Engineering of the Sealed Cabin Atmosphere Control System

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THE DESIGN of an environmental control system for a manned cabin must be planned around the physiologic and safety requirements of the passengers. The design of any specific system is a unique optimization problem which can be attacked intelligently only after the system parameters have been defined. However, all such systems have common problem areas which can be fruitfully explored in the interest of planning and defining research and development work.

Problem areas common to all environmental control systems for sealed cabins are control of temperature, gas composition, and total pressure. The criteria applied to possible control scheme choices are those of safety, reliability, weight, volume, and power requirement.

POWER SUPPLIES

To be able to convert power requirements of control schemes to equivalent weight factors, one must establish estimated power supply weights. There is an especially wide range of secondary power supply weights in the literature. Virtually all suitable sealed cabin power supplies, except chemical batteries, are in a state of early development or even speculation. Precise weight estimates are affected by many variables including size of power plant, useful man hours (UMH), and, perhaps even more profoundly, the state of technology.

No serious attempt is made to analyze atmosphere control systems for cabins to be used on missions which might last longer than six months. The nature of some power supply systems is such that their weight for a given power level remains relatively constant over such a period of time. Weight estimates for these systems are stated in watts per pound:

1. Solar battery-storage battery systems 0.25 watts/lb
2. Thermocouple generators 0.30 watts/lb
3. Nuclear reactors 4.0 watts/lb
4. Regenerative fuel cells 10.00 watts/lb (feasibility unproved)

Other power supply systems use expendable materials or are essentially irreversible devices. These system weights are stated in watt hours per pound:

1. Chemical batteries 50 watt-hrs./lb
2. Advanced fuel cells 400 watt-hrs./lb

Some equipment, such as regenerative adsorber columns, are able to use

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thermal energy for operation. For analytic purposes, a useful thermal energy yield of 3,500 to 5,000 BTU per pound of reactants is considered representative of some of the more energetic chemical reactions. A "guestimate" of the initial (and constant) weight of a solar heat collector is set at 10 BTU per pound of collector equipment.

TEMPERATURE CONTROL

Sources of heat found in the sealed cabin include electronic equipment, heat liberated by chemical reactions, heat produced by friction in mechanical systems, and the metabolic heat of the passengers. The cabin wall temperature may be allowed to rise to levels as high as 400°F (477°K) for brief periods.[6] However, the cabin temperature will, for the most part, have to be controlled to nearly 70°F (294°K).

Regardless of the cooling scheme used, except evaporative cooling, the ultimate heat sink will be "space." The effective temperature of this heat sink can vary markedly depending upon the proximity of the earth, moon, or other celestial bodies. The most favorable direction for radiation of heat is toward "star speckled space" with an effective temperature of about -452.4°F (4°K).[3] A less favorable direction for radiation is toward the earth, which presents an average temperature of approximately 40.4°F (278°K).[5] Orientation of the cabin heat exchanger toward the sun is the most undesirable condition and must be ruled out. It is assumed that a vehicle employing space as a heat sink will be capable of controlled orientation and will thus avoid heat exchanger orientation toward the sun.

An exact treatment of the cabin temperature control problem becomes highly involved. We can perform some calculations to get approximate values for the cabin cooling problem. Assume a six-foot diameter spherical cabin (area = 113 ft^2). Further assume that one-half of the cabin outer surface (56.5 ft^2) is available for radiation of excess cabin heat. The remaining one half will be oriented toward the sun except when in the shadow of a near body. Internal heat loads of early one-man cabins may be in the vicinity of 2000 BTU per hour. More advanced one man cabins may go as high as 4,000 BTU per hour. If only passive temperature control is depended upon (that is, control by virtue of the natural flow of heat from the cabin due to the space-cabin temperature difference), even the lower 2,000 BTU per hour heat load would require 16 ft^2 of radiator area under the most favorable (space oriented) condition and 115 ft^2 for the earth oriented condition.

