Selection of a Sealed Cabin Atmosphere

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CONSIDERABLE experience has been gained with sealed cabin atmospheres incidental to twenty-four-hour balloon-borne animal flights above 100,000 feet.[13] The temperature and pressure problems encountered while floating at this altitude are space equivalent, corresponding closely to the conditions that would be encountered by an orbiting satellite. Design of a manned, sealed cabin under similar flight conditions will be discussed with the following assumptions: the sealed cabin will operate entirely from self-contained sources without attempt to pressurize from ambient air, and will be designed for essentially zero leakage. Systems will be selected for maximum performance and reliability at minimum weight consistent with reasonable cost and availability. This report will consider the selection of oxygen supply, carbon dioxide and water vapor removal systems, and the determination of the cabin atmosphere pressure and composition based on a flight duration of twenty-four hours. Tolerable limits will be selected for no performance decrement rather than for comfort or survival.

Basic considerations that governed selection of the cabin environment used in Operation Manhigh high altitude balloon ascents, flights I and II of 1957, will be presented.

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MECHANICAL SYSTEMS

The sealed cabin is assumed to have negligible leakage so that all the oxygen is available for metabolism. Therefore, gaseous metabolic waste products must be removed within the system. Less than 5 per cent of the gas respired through a standard mask or helmet system is utilized for metabolism by the body. The remaining 95 per cent of the respired gas derived from the stored source is discarded. Using a mask or helmet within the sealed capsule would make its atmosphere gradually approach the composition of the source and would require more than twenty times the gas needed if the subject merely breathes the ambient capsules atmosphere gas. Assuming an average metabolic rate of 800 cm.^{3}/min., then 1,730 liters of oxygen would be required over a thirty-six-hour period. A 36-pound standard liquid oxygen converter supplies with a capacity of 5 liters about 4,150 liters of the gas (STPD), providing an ample safety factor for a twenty-four-hour flight. In addition to being a nuisance to wear, a standard oxygen mask would require 34,600 liters (STPD) of oxygen or two 20-liter converters which weigh more than 200 pounds and include no safety factor. Preliminary design studies indicate that an air regeneration system required to remove carbon dioxide and water vapor should weigh no more than 30 pounds. Thus, for twenty-four hours or longer the equipment required to regenerate the air weighs considerably less than the additional oxygen supply required for an open system. Previous studies have established, for this quantity of oxygen, the weight advantage of liquid oxygen systems compared to a compressed gas source.[14]

Experience gained from submarine practice established 3 per cent carbon dioxide as an upper limit for prolonged exposure.[8] One per cent is a more conservative value to preclude any performance decrement. The maximum permissible relative humidity without performance decrement is a function of temperature, and becomes critical between 30° C. (85° F.) and 34° C. (95° F.) at a relative humidity of 70 per cent. Death may result from several hours exposure to temperatures of 32° C. (90° F.) at 100 per cent relative humidity.[7] Cabin humidity is also important at low temperatures because of frosting of windows, which would reduce visibility, but night window temperature data is not available at this time. A maximum value of between 30 and 50 per cent relative humidity should satisfy the above requirements.

Consideration of possible techniques for removable of carbon dioxide[5] clearly indicate that for a 24-hour flight, mechanical freeze-out techniques require much more total equipment weight and power for operation than chemical absorbent systems. Complete review of known absorbents established anhydrous lithium hydroxide as the best choice.[6] Only 1.35 pounds of LiOH compared to 2.95 pounds of baralyme or soda lime are required to absorb 1 pound of CO_2. Anhydrous lithium hydroxide is porous and non-deliquescent, but will pick up 5 to 6 per cent water at 35 per cent relative humidity in a highly exothermic reaction. This hydration is undesirable because it impairs CO_2 absorption. The disadvantages of LiOH are its high price and tendency to dust. The latter can be controlled by filtering the air.

