[redacted] WADD TECHNICAL REPORT 61-129

[redacted]

CLOSED ECOLOGY

Donald A. Keating
Robert W. Roundy

Life Support Systems Laboratory
Aerospace Medical Laboratory

MARCH 1961

WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

☆

Qualified requesters may obtain copies of this report from the Armed Services Technical Information Agency, (ASTIA), Arlington Hall Station, Arlington 12, Virginia.

☆

This report has been released to the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C., for sale to the general public.

☆

Copies of WADD Technical Reports and Technical Notes should not be returned to the Wright Air Development Division unless return is required by security considerations, contractual obligations, or notice on a specific document.

WADD TECHNICAL REPORT 61-129

CLOSED ECOLOGY

Donald A. Keating
Robert W. Roundy

Life Support Systems Laboratory
Aerospace Medical Laboratory

MARCH 1961

Project No. 6373
Task No. 63120

WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

1,200 – May 1961 – 27-1,012

FOREWORD

This report is the result of a series of lectures presented by Donald A. Keating as a guest lecturer at the Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio. The lectures were given in December 1959 in the first "Bioastronautics" graduate course presented in the United States. These lectures were based on work performed in support of Project 6373, "Equipment for Life Support and Aerospace," Task 63120, "Respiratory Support Equipment.

ABSTRACT

The concepts of closed ecology as well as the design requirements for three degrees of closure in closed ecological systems have been presented in a fundamental manner basic to the reader's understanding of such aerospace life support systems.

The degree of ecological system closure is dependent upon reliability, weight, bulk, energy input, and mission duration.

The basic closed ecological system concepts are presented fully with the understanding that the design of such systems is dependent upon future research. Design philosophy has therefore been presented in place of actual design.

PUBLICATION REVIEW

Wayne H. McCandless
W. H. MC CANDLESS
Chief, Life Support Systems Laboratory
Aerospace Medical Laboratory

CLOSED ECOLOGY

INTRODUCTION

As man explores outer space, he must depend on the space vehicle's inner environment for his life needs. Such space explorations require the utilization of sealed environments, since outer space is void of the life giving substances. For the most part, the sealed environment should closely resemble that which the astronaut is accustomed to on earth.

Ecology is better known as that branch of biology dealing with the mutual relation of man and his environment. Closed ecological systems provide complete life support for man in flight. Such systems satisfy the astronaut's physiological requirements by recycling the life giving substances within the environment and by adding from external sources those substances which need be replaced. The mission duration, system weight, size, and power requirements determine the type of system to be used.

The advantages of closed ecological systems in space flight will become more apparent from discussions of figures 1 - 4 which illustrate a theoretical and highly idealized analysis of various life support systems with increasing degrees of closure.

As shown in figure 1 (which represents an open ecological system as found in present day commercial aircraft) man inhales 22.7 pounds of oxygen per day, requires a food intake of one pound per day and a water intake of 4.7 pounds per day. He exhales 20.7 pounds of oxygen and 2.2 pounds of carbon-dioxide per day. He excretes 3.3 pounds of waste material per day as well as 2.2 pounds of respired water vapor per day. Perspired water is disregarded for the purpose of simplification. The amount of water perspired would be reflected by an increase in the man's water intake. His total combined input weight of oxygen, water, and food is 28.4 pounds per day, yet much of this is not utilized.

Unlike aircraft, space vehicles cannot extract oxygen from their respective ambient environment and must carry it within their sealed cabins. Such uneconomical utilization of oxygen as shown in figure 1 cannot be tolerated in space vehicles, and another system must be used. The closed respiratory system economically recycles the exhaled oxygen and is shown in figure 2. This system represents the first degree of closure in the closed ecological system.

