Man's Milieu in Space A Summary of the Physiologic Requirements of Man in a Sealed Cabin

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N AN AGE of high altitude and high performance aircraft, it is necessary to develop a method for designing and constructing sealed cabins for flights beyond the atmosphere of the earth. This subject is of interest since it is apparent that, strictly from an engineering standpoint, it is now possible to build craft which can travel at great heights and at high velocities. The problem is now that of providing a safe and comfortable gaseous environment for the human occupants. Such a physiological environment can be provided above 70,000-80,000 feet altitude only by an isolated, self-sustaining capsule; a true sealed cabin.

The term pressurized cabin refers to those cabins in which the atmospheric pressure is maintained and the cabin ventilated by superchargers or compressors. This is not a serious problem for commercial aircraft which rarely fly at extreme altitudes. But for very high flying military aircraft, pressurized cabins become a practical impossibility, for at 100,000 feet altitude the cabin pressure/ambient pressure ratio would be approximately 65 to 1 with an interior pressure of 10 psi (corresponding to a cabin altitude of 10,000 feet). The exit temperature of air compressed to 10 psi at 100,000 feet altitude from a compressor capable of such a prodigious feat would be of the order of 1000° F. At this altitude 6.5 horsepower are required to compress one pound of ambient air to 10 psi, a power output that is far beyond the practical capacity of present-day compressors, not to mention the problem of dissipating the heat produced.¹¹

Furthermore, an aircraft equipped with a sealed cabin can fly with safety through such hazards as toxic and radioactive clouds since no outside air reaches the occupants of such a cabin. Were an aircraft flying above 80,000 feet equipped with a compressor capable of pressurizing its cabin to a comfortable atmosphere for human occupants, its cabin probably would contain toxic amounts of ozone. Pressurized cabins then, are of limited usefulness by reason of low atmospheric pressure and the presence of ozone at high altitudes.

In the following paragraphs a critical review of the available information on this subject will be presented as compiled in the Department of Space Medicine, USAF School of Aviation Medicine, Randolph Air Force Base, Texas. Its purpose is to help provide an up-to-date source of information which can be used for further research.

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HISTORICAL

Until recent years, little thought has been given to the engineering details of sealed cabins for stratosphere and space flight.² Probably the idea originated in Science Fiction writings, or rather in the minds of Science Fiction readers. Early authors in that field of fantasy, glibly sidestepped the problem of artificial atmospheres in space ships. However, at the first symposium on Space Medicine, organized by General Harry G. Armstrong at the USAF School of Aviation Medicine in 1948, the problem of O_2 storage for space flight, among other things, was touched upon for the first time from a strictly scientific viewpoint.4

The most valuable information on cabin acclimatization to date has come from balloon ascensions. In March 1933, Auguste Piccard published the results of his ascensions in a sealed gondola.14 The first flight, in 1932, was deemed a failure because of severe discomfort to the occupants of the gondola. Prior to the flight, while inflating the balloon, the gondola was dragged from its cradle, causing damage to the rotating apparatus. The black portion of the gondola faced the sun throughout the flight, causing the interior temperature to rise to 104° F. Furthermore, the valving apparatus failed and the balloon descended only after nightfall when the gas in the balloon had cooled sufficiently to lose lift.

Only a very short description of the oxygen supply and CO_2 and H_2O absorption apparatus was given by Piccard. Liquid O_2 was used and the CO_2 was absorbed by alkali.

Stevens and Anderson in 1934 and

Pounds
Oxygen consumed 1.71
Oxygen evaporated
Oxygen carried
Nitrogen evaporated
CO ₂ given off by occupants 1.99
H ₂ O in gondola at time of closing ports .04
H ₂ O in gondola at time of opening ports .02
H ₂ O given off by occupants 2.80
Maximum H ₂ O removal by 15.25
pounds of NaOH 3.20

1935 made two historical balloon flights, the first of which nearly ended in disaster when the hydrogen in the balloon exploded.¹⁸

The second flight, in the *Explorer II*, in which helium was used, was a smashing success. The record altitude of 72,395 feet was reached and much valuable data obtained relative to atmospheric conditions at high altitude. These data were published by the National Geographic Society¹⁹ and medically evaluated by Armstrong.³.