We must tolerate a much larger radiator area or employ an active cooling system to increase the rate of heat loss from the radiator surface. By far, the most effective method of increasing heat radiation rate is raising the radiator temperature. This is the method used by power consuming cooling systems. For a space cabin using such a system, the exterior cabin radiator will be the condenser heat exchanger of the cabin cooling system. The evaporator section of the cabin cooling system is located within the cabin and is fixed approximately at the cabin temperature of 70° F. Raising the condenser temperature to increase the radiation rate then increases the temperature difference through which the cooling system must operate, thus increasing the required power. In general, of the power consuming cooling systems, a vapor cycle system is the heaviest but has a high coefficient of performance (COP). The air cycle is lightest, but it has a low COP and its most economical operation depends upon a source of ram air. The absorption cycle system has a COP similar to that of the air cycle and a weight comparable to the vapor cycle. If an absorption cycle could be engineered to operate in zero G it would offer the advantage of requiring primarily heat energy for its operation rather than shaft work.

It is likely, then, that of the power consuming systems, the best solution to the sealed cabin temperature control problem (during extra-atmospheric flight) is the use of a vapor cycle cooling system.

An expendable coolant system is a cooling system which requires no power supply for its operation but whose initial weight is a function of the total heat to be rejected and its UMH. This system rejects heat as the latent heat of fusion, vaporization, and sensible heat of the expendable coolant. The most probable choice of an expendable coolant for our purpose is water. Efficient use of water as a heat sink suggests that it be frozen at the beginning of the mission and should undergo two changes of state, boiling at as high a temperature as is compatible with cabin temperature requirements. Sacrificing one state change (ice-liquid) would eliminate approximately 16 per cent of the total cooling capacity. An expendable type of system should be competitive with a constant weight power consuming system such as just discussed. The competitive period will, however, be relatively short since the weight of the system rises rapidly with UMH.

Figure 1 compares an expendable coolant cooling system employing water (with two state changes), and two vapor cycle systems (COP=2.0) employing six different types of power supplies. All systems are based on a 2,000 BTU per hour cooling load. A power supply capable of delivering approximately 670 watt-hours per pound would make the vapor cycle machine competitive. A vapor cycle system used in conjunction with nuclear or regenerative fuel cell power supplies becomes competitive with the expendable coolant system at about 7 and 3 useful man days respectively.

TOTAL PRESSURE CONTROL AND GAS SUPPLY COMPOSITION

There appear to be several factors affecting the choice of a total cabin pressure and gas supply composition.

Physiologic Factors.—To preclude impairment of passengers performance due to hypoxia, it is desirable to maintain an oxygen partial pressure approaching that of our sea level atmosphere (150 mm Hg). A reduction of this partial pressure can be tolerated but is undesirable.

Another physiologic phenomenon is aeroembolism. A reduction of ambient pressure to less than that at 25,000 feet (5.45 psia) is highly undesirable because of the increased likelihood of the occurrence of aeroembolism.

Effects of unprogrammed cabin decompressions also warrant consideration as a physiological design criteria. The nature of this problem varies with the state of refinement of the cabin, and we must consider the character of early versus advanced types of cabins. The former is expected to be of minimal size and contains one passenger wearing a protective pressure garment. The helmet facepiece will probably remain open during the passenger's periods of normal duty. In the event of an emergency decompression of any type, the facepiece will be closed either manually or automatically, with the suit being simultaneously pressurized. The advanced cabin will be larger and may contain more passengers whose garb can be described as "shirtsleeves."

A decompression of the early model cabin would be a serious matter, but given time to operate, the pressure suit will be capable of preventing death as a result of the lowered cabin pressure. The most serious physiologic threat to the passenger's safety during a violent decompression is possible injury due to a rapid expansion of gases in his body. The degree of damage to a healthy human due to violent decompression would be a function of the internal force of bodily gas expansion. This is a function of the time of decompression, total pressure change during decompression, and the density of air at the onset of the decompression.

