed approach to the selection of space cabin atmospheres, I would refer you to the article in the August 1963 issue of Astronautics and Aerospace Engineering by Parker and Ekberg.[3] However, before leaving the subject of a livable atmosphere and moving on to the other aspects of life support systems, some mention of carbon dioxide management, control of toxic materials and the control of temperature and humidity must be made.

The present threshold limit value for carbon dioxide, as recommended by the American Conference of Governmental Industrial Hygienists, is 5000 parts per million. This is based on exposure at sea level, 8 hours per day, 40 hours per week. This corresponds to a partial pressure of carbon dioxide in respired gases of 3.8 mm of mercury. This is a safe level at which no symptoms would be expected. The anesthetic level for carbon dioxide is about 75 mm of mercury. At levels of 20 to 25 mm of mercury, corresponding to an early submarine level, symptoms have been described of a biphasic excitation-depression reaction in humans.[4] The minimum level at which symptoms of carbon dioxide toxicity might be expected lies somewhere between the 3.8 mm partial pressure, as recommended in the threshold limit values, and the 20 to 25 mm level. I would suggest that, for planning purposes, one should strive for the 3.8 mm level or less.

For other contaminates of the space cabin atmosphere, I would suggest that the threshold limit values for toxic substances, as recommended by the American Conference of Governmental Industrial Hygienists, be used as a guide, keeping in mind that these levels are based on the 40 hour work week and not the 168 hour week to which astronauts will be exposed. As in the nuclear submarine program, every effort must be made to keep all contaminates out of the space cabin atmosphere. When contaminates are unavoidable, they must be identified and dealt with on an individual basis, keeping in mind that two or more contaminates might act synergistically.

The remaining variable, so far as a livable atmosphere is concerned, is that of temperature and humidity. In order for the space crew to maintain heat balance, it will be necessary for them to exercise some degree of control over the temperature and humidity of their atmosphere. Maintaining heat balance is a function of heat gain vs. heat loss by the body. The more important sources of heat gain are metabolic activity and absorption of infrared radiation from the surroundings. Heat loss is primarily controlled by the evaporation of water and the irradiation of infrared radiation by the body. The rate of heat loss by the evaporation of water is dependent upon the temperature and humidity of the air and the rate of circulation of air over the skin. With this many variables to consider, it is impossible to choose any one temperature and humidity standard for the space cabin atmosphere. Heat loss or gain by radiation will be dependent upon the clothing worn by the space crew and the effective temperature of the walls of the space cabin. Heat gain from metabolism will depend upon the activity of the space crew. The amount of clothing worn, the heat load on the space cabin and the activity of the crew will all vary over rather wide ranges during prolonged space flight. The life support engineers must consider all of these factors, in light of the particular mission, in their design of the degree of control the space crew must have over the temperature and humidity of the space cabin.

Food and Water. After provision of the space crew with a livable atmosphere, the next most important biomedical requirement will be that for food and water. I feel that the most important factor to consider in provision of a diet for space crews is that of palatability. The food must be appetizing and palatable, or it will not be eaten. This is important, not only from a nutritional standpoint but also it is an important morale factor. This will be especially true for the longer space missions. Aside from providing space crews with food that is sufficiently palatable to be eaten, other prime factors to be considered are providing adequate nutrition and avoidance of foodstuffs that might cause gastrointestinal disturbances such as diarrhea or constipation. The food must also be provided in such a manner that it requires a minimum of storage space, will not spoil, is readily prepared for consumption and can be consumed under weightless conditions.

So far as content is concerned, the space diet must provide for a total calorie intake of between 2500 and 3000 calories. It should be a high protein, low bulk, low residue diet, containing all of the essential amino acids, fats, minerals and vitamins. Foodstuffs that are diuretic or of high cellulose content must be avoided in order to keep the space crews' output of urine and feces at a nominal value. The problem of urination or defecation while wearing a pressure suit is still a major one with no easy solution. Not only is there a problem in removing and donning of pressure suits, but also one of collection and disposition of these body wastes in the cramped quarters that can be provided the space crew.

The requirement for water will depend on a number of factors, such as the loss of water from the body by evaporation, perspiration, urination and defecation, and the water gained by the body from that contained in foodstuffs and from the metabolism of food. It is estimated that space crews will require from five to ten pounds of water per day for drinking and reconstitution of foodstuffs. The lower value is for the shirt-sleeve environment where heat balance is controlled primarily by control of the environmental temperature. The higher value, ten pounds per man per day, is an estimate of the water requirement when wearing pressure suits where heat balance is maintained by evaporation of perspiration.