The gondola was constructed of Dowmetal, a light magnesium alloy. After the hatches were sealed at an altitude of 16,000 feet, O2 was supplied from a mixture of 45 per cent liquid O2 and 55 per cent liquid N_2 in a vented container. The liquid was forced through a vaporizing coil placed at the top of a column containing the CO² and H₂O absorption apparatus. A fan forced continuous circulation of the gondola air through this vaporizing coil and thence through the CO₂ and water absorbing column which contained 15.25 pounds of sodium hydroxide (NaOH) pellets in twelve cotton gauze bags. Cabin altitude was maintained at about 13,000 feet by an automatic siphon type valve. Table I shows the pertinent

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TABLE II. AVERAGE 02 CONSUMPTION AT VARIOUS LEVELS OF ACTIVITY (cubic feet/hour)

Rest		
Moderate exercise	(walking 3	mph)2.26
Strenuous exercise	(walking 5	mph)5.40

data on CO_2 and H_2O absorption and O_2 consumption by the two persons in the gondola.

The interior of the gondola was quite comfortable throughout the 5.75 hours during which the hatches were sealed. The rotating mechanism, consisting of an electric fan on a steel arm worked perfectly even in the rarified atmosphere, and the temperature inside the gondola rose from 21 degrees F. at the start to 43 degrees F. at the ceiling although the outside temperature fell to —81 degrees F. at 68,000 feet.

The atmosphere within the gondola was quite comfortable. However, the use of NaOH as both a CO_2 and H_2O absorber was not recommended due to the narrow margin between the amount of H_2O actually absorbed and the amount which would have saturated the NaOH (Table I).

Experiments are currently being conducted at Hollomann AFB, New Mexico, with animals in aluminum cannisters in an effort to provide a livable sealed cabin atmosphere for high altitude studies of cosmic ray effects. To date more than a dozen balloon flights have been made by the Aeromedical Field Laboratory at Hollomann and work has been done by General Mills, Inc., the Lovelace Foundation, various engineering companies, and others, in the quest for a satisfactory method. Animals have been recovered alive after ascents in excess of 90,000 feet.¹⁷

The Aerobee Rocket flights with monkeys and mice, heralded as milestones in the conquest of space, did not contribute significantly to the solution of sealed cabin problems since the flights were so short that it is possible the animals could have survived on the oxygen in the cabin alone.⁸

PHYSIOLOGIC REQUIREMENTS OF MAN IN A SEALED CABIN

Since it is mainly within the province of the engineers to construct a shell which can maintain a comfortable range of heat exchange and resist high pressure differentials, little attention will be paid to construction details except in a general way. An air-conditioning survey has been conducted by the Harper Engineering Company outlining requirements for a specific type of high altitude research vehicle.¹

In general, the physiologic requirements are as follows:

A. Oxygen Requirements.—As seen in the data of *Explorer II* (Table I), nearly forty times as much O2 was carried as was actually consumed by Stevens and Anderson in a 5.75 hour flight. Roughly one-third of the O2 carried was vented in order to maintain a cabin altitude. Only steady 1.71 pounds of liquid O2 were consumed by two adult men performing moderate exertion in a confined space. This suggests that if venting can be held to a minimum, O2 supply will not be too difficult a problem. Table II shows average oxygen consumption at several levels of activity. These may be lowered somewhat by a prolonged gravity free state.