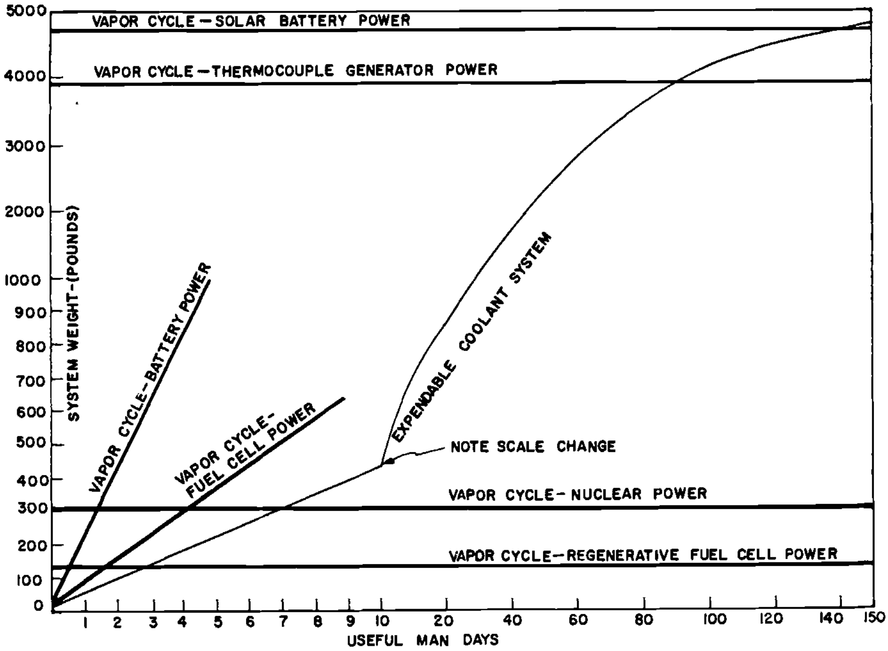

Fig. 1. System weight versus useful man days for various cooling systems.

The greatest rate of decompression occurs at higher cabin pressures. From this aspect, a reduced cabin pressure is favored for early cabins.

Without protective pressure garments, passengers of the advanced type cabin would not survive in the event of a violent decompression. The event of a slow decompression presents quite a different problem. In such an event, the passengers will have to locate and repair the leak or don emergency garments before the cabin pressure leaks to a critical level. This situation has been quite thoroughly analyzed.[2] The conclusion reached is that a higher cabin pressure pays considerable dividends by virtue of the fact that in a slow leak situation, decompression time is considerably extended.

Structural Weight and Leakage.—The structural weight penalty imposed by higher cabin pressures is nominal for a sphere and becomes very serious for a flat-sided shape. It is conceivable that spherical shaping of the cabin is not always possible because of other considerations. This situation was met in a preliminary design for a weapon system. Here, an increase in cabin total pressure of 3 psia would have penalized the structure by 50 to 100 pounds.

Frequently, a special "one time" load such as a crash condition must be designed for. If so, this design situation usually requires a heavy enough structure to resist any cabin total pressure within the range from 5 to 15 psia.

Increased internal pressure may bring about a weight penalty by virtue of an increased tendency for cabin leakage. This must be counteracted by additional gas supply storage or by better sealing schemes requiring additional equipment or material.

Fire Hazard.—In early model cabins, the factors heretofore discussed tend to favor depression of total pressure and subsequent oxygen enrichment of the atmosphere to avoid hypoxia. The possibility that this enriched atmosphere might pose a fire hazard has been investigated by various persons. Simons and Archibald[7] have concluded from their investigation of the burning characteristics of paper and cotton cloth in the presence of varying oxygen concentrations, that a relatively safe compromise would be to maintain total cabin pressure of no less than 6.75 psia (20,000 ft equivalent) with an oxygen partial pressure of approximately 3 psia (142 mm Hg). A more recent and as yet incomplete study of the fire hazard problem is being conducted in the Aeronautical Accessories Laboratory at the Wright Air Development Center.[4] Here, electrical insulation burning tests in oxygen rich atmospheres have been conducted. The results suggest that to eliminate a fire hazard, one could safely use a polyvinylchloride insulation in a 3 psia partial pressure of oxygen atmosphere if the cabin atmosphere contained sufficient nitrogen to bring the cabin pressure to 12 psia.

The cautious designer might now raise total cabin pressure from 7 to 12 psia in order to maintain sea level oxygen partial pressure without creating a fire hazard. This is probably sound judgment in the case of advanced cabins. However, consideration of all factors could well result in a venture into the "less safe" fire hazard area, provided proper precautions are taken.