Removal of water vapor may be accomplished by condensation after cooling the air below its dewpoint, or by chemical absorption. Other methods which have been proposed require equipment that is too heavy for this application. Because a twenty-four-hour flight will require either supplementary heat at night or cooling during the day, a daytime cooling system can serve the double purpose of drying the air and cooling it. Chemical absorption will be required at night, and may be required to supplement the condensation system during the daytime. In terms of pounds of water absorbed per pound of absorber, the most efficient drying agent is lithium chloride.[5] It has the disadvantage of deliquescing by forming a saturated solution on the surface. The undesirable consequences of this property can be minimized by a suitable mechanical arrangement. Magnesium perchlorate (anhydrone) requires about 2 pounds of material per pound of water removed, but has the double advantage of not deliquescing and of drying efficiently at a much lower relative humidity. Best advantage can be taken of the strong points of both drying agents using a two stage system which employs LiCl to remove the bulk of the water and anhydrone ($Mg(ClO_4)_2$) as a final drying agent.[16]

SELECTION OF ATMOSPHERE

The sealed cabin atmosphere should provide an adequate partial pressure of oxygen so that a face mask need be used only under emergency conditions. The minimum non-hypoxic alveolar pO_2 although a highly variable factor is generally considered to be 61 mm. Hg. This value is reached when the atmosphere is 100 per cent oxygen at a total pressure of 144 mm. Hg., or a pressure altitude of 39,500 feet, and is equivalent to alveolar pO_2 when breathing natural air at 10,000 feet.[1,12]

The occurrence of bends without extensive oxygen pre-breathing may become a serious consideration between 20,000 and 25,000 feet altitude (350 to 280 mm. Hg.), depending on the amount of physical exertion required of the subject. On the other hand, cabin pressure corresponding to an altitude of less than 18,000 feet represents a hazardous condition in the event of rapid decompression at ceiling altitude. An emergency partial pressure suit will provide approximately 140 mm. Hg. pressure, the equivalent to 40,000 feet altitude. Navy submarine practice[15] has established a maximum pressure change ratio of 2:1 without danger of bends. The same criterion permits capsule pressurization to a maximum of 280 mm. Hg. (25,000 feet), *i.e.*, the 280 to 140 mm. Hg. pressure change does not exceed a 2:1 ratio.

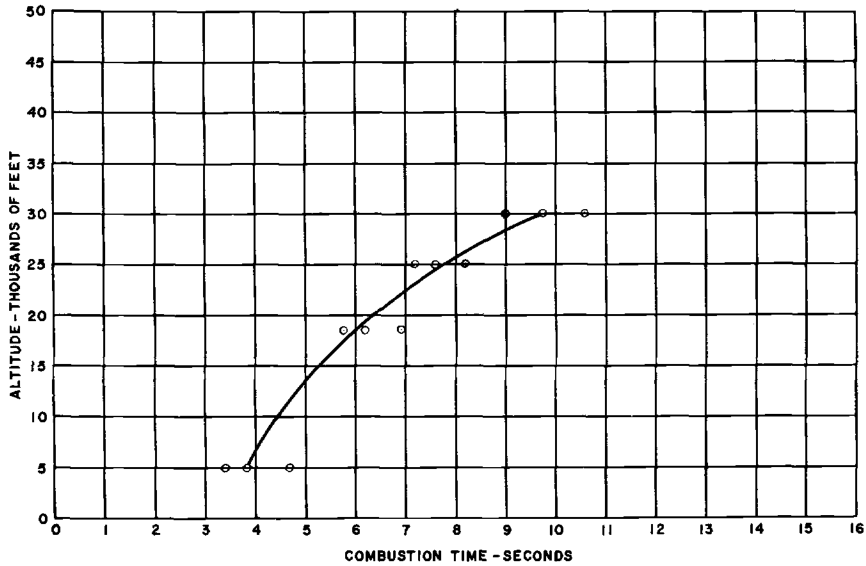


Fig. 1. The flammability of flight clothing in an atmosphere of 100 per cent oxygen. Data were obtained in test No. 6, using a lightweight flying suit.