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TABLE III. ESTIMATION OF CO₂ PRODUCTION, WEIGHT OF ALKALI CANNISTERS NEEDED FOR CO₂ ABSORPTION FOR VARIOUS PERIODS OF SUBMERGENCE ON A GERMAN FLEET-TYPE SUBMARINE CREW, 50 MEN*¹⁶

After	1	4	8	12	16	Hours
Total CO ₂ produced; liters CO ₂ Content, percent No. Cannisters needed for total absorption of CO ₂ Weight of Cannisters in Kg.	1050 0.21	$\begin{array}{r} 4200\\ 0.84\\ 10.5\\ 525\\ 26.25\\ 1312.5\end{array}$	$\begin{array}{r} 8400\\ 1.68\\ 21\\ 1050\\ 52.5\\ 2625 \end{array}$	$\begin{array}{r} 12,600\\ 2.52\\ 31.5\\ 1575\\ 78.75\\ 3937.5\end{array}$	$\begin{array}{r} 16,800\\ 3.36\\ 42\\ 2100\\ 105\\ 5250 \end{array}$	per day for 50 days per day for 50 days

*German U-boats during World War II were normally supplied with 800 such cannisters.

The problem of weight is an important one if long flights are to be considered. Even in submarines, where storage space is at a premium, it is necessary for the crews to be subjected to long periods of oxygen depletion, necessitated by the ever-increasing ability of these craft to remain submerged.9 Clearly, an efficient CO2 and H2O absorbing apparatus is necessary for long flights in order to conserve supplies. A fiberglass oxygen container now under development should alleviate the weight problems in aircraft considerably. An experimental model has the same weight as a standard USAF D-2 oxygen bottle (5 lbs. when full) but holds five times its capacity of oxygen under a pressure of 5,000 psi.* The capacity of the D-2 bottle represents 221 liters of oxygen at standard temperature and pressure. Liquid oxygen would be most economical if a container of sufficient strength to contain it without venting were available.

B. Carbon Dioxide.— (CO_2) and water (H_2O) elimination.

There are four basic methods of CO₂ removal:

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which are satisfactory for flights of less than thirty hours' duration.1 Sodium hydroxide (NaOH) was found satisfactory by Stevens and Anderson for CO₂ removal, but not for H₂O removal due to the small safety factor.19 Magnesium Perchlorate $(Mg(Cl0_4)_2)$ was found to be satisfactory by the Harper Engineering Company.1 Others are soda lime (a mixture of calcium and sodium hydroxides), lithium hydroxide (LiOH) and other alkalies. The disadvantage of chemical absorbers is that they all have a limit of saturation and the cabin continues to carry with it all the H₂O and CO2 that has been absorbed from its atmosphere, while the efficiency of the absorber continues to decline. Table III represents a calculation of the number of alkali cannisters, and their combined weight, necessary to remove the CO2 from a submarine with an air volume of 500 cubic meters and a crew of 50 men. By interpolation it is seen that for a crew of five men in continuous flight for seventy-two hours, 18.9 of these cannisters with a weight of more than 100 pounds would be needed.16 However, most chemical absorbers can be induced to part with their H2O and CO2 rather easily and a method may be developed of heating to drive off H2O and CO2 and release of same through an airlock without loss of oxygen.

Table III also shows an increase in CO_2 content to 3.36 per cent after sixteen hours of continuous operation. Studies of the composition of the atmosphere in submarines have shown that after prolonged submerged operation the CO_2 content may reach 5-6 per cent while the oxygen drops to as low as 15-17 per cent.¹⁶ Under these conditions the combined effects of hypoxia

^{1.} Chemical.—Several excellent chemical methods of CO_2 absorption have been used

^{*}Simons, Major David G.: Personal communication.

and CO_2 accumulation are additive and may result in depression, headache, disorientation and loss of judgment and efficiency. These conditions appear even in snorkel equipped vessels. It is essential that the CO_2 content of a sealed cabin atmosphere be kept well below 3 per cent.