Gas Supply Composition.—If cabin leakage is high enough, as it may be in early cabins, the atmosphere could be stored as a two-gas mixture of the desired composition. The mixture would be metered out at a rate high enough to maintain cabin pressure. Such a scheme fails in a better sealed cabin. In this case, the partial pressure of an inert gas continuously fed to the cabin atmosphere, in a mixture would steadily build up. For this reason, the semisealed cabin poses the greatest problem. This type of cabin will soon be a reality, and we will have to settle for a 100 per cent oxygen atmosphere or develop a suitable partial-total pressure regulator.

In a well-sealed cabin, a two-gas atmosphere is a simple matter to arrange. At the beginning of the mission, the cabin is sealed and filled with the proper partial pressure of inert diluent. After that, only oxygen need be added to maintain cabin pressure.

GAS SUPPLY

Inherent in the problem of atmosphere control in an "extra atmospheric" sealed cabin, is the requirement for storage of oxygen and/or diluent gas. This is used as "make-up," replacing metabolized oxygen and gas lost by leakage.

There are three primary approaches to the problem of "gas" storage: (1) storage in the gaseous state at elevated pressures; (2) storage in liquid state in specially insulated containers; and (3) storage in a chemical compound with a high oxygen content. Aviation-breathing oxygen as well as other commercially available gases have been stored at pressures of 2,000 psia for many years. Better materials and manufacturing techniques have made the use of gas containers working at pressures as high as 15,000 psia a reality for some missile applications. One could continue compressing stored gas and thereby decreasing its volume indefinitely. Boyle's ideal gas law holds well for real gases until pressures of approximately 3,000 psia are reached. From this point, a real gas behaves in an increasingly less "ideal" manner.

The weight of a container to store a fixed quantity of a real gas remains relatively constant with increasing pressures up to the point where the non-ideal behavior of the gas becomes significant. Here, the increased amount of material required to resist the greater storage pressures is approximately offset by the reduced amount of material required to inclose the smaller storage volume. Above this point, the trend is reversed and the weight penalty becomes very significant. For a similar reason, the gross volume of a gas storage container decreases with increasing pressure to the point of marked onset of non-ideal gas behavior and then begins to increase.

The optimum weight and volume systems for oxygen storage considering these criteria are approximately 300 and 1,000 atmospheres (4,500 and 15,000 psia) respectively.[1]

In designing a system for gaseous storage in a particular cabin, a survey of volume available for gas storage should be conducted. Then, knowing the weight of gas required for the mission, the container should be designed to hold it at an internal pressure such that the resulting volume of the stored gas plus container just occupies the available space. If required, decreased volume with minimal weight penalty can be had by storage up to 3,000 psia. The container should be fabricated from a material whose weight-to-strength ratio is very low. The system so designed is optimum for the particular application.

In cabins designed for multi-passenger and/or long duration missions, a cryogenic storage system becomes practical. For short missions cryogenic systems are impractical. Equipment for evaporation and control of the liquid are comparatively heavy. Stored liquid constantly evaporates regardless of use rate because of imperfect insulation of the storage containers. For this reason, excess liquid must be stored to compensate for this "boil-off" when the use rate is not equal to or greater than the boil-off rate. The boil-off rate is more severe for the smaller containers because of the higher surface/volume ratio which offers more heat transfer area.

A valid comparison of gaseous versus liquid storage can only be made after the "optimum" gaseous system has been designed to suit the particular application under study. Handling cryogens in zero G requires some special technique. Methods are now under study by the Aero Medical Laboratory at the Wright Air Development Center.

Storage of an oxygen containing chemical is a third possible method of carrying an oxygen supply. One such chemical is potassium superoxide (KO_2). When reacting with water, it yields oxygen and potassium hydroxide (KOH). The hydroxide can be used to absorb carbon dioxide by combining with it to form potassium carbonate ($K_2 CO_3$). The details of reaction rate control and chemical packaging need further consideration. A chemical storage system might then compete with a gaseous oxygen-carbon dioxide absorption system.