In addition to the question of dysbarism because of evolved gas, a low pressure atmosphere must be enriched with oxygen if the pilot is to breathe without a mask or closed helmet. The question arises as to how much increase in fire hazard is associated with low pressure atmospheres whose composition approaches 100 per cent oxygen.

Let us assume we have a capsule located in space. Its cabin pressure is maintained at an equivalent of 18,000 feet. If gradual leakage were to occur, and if cabin pressure were maintained by pre-set aneroid devices controlling the pressure of gas delivered to the cabin from the liquid oxygen converter, the cabin ambient atmosphere would approach 100 per cent oxygen after a few hours. In order to evaluate the possible fire hazard associated with such a contingency we performed a series of burning tests at Holloman Air Force Base. Figure 1 shows the results of one such series.

The curve shows combustion time in seconds, plotted against pressure altitude in thousands of feet when strips of cotton twill are burned in an atmosphere of 100 per cent oxygen. It appears that, in terms of burning rate, the fire hazard at 18,000 feet is only half as great as that at 5,000 feet. In view of the very great danger associated with atmospheres of 100 per cent oxygen at ground level, the reduced flammability at 18,000 feet does not offer much consolation, however. We may also note from the above curve that increasing the cabin altitude from 18,000 feet to 30,000 feet would provide considerable additional protection from the fire hazard of an atmosphere of 100 per cent oxygen. This graph also shows the "scatter" encountered when the same measurement is repeated several times.

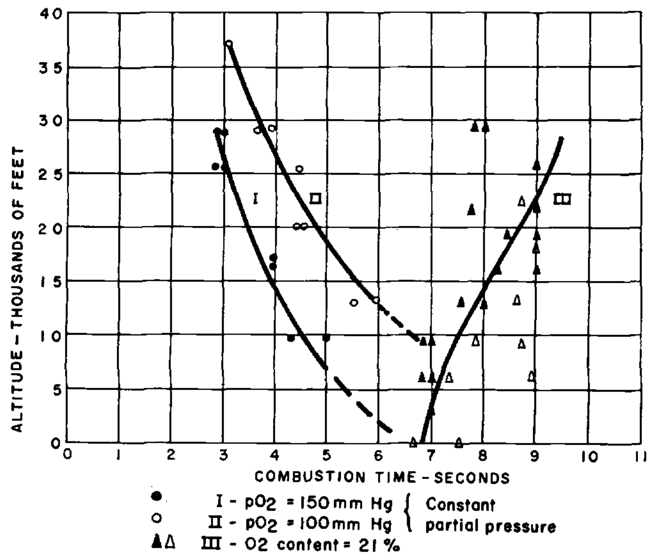
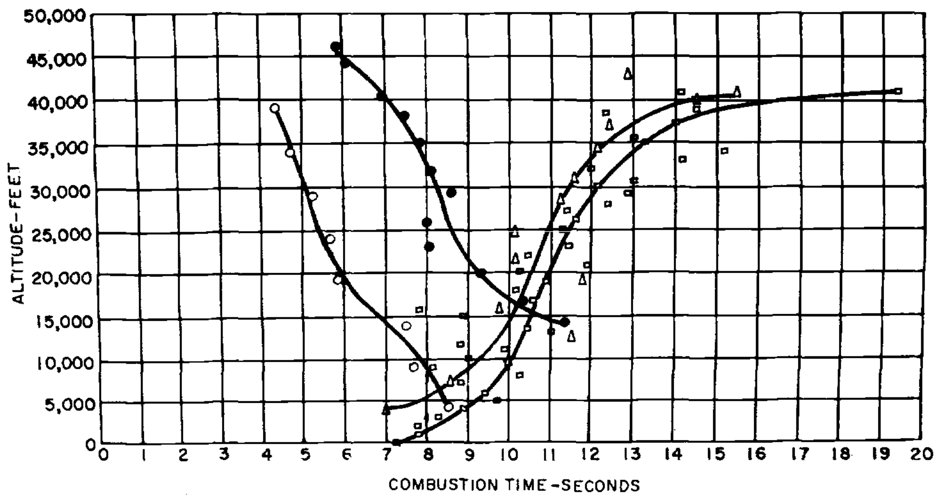