- 2. Physical Methods
- (a) The "water scrubber." A method of washing out CO₂ with sea water. It is said to work well in submarines.
- (b) Filters. The basic principle is selective permeability, e.g., a thin rubber dam is more permeable to CO_2 than to O_2 .
- (c) Venting. Controlled venting would be a simple solution for flights of short duration. It would be wasteful of O₂ supplies on a long flight, however, and probably of limited usefulness for this reason.
- 3. Air reduction-liquefaction.—Essentially a distillation method of CO₂ removal. Liquid CO₂ could then be jettisoned. This type of apparatus is at present heavy and bulky.

4. Enzyme systems.—Theoretically, carbonic anhydrase could be made to remove CO_2 which could then be compressed or liquefied and jettisoned.

Experiments are being conducted with plants to determine if photosynthesis can be utilized. J. Meyers, on the basis of preliminary work with algae, indicates that not only may the oxygen requirement be met, but the CO₂ removed as well, while providing part of the food requirements.13 This is widely done in balanced aquaria, why not in sealed cabins? Unfortunately, the efficiency of a photosynthetic gas exchange system is low. Myers estimates that for a 167-lb. man at 120 Kg calories per hour (150 per cent of normal BMR), 25 liters of O_2 at an R.Q. of 0.825, would be required and could be supplied by 2.3 kilograms (fresh weight) of Chlorella pyrenoidosa, a species of green alga.13 This does not seem unreasonable until the requirements of this plant are examined. A suspension of 10 grams/liter provides maximum absorption (98 per cent) of light at 6800 AU in a layer not more than 1.0 centimeter thick if illuminated from both sides. This requires an illuminated surface of 240 square feet for 230 liters of suspension per man. Based upon the efficiency of fluorescent lamps (the highest obtainable) at 19 per cent and the $CO_2 \rightarrow O_2$ efficiency of the alga at 10 per cent, 10 horsepower would be required to produce one "man-unit" or 130 Kg. Cal O₂ equivalent per hour. This is a rather impractical power requirement. Moreover, this type of machinery would require about 80 cubic feet of space per man-unit.

However, in view of its very newness, and the high probability that more efficient photosynthetic gas exchangers may be developed, this line of research should not be abandoned as long as the prospect of new and improved power, as well as light sources, exists. N. J. Bowman has suggested the use of algae for food and atmosphere control on long flights but recommends the lighter and less complicated oxygen storage method with chemical CO_2 removal and storage of dehydrated food for shorter flights.⁶

C. Temperature. — Early thought along this line was concerned with keeping warm since the temperature at 70,000 feet can be as low as —80 degrees F. Indeed, it has been, and still is, a large factor in aviation today. However, with increasing speed of aircraft exceeding Mach 2, high skin temperatures and hence high cabin temperatures are being encountered. This will become an increasing problem as clouds) to conduct and absorb heat. The problem, then, is essentially one of reflection-absorption of radiant heat; the dark body absorbs and the light body reflects. A properly con-



frosting,

speeds increase within the earth's atmosphere with current thought being directed toward refrigerated cabins, and ventilated pressure suits.

Space, on the other hand, cannot be truly said to have any temperature at all, since there is no atmosphere (except for some widely dispersed gas DECEMBER, 1954 trolled balance between reflectors and absorbers is necessary for the cabin in flight outside of the atmosphere.

The comfortable range for human occupants of a sealed cabin is 50-75 degrees F. However, frosting of hull and windows occurs with an interior temperature of 50 degrees F., a rela-

tive humidity of 47 per cent (comfortable humidity range 40-60 per cent), and an interior surface temperature of 30 degrees F.¹ According to these findings the lowest possible interior temperature and lowest possible humidity consistent with comfort pheric temperature of 60 degrees F., and internal hull temperature of 30 degrees F., frosting will occur at 35 per cent humidity according to the Harper Engineering Company. Clearly, in order to maintain a comfortable range of atmospheric temperature, the



Fig. 2. Safe limits in cabin pressure when breathing air or breathing oxygen for normal individual (A) and for crews who have been specially adapted to low barometric pressure by natural acclimatization (B). The columns are based upon the partial pressure of gases for inspired air saturated with water vapor at body temperature. Copyright 1952, The Lovelace Foundation.

should be maintained since the lower the temperature, the higher the humidity can be without frosting. (Fig. 1).