CARBON DIOXIDE CONTROL

At least four methods for carbon dioxide control are being, or have been, investigated, by the Aerospace Medical Laboratory. These include (1) continuous "bleed off" of dilute carbon dioxide; (2) chemical absorption; (3) adsorption; and (4) reduction to carbon and respirable oxygen.

If we provide a controlled leak of the gas from the cabin, the amount of carbon dioxide thus exhausted will be a function of its concentration in the cabin atmosphere. Cabin pressure would be maintained at the desired level by continuous addition of pure oxygen. The feasibility of this scheme has been investigated analytically.

Chemical absorption systems for the removal of carbon dioxide have found considerable use in submarine and diving applications. Hydroxide-containing molecules have a high affinity for carbon dioxide and combine readily to form carbonates, with the liberation of water and heat. The lightest hydroxide forming element is lithium and lithium hydroxide (LiOH) is a very satisfactory carbon dioxide absorber. It was found that a package of lithium hydroxide weighing 5.15 pounds (including container weight) will absorb one man's CO_2 production (0.12 pounds/hour) for one day.

The next logical advance in carbon dioxide control seems to be an adsorption carbon dioxide removal system, capable of periodic regeneration. Several adsorbents including silica gel, activated charcoal, activated alumina and "Molecular Seive" were investigated for use as carbon dioxide adsorbers. Of these, the molecular seive (MS) type 5A offered the most hope. The MS material is regenerated by heating to approximately 600°F, preferably in the presence of a vacuum. It has been estimated[1] that five pounds of type 5A MS (2.5 pounds in each of two adsorber columns) could adsorb one man's carbon dioxide production (0.12 pounds per hour). This estimate is based on a system having one column in use while the other is being regenerated. Use or regenerating time would be 100 minutes.

It is estimated that a two column system would weigh 25 to 30 pounds and require an average power input of 400 watts and 4.8 pounds of chemical per day (high energy 5,000 BTU) as a heat source for adsorbent regeneration. The 400 watts would be primarily used for cooling. Electrical rather than chemical heat for regeneration would boost the power requirement to about 700 watts. A solar source of heat to do the regeneration job would weigh an estimated 90 pounds.

All carbon dioxide control schemes discussed thus far gather and/or dispose of the gas in some way. The metabolic oxygen supply required for one man day is approximately two pounds. In addition, a container weighing another one to three pounds per day, depending on UMH, is required for oxygen storage. Of the two pounds of oxygen taken in by a man, approximately 85 per cent (1.7 pounds) is expired as carbon dioxide. A device capable of reclaiming this oxygen could pay for itself on long missions, in terms of a reduction in weight of the oxygen storage system. Present estimates put a one-man system at approximately 75 pounds in weight with a power requirement of 1,000 watts. This power requirement includes both heat and electrical power.

Figures 2 and 3 compare carbon dioxide control system weight estimates for the four systems discussed here. Figure 2 shows the controlled leak scheme plotted for a system useable in a 1 to 2 cubic foot space. This type of system would be of value in early cabins in which a protective garment with a short duration emergency operation mode is employed.

Figure 3 compares the absorption, adsorption, and reduction systems using various power sources, where required. The chemical absorber system is the lightest for missions up to the 18 useful man-day (UMD) range. At this point two column adsorber systems of various types are more highly favored and became especially attractive after the 35 UMD point is reached. A reduction system with its "modest" weight, because of the continual oxygen storage system savings realized, becomes especially attractive for missions in the 75 UMD range. The fuel-consuming two column adsorber systems do not compete with LiOH systems until around 300 UMD systems are reached.

MISCELLANEOUS PROBLEMS

A number of sealed cabin problem areas have not been discussed. For the sake of brevity they will be only superficially discussed here.