Fig. 2. The flammability of paper strips, redrawn from Clamann's data..[3]

A stimulus for further research on the flammability question was provided by Clamann[3] who reported in 1939 that the combustion time of paper strips was reduced from five seconds at 3 kilometers altitude to three seconds at 9 kilometers at a constant pO_2 of 150 mm. Hg. (Fig. 2).

We were unable to obtain any additional information on the question of increased flammability at constant pO_2 and decreased barometric pressure from sources available to us. The practical importance of additional data on this subject is obvious. Consequently, we decided to investigate the problem. The results of our first series of tests are shown in Figure 3.



Test No. 1 – Δ, Test No. 2 – □, : Atmospheric Air
Test No. 3 – ○ : Constant pO_2 = 142 mm Hg
Test No. 4 – ● : Constant pO_2 = 100 mm Hg

Fig. 3. The flammability of paper strips under varying conditions.

Comparison of Figure 3 with Figure 2 reveals that our results are in good agreement with those reported by Clamann. The finding, that combustion of paper strips is more rapid at decreased barometric pressures and constant oxygen partial pressures, requires some explanation. Clamann[4] has suggested that the inert nitrogen molecules act as fire extinguishers by absorbing heat in the flame zone, quenching the oxidation reaction. Since there are fewer nitrogen molecules per oxygen molecule at increasing altitudes, the reaction proceeds more rapidly. Another possible factor is the relative heat conductivity of the gases comprising the atmosphere in question. Because helium has a relative heat conductivity about six times greater than that of nitrogen, repetition of the flammability measurements in a helium-oxygen atmosphere should serve to clarify the explanation of the increased rate of combustion at lowered barometric pressures. Further investigation into the question is planned, and the results will be reported later. Whether a comparable effect might be detectable in the case of human metabolic oxidation at decreased barometric pressures is hypothetical. We are not aware of any findings which report such an effect.

Work is in progress to determine to what extent the paper strip combustion findings are applicable to various types of standard flight clothing. Figure 4 shows the results of one test on a light cotton twill flying suit at an oxygen partial pressure of 142 mm. Hg. It is possible that certain types of fabric or other substances may be more reactive to combustion at reduced pressures. Our results to date indicate that anything that will burn at ground level will burn much more rapidly at high altitudes at the same pO_2. These observations will be extended to obtain data on various other types of combustible materials.

From available data we may draw certain conclusions regarding the fire hazard associated with sealed cabin atmospheres. In Figure 3 note that at 5,000 feet altitude (elevation of Holloman AFB) the combustion time of a paper strip is about eight seconds. At 18,000 feet with the same pO_2 (142 mm. Hg.) combustion time is about six seconds. At 25,000 feet and 142 mm. Hg. pO_2, combustion time is about the same as at 18,000 feet. Gradual leakage of the capsule gases, through a flushing effect, will produce increasingly higher percentages of oxygen. The maximum hazard would be encountered at 18,000 feet and 100 per cent oxygen when combustion time is reduced to four seconds. Reduction of capsule total pressure to 30,000 feet (with 100 per cent oxygen atmosphere) would increase the combustion time to above five seconds. A capsule atmosphere of 100 per cent oxygen at 30,000 feet would probably represent the upper limit of safe depressurization from the hypoxia standpoint. At this altitude, combustion time is at least 50 per cent more rapid than at ground level.