Radiation Protection. I have listed radiation protection as next in priority after provision for a livable atmosphere and for food and water. This is not a very critical consideration for earth orbital missions, but is a factor of considerable importance for moon probes and especially deep space probes. It is outside the scope of this presentation to discuss the amounts and types of ionizing radiation that might be encountered on a space mission, or how much of what kind of shielding will be required. Rather, it is my purpose to outline the limits to which crews might be exposed and the risks entailed by such exposure.

At present, the limits for exposure to whole body ionizing radiation for workers in industry where radiation exposure is a hazard is set at 5 rem per year. Such an exposure entails no measurable risk. Approximately the lowest level of exposure to ionizing radiation at which some measurable effect can be detected in man is about 50 rem. Clinically, about all that can be detected following an exposure to 50 rem are some slight changes in the morphology of the cellular elements of the blood. Even this is only a transitory effect. However, statistically, it is estimated that this level of exposure to the entire population would approximately double the incidence of genetic mutations and of leukemia. For the crew of a space craft, this is a rather small risk in comparison to other risks entailed on deep space probes. I would think that designing shielding to prevent an acute exposure in excess of 50 rem in the event of an unpredicted solar flare would not be unreasonable. This is less than half the dose of whole body ionizing radiation that might produce symptoms of radiation sickness. It would require an acute exposure to something on the order of 150 to 200 rem to produce any symptoms of radiation sickness among the members of a space crew.

Another type of electromagnetic irradiation from which crews must be protected are the direct rays of the sun. Provision must be made to prevent crews from inadvertently looking into the sun. Also, adequate protection must be provided from the intense infrared radiation to which crews will be exposed during extravehicular activities in space.

Provision for Personal Hygiene. I have listed next, in order of importance so far as biomedical requirements are concerned, the provision for personal hygiene. For prolonged space missions, provision for personal hygiene is important as both a biomedical and morale factor. This entails provision for elimination of urine and feces, cleansing of the skin, shaving and cleansing of the teeth. For missions of a few weeks, I suppose the crew can get by without haircuts, but for extremely long missions some provision may even be necessary for haircutting.

For short missions, up to two days, the crew can manage without removal of the pressure suit. However, for anything longer than this, provision must be made for at least partial removal or opening of the pressure suit for purposes of urination, defecation and cleansing of the skin. For the long range missions, more than two weeks, provision must be made for complete removal of the pressure suit and for a shirt-sleeved environment. We must also provide for changing into clean clothing. If we are to prevent skin disease, it is just as important to have clean clothing as it is to bathe.

In providing for personal hygiene, the importance of preventing contamination of the cabin atmosphere should be emphasized, especially in reference to such details as whiskers from shaving and/or materials used in cleaning the skin that might be toxic in recirculated air.

Provision for Control of Fatigue. For shorter space missions, control of fatigue has not been a serious problem. Astronaut Gordon Cooper reported having no difficulty in sleeping during the MA-9 flight.[6] At this point in time, I don't feel that we can say much about sleep during space flight, other than that it is possible to sleep while strapped in one's seat wearing a pressure suit during the weightless state. Whether adequate sleep can be obtained in this manner to prevent fatigue as a result of inadequate rest over a period of days is still a matter of conjecture. The programmed two week Gemini missions should prove very enlightening regarding the requirements for sleep over prolonged periods of space flight.

Fatigue is a difficult thing to measure. Sleep, recreation and work are all factors influencing fatigue. For certain critical phases of space flight it is important that crews are alert and at their peak, so far as performance goes. To insure that this is so, it will be necessary to work out cycles for work, rest, recreation and sleep. However, since it is impossible to simulate the conditions of space flight, especially the weightless state and the anxiety which influences all of these to an unknown degree, we must wait for the longer Gemini flights before defining the requirement for rest, recreation and sleep during longer missions.

Protection from the Effects of Weightlessness. I have listed as the last of the biomedical requirements for space cabin environments, protection from the effects of weightlessness. Before the first orbital flight, there was considerable speculation regarding the possible adverse effects that might result from prolonged weightlessness. However, at least for these shorter flights, exposure to the weightless state has had no ill effects. For longer flights, one might still speculate that there may be undesirable effects. There may be some problem as a result of disuse of certain muscles, the lack of weight bearing on the skeletal system, or the lack of stimulation of the proprioceptive reflexes for control of balance. However, if such effects should result from longer exposure to the weightless state, I feel certain that exercises can be utilized to prevent most, if not all, of these ill effects.

Conclusion

In conclusion, I have attempted to outline the biomedical requirements for the space cabin environment. I have discussed the more important factors bearing on the selection of the cabin atmosphere, food and water requirements, protection from radiation, provision for personal hygiene, control of fatigue and the effects of weightlessness. The satisfactory solution to the many problems entailed in providing for these biomedical requirements for prolonged space flight is a considerable task, but one that the designers of life support systems are accomplishing in an admirable manner.

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