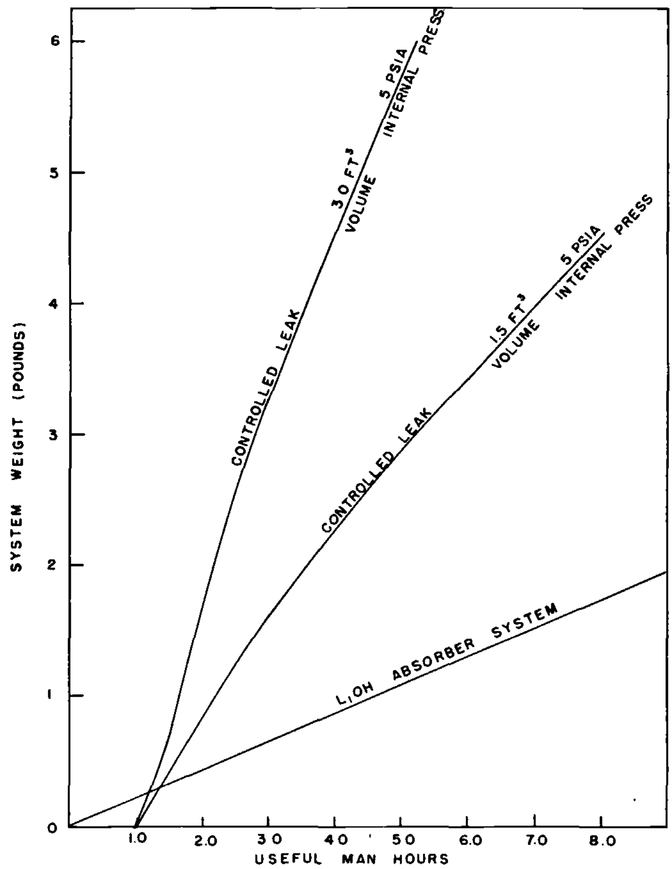

Fig. 2. System weight versus man hours for carbon dioxide control schemes.

Water production in a one-man sealed cabin should be about 8 pounds per day. To maintain comfortable conditions in the cabin, a dew point of around 50°F is desired. This requires that excess moisture be removed from the atmosphere. Like carbon dioxide, water vapor concentration may be controlled by leakage, absorption, and adsorption. A simple way of accomplishing water removal is by condensing it out of the cabin gas stream. If possible, the water condensed should be separated and re-evaporated to space making its heat of vaporization available for supplemental cooling of the cabin.

Odor control is not believed to be a serious problem in one-man systems.

In more elaborate systems, an activated carbon bed or some similar material should be included to eliminate objectionable odors and/or volatile irritants which may accumulate in the cabin as the passenger's body excretes them.

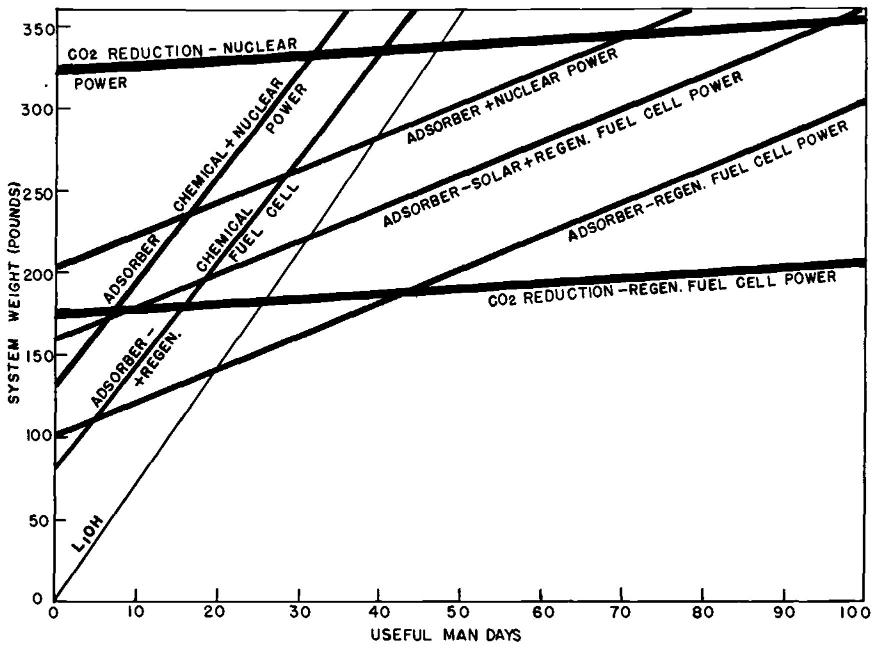

Fig. 3. Effective system weight (equipment plus consumed oxygen) versus useful man days for carbon dioxide control systems.