The possibility of using helium as an inert gas in place of nitrogen was

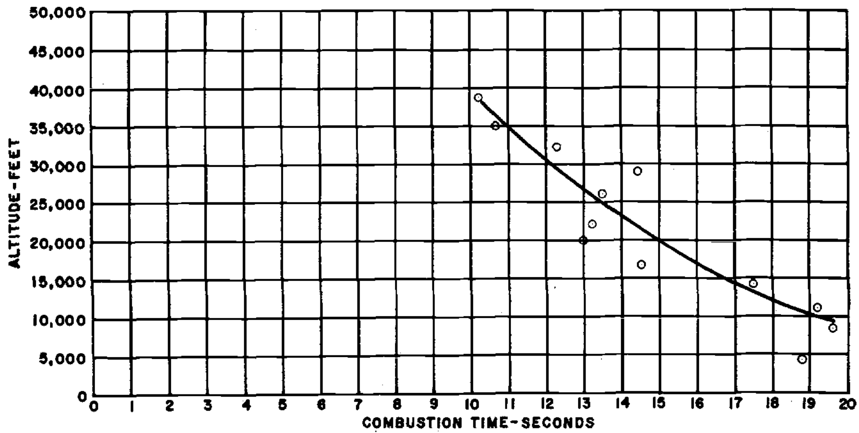


Fig. 4. The flammability of flying clothing in an atmosphere with a constant pO_2. Data were obtained from test No. 5, using a very lightweight flying suit with a pO_2 of 142 mm. Hg.

considered. The rate of diffusion of helium is 2.57 times greater than that of nitrogen. However, the greater mobility[9] that one might expect from helium is not realized because the gas exchange rate in the body is determined almost exclusively by the rate of tissue perfusion by the blood.[11] Denitrogenation curves[11] clearly indicate the multiphasic nature of inert gas elimination. The fat reservoirs are cleared of inert gas very slowly, a fact which reflects the low tissue perfusion rate of the fat depots. Fatty tissue contains about five times the amount of dissolved nitrogen contained in blood and other tissues.[2] On the other hand, the solubility of helium in water is about half that of nitrogen.[9] Furthermore, the solubility of helium in fatty tissues is about the same as for nonfatty tissues.[11] The inescapable conclusion is that the body of a man breathing helium-oxygen mixtures contains far less dissolved inert gas than it would if he were breathing nitrogen-oxygen mixtures.

Pathologic evidence reported by Haymaker[10] indicated that fat emboli may be generated within the body in obese persons experiencing severe bends. A curve prepared for underwater diving,[8] but applicable to the dysbarism problem, suggests that a 50 per cent helium and 50 per cent nitrogen mixture would present less dysbarism hazard than either alone. The increased heat conductivity of helium has advantages and disadvantages to temperature control, but in any case would have to be given serious consideration. A helium-oxygen mixture might influence communication because of changes in voice timbre and elevation of pitch by half an octave. Until more experimental evi-

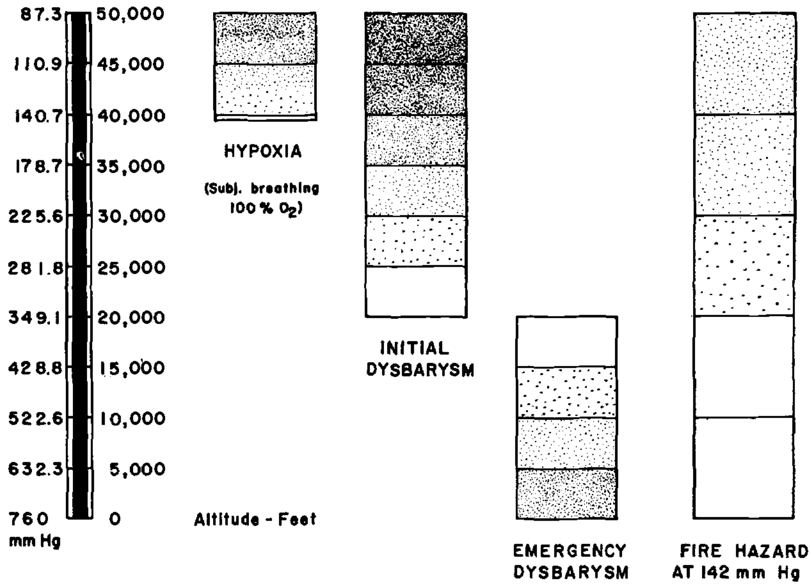


Fig. 5. Factors which govern the selection of pO_2 and total pressure in a sealed cabin. Greater density of shading indicates increasing hazard.