Conversely, with an interior atmos-

internal hull temperature should be higher than 30 degrees F., if frosting is to be prevented. Moreover, an individual surrounded by an atmospheric temperature within the "comfort

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zone" could lose large amounts of body heat by radiation toward a cold wall with resultant discomfort and danger to health.

In actual space flight, except for periods of acceleration and deceleration, a condition of zero G or gravity free state will prevail. This will almost certainly bring heat exchange by conrotation of the cabin or by continuous acceleration.

D. *Pressure.*—The ideal atmospheric pressure is, of course, that pressure at or near sea level. But this would exert a pressure of more than 2,000 pounds per square foot on the interior of a hull in space. Comfort-



Fig. 3. Tolerance to oxygen as related to total pressure and oxygen content in a pressure cabin. At partial pressures of O_2 in excess of 425 mm Hg. toxic effects may ensue, depending on time of exposure. Copyright 1952, The Lovelace Foundation.

vection to a standstill. A human being would be surrounded by an atmosphere of his own expiratory gases—a condition which, though not dangerous, could be quite uncomfortable. During sleep there might be danger of suffocation as well as overheating. Forced circulation of the cabin atmosphere then will be necessary during any period of zero G, either by fans or by artificial gravity induced by

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able cabin pressure would vary with the amount of O_2 present. Probably the lowest safe cabin pressure is that equivalent to not more than 30,000 feet altitude if the cabin air were 100 per cent O_2 This would exert a hull pressure of only 628 pounds per square foot. Clearly, the lower the inside pressure, the lighter the hull can be. On the other hand, long exposure to 100 per cent O_2 at higher

pressure causes irritation of the lungs and eventually pulmonary congestion and edema. Probably the space ship of the future will have less weight restriction than is imposed by present fuels, allowing for stronger hulls and higher interior pressures. The lower limit of comfortable oxygen partial pressure is about 90 mm Hg. CO₂ should not exceed 10 mm Hg. These limits can - be reduced slightly by acclimatization¹⁰ (Fig. 2). According to Clamann and Luft, tolerance to oxygen is limited only if its partial pressure exceeds 425 mm Hg. This means that an atmosphere of pure oxygen is safe if its equivalent altitude is above 15,000 feet.¹⁰ (Fig. 3).

E. Noxious Gases. — Armstrong doubts that odors can be controlled.¹²

Although noxious gases such as carbon monoxide and exhaust fumes can and must be held within safe limits, the removal of cooking odors, body odors and the like, while not essential to life, certainly effect comfort and morale. It is not inconceivable that foul odors can be a danger to life if they result in severe nausea, vomiting and concomitant loss of crew effectiveness.

Satisfactory methods of odor masking are in use throughout the civilized world. Most of these, however, depend upon displacing of one odor with another and subsequent dispersal into that vast diluent, the atmosphere.⁷ This is manifestly impossible in the limited atmosphere of a sealed cabin. Toxic materials such as exhaust fumes, fuel and hydraulic fluid vapors can be excluded from the cabin by engineering means. But such normal physiologic

excreta as methane, hydrogen sulfide, indol, skatole and the excretory amines are very much with us, and when they cannot be removed by dilution and dispersion, other means must be employed. Even the commonplace odor of acrolein, produced from overheating of cooking fats can give way to toxic concentrations in a confined spaceoccupational hazard of chefs. an Smoking, ordinarily a benign habit, could produce dangerous amounts of carbon monoxide over a prolonged period of time. Suggested by H. Specht are absorption of many of these substances by the same alkali which removes CO₂ and water and, more important, continued research for specific methods of removing those which must be considered hazardous during prolonged exposure.18 Activated carbon filters are effective for many substances. Toxicity data for individual compounds and time-concentration curves have been outlined by the Committee on Aviation Toxicology, Aeromedical Association.⁵