A blower or "gas pump" is required in virtually any conditioning system. Early systems which incorporate a protective pressure garment with ventilation garment, would require flows in the 12 cfm range at from 20 to 30 inches of water pressure. More advanced systems ought to require increased flows at reduced pressures.

DISCUSSION

Early cabin systems will carry one passenger. These systems will probably use an atmosphere scheme comprised of LiOH absorbers for carbon dioxide control, gaseous oxygen storage, evaporative cooling and chemical batteries. A full pressure protective garment will be constantly worn by the cabin passenger. The cabin will have an oxygen partial pressure in the range of 130 to 150 mm Hg with a reduced total pressure of 5 to 8 psia. The cabin leak rate will probably be high enough to allow use of a gas mixture for oxygen-diluent mixture control. If the cabin leak rate is very low, these cabin systems may employ a 100 per cent oxygen atmosphere.

Intermediate systems will carry from one to three passengers. This type of cabin will use regenerative adsorbers for carbon dioxide control, cryogenic gas storage, and will probably have vapor cycle cooling equipment. Development of an advanced power supply appears to be the biggest stumbling block to employment of more advanced atmosphere control equipment. The cabin leakage will be considerably reduced and a partial-total pressure regulator will be used for control of the cabin gas mixture and pressure. Passengers will not wear protective pressure garments but will have them close at hand ready for donning. Cabin total pressure and composition will closely resemble that of a sea level atmosphere.

Advanced systems will carry three to six passengers. This cabin will have to be equipped with an advanced power supply of a character similar to the regenerative fuel cell. The system may also employ solar heat for some power applications. Gaseous, or in later advanced cabins, cryogenic gas storage will be employed. Carbon dioxide regeneration will be employed and vapor or perhaps absorption cycle cooling will control temperatures. Leakage will be sharply reduced and gas mixture control may be accomplished by the "one fill" of inert gas method. Cabin total pressure and gas composition will closely resemble that of a sea level atmosphere.

Ultra advanced systems provoke much speculation. These systems will probably carry numerous passengers and spend long periods outside of a friendly atmosphere. Biologic systems such as algae, will be of great value in achieving a more nearly closed system. Biologic systems present the promise of affording a food source and waste disposal system in addition to performing the atmosphere control function. While such an ecologic system is quite inefficient, there is good reason to doubt that a non-biologic system could be developed in equal or less time to do the same job.

SUMMARY

The increased emphasis on manned space vehicles has given rise to an intense interest in the environmental control of sealed cabins. This report includes the results of a general analysis of atmosphere control problems and solutions. Control of carbon dioxide and temperature, as well as supply of oxygen, is analyzed, and weight-time curves are plotted. In this manner, an outline schedule for future research and development work is indicated and a groundwork is laid for further analyses of atmosphere control problems.

REFERENCES

1. Bi-monthly progress report six. WADC Contract AF 33(616)-3856 Air Reduction Company Research Laboratories, Murray Hill, N. J., Feb. 21, 1958.
2. Dickey, F. L., and Knipp, G. H.: Climatic and structural aspects of sealed cabins. New York, N. Y. Preprint 699-58. Presented at 13th Annual Meeting, American Rocket Society. Nov. 17-21, 1958.
3. DiTaronto, R. A., and Lamb, J. A.: Preliminary investigation of hyper environments and methods of simulation—U. S. Air Force WADC Technical Report 57-456.
4. Effects of cabin atmosphere on fire hazards. Preliminary Report of Results. Project 6146-60942, Mechanical Branch, Aeronautical Accessories Laboratory, Wright Air Development Center, Ohio.
5. Goldman, D. T., and Singer, S. F.: Studies of a minimum orbital unmanned satellite of the earth. Part IV, radiation and equilibrium temperature. University of Maryland, College Park, Md., 1943.
6. Human tolerance to a slow heat pulse. WADC Technical Report in preparation at the USAF Aerospace Medical Laboratory.
7. Simons, D. G., and Archibald, E. R.: Selection of a sealed cabin atmosphere. *J. Aviation Med.*, 29:350, 1958.