dence is available, there is no clear advantage to an atmosphere of half oxygen and half nitrogen, or one of equal parts oxygen, helium, and nitrogen. The oxygen and nitrogen mixture would probably be simpler to obtain.

Integrating the limiting factors produces a composite picture presented in Figure 5. The best compromise between all factors is a 50 per cent oxygen atmosphere at a total pressure of approximately 349 mm. Hg, (20,000 feet).

SUMMARY

High altitude balloon capsules carrying animals have furnished enough data so that it is now feasible to design a sealed cabin to operate at space equivalent altitudes. The various physiologic variables to be considered in designing a balloon-borne capsule for a 24-hour manned flight are outlined. Design of environmental control equipment should be based on maintaining an atmosphere that provides for no performance decrement rather than for comfort or survival. A standard liquid oxygen converter can be used for initial exploratory flights. The selection of cabin pressure in relation to possible occurrence of bends in the event of decompression is discussed. All possible precautions must be observed to prevent ignition of combustible material. The possible use of helium as a replacement for nitrogen is proposed.

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REFERENCES

1. Boothby, W. M., Lovelace, W. R., and Benson, O. O.: High altitude and its effect on the human body. *Int. J. Aeronaut. Sci.*, 7:461, 1940.
2. Campbell, J. A., and Hill, L.: Studies in saturation of tissues with gaseous nitrogen: III. *Quart. J. Exper. Physiol.*, 23:219, 1933.
3. Clamann, H. G.: Uber brandgefahr in sauerstoff-gleichdruckkabinen. *Luftfahrtmed.*, 4:23, 1939. Reviewed in *German Aviation Medicine, World War II*, Washington, D. C.: Dept. of Air Force 1950. p. 494.
4. Clamann, H. G.: Personal communication.
5. Dryden, C. E., Hans, L. S., Hitchcock, F. A., and Zimmerman, R.: Artificial cabin atmospheres for high altitude aircraft. USAF Aero Med. Lab. WADC Tech. Rpt., 55-353, 1956.
6. Ellis and Watts, Inc.: Contract AF-33(616)-470, USAF Aero Med. Lab., WADC Rpt., 1954.
7. Evans, C. L.: *Principles of Human Physiology*, 11th edition. Philadelphia: Lea & Febiger, 1952.
8. Goff, L. G.: Proceedings of the underwater physiology symposium. National Academy Science Pub., No. 377, 1955.
9. Haviland, R. F.: Air for the space ship. *J. Astronaut.*, 3:31, 1956.
10. Haymaker, W., Johnston, A. D., and Downey, V. M.: Fatal decompression sickness during jet aiircraft flight. *J. Aviation Med.*, 27:2, 1956.
11. Jones, H. B.: Respiratory system: nitrogen elimination. In *Medical Physics*, Chicago: Yearbook Publishers, Inc., 1950, pp. 855-871.
12. Lutz, B. R., and Schneider, E. C.: Alveolar air and respiratory volume at low oxygen tensions. *Am. J. Physiol.*, 50:280, 1919.
13. Simons, D. G., and Steinmetz, C. H.: The 1954 aero medical field laboratory balloon flights. *J. Aviation Med.*, 27:100, 1956.
14. Stratolab Development, General Mills, Inc., Final Rpt., 1956.
15. Submarine Medicine Practice: Bureau Medicine & Surgery, Navy Dept., Washington, D. C., 1956.
16. Winzen Research, Inc.: Post flight report; flight 747, March 21, 1957, AF contract 26(600)-808.