F. Noise.—Flight above the atmosphere is probably noiseless. However, although jet aircraft are said to be almost noiseless, the sound level in a jet cockpit in flight is of the order of 117 DB.² Engine noise cannot be entirely eliminated, but overall noise level should be below 70 DB¹² for comfort, lessening of fatigue, and prevention of acoustic trauma.

G. Radiation.—Research in this sphere belongs more properly to the physicist and engineer but must be considered by the Flight Surgeon along with safe limits of other factors.

According to C. A. Tobias,²¹ even extensive high altitude flying presents only a small hazard from cosmic and other radiation. He estimates that a pilot flying 1,000 hours a year at 55,000 feet receives about 16 MR per week, clearly a safe dosage. How much this dosage would be increased above the ionization layers of the atmosphere is not known. Some shielding is apparently necessary for space flight, although it is possible that cosmic radiation above the ionization layer of the atmosphere may be entirely innocuous to living tissue.²² It is presumed by some workers²¹ that dosage above the atmosphere may approach or exceed the 0.3 REM per week now considered permissible. H. J. Schaefer theorizes that large increases will be met with at very high altitude due to the removal of the shadow effect of the Earth and the absorbing qualities of objects of large (aircraft).15 The mass latter is significant because the hull of an aircraft might induce dangerous ionizing radiation through collision of high speed particles which might otherwise pass through the body without causing significant damage.

DISCUSSIONS AND RECOMMENDATIONS

It is clear at this time that more work should be done on all phases of sealed cabin acclimatization, a need which daily becomes more apparent.

Since man's environment — his Milieu in Space—must be controlled within rather narrow limits, it is apparent that the engineering aspects of sealed cabin acclimatization have been neglected, while the experts worked

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with fuels, engines, metals, and control systems. This writer is of the firm opinion that judgment and perspective thinking can never be built into a machine, therefore, man must go aloft and see, and learn for himself.

It is recommended that pressurization of very high altitude aircraft cabins by superchargers or compressors be de-emphasized in favor of the sealed cabin approach, since pressurization is dependent upon the presence of an atmosphere, thereby limiting the flight of man in a pressurized cabin to that very narrow range of altitude in which a compressible and non-toxic atmosphere can be found. There will always, of course, be a need for low flying, low velocity aircraft. For these the pressurization type of cabin with auxiliary oxygen will be the simplest and most economical to build and operate.

A self-sustaining "b a l a n c e d aquarium" in space should be the ultimate aim of those concerned with this problem. A possible solution lies in a chemical, mechanical, or photosynthetic gas exchanger or combination of these for the maintenance of our gaseous environment.

Space flight is a fact; space travel is not. Whether or not space travel becomes a fact in our time depends upon the care with which we construct and maintain Man's Milieu in Space.

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Wives' Wing Plans Fourth Annual Meeting

Plans for the fourth annual meeting of the Wives' Wing, to be held in conjunction with that of the Aero Medical Association in Washington, March 21-23, 1955, were completed at a meeting of the Executive Board of the ladies auxiliary at the Officers' Mess of the Naval Medical National Center. Bethesda, Maryland, on December 2. Details will be announced in the February issue of the JOURNAL, according to Mrs. W. P. Dana, president of

the Wing. Mrs. Langdon C. Newman is chairman of the Arrangements Committee for the 1955 meeting.

Wives and adult daughters of members of the Association who have not joined the Wives' Wing may send an informal application for membership to Mrs. Norman L. Barr, secretarytreasurer, P.O. Box 5589, Washington 16, D. C., and enclose annual dues of two dollars. There is no initiation fee.