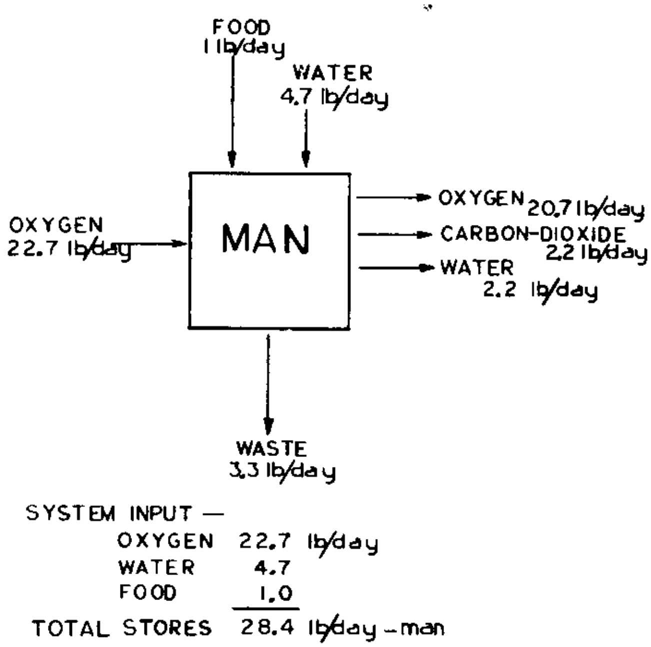

Figure 1. Open Ecological System

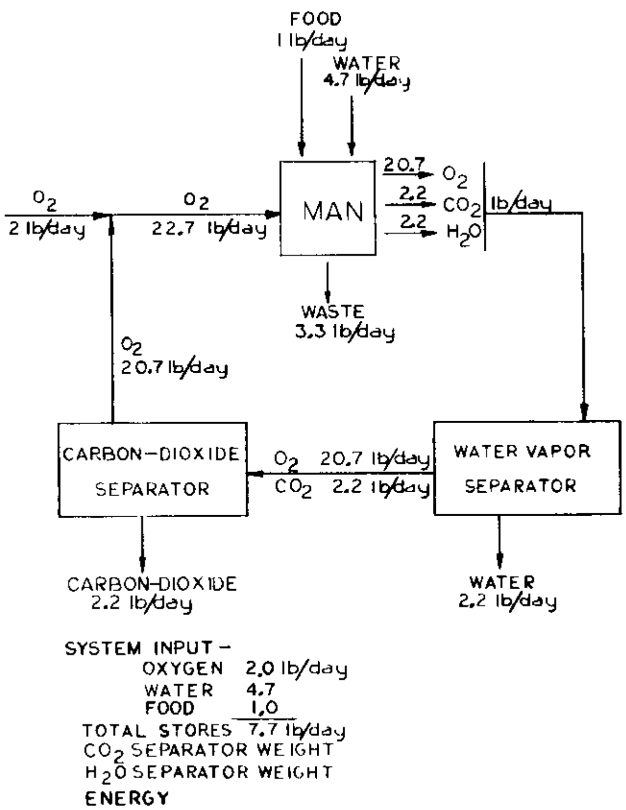

Figure 2. Closed Respiratory System

The closed respiratory system selectively separates oxygen from the exhaled gases of oxygen, carbon-dioxide, and water vapor. This oxygen is recycled so that the external system input is only 2 pounds of oxygen per day, 1 pound of food per day, and 4.7 pounds of water per day. A theoretical oxygen savings of 20.7 pounds per day results by the use of the closed respiratory system, figure 2, as compared to the open ecological system, figure 1.

A comparison of figure 1 and figure 2 must include not only the theoretical oxygen weight savings, but also the energy-weight requirements of the carbon-dioxide and water vapor separators as well as system reliability and the energy-weight requirements of a conditioning system for the recycled oxygen. Assuming system reliability, the closed respiratory system is more advantageous than the open ecological system when its total system energy-weight requirements are less than those for the open ecological system. A comparison of this sort is dependent upon mission duration.

A further oxygen weight savings would occur if the exhaled carbon-dioxide were decomposed into its components of oxygen and carbon. Such a system utilizing carbon-dioxide decomposition can be called an improved closed respiratory system and is shown in figure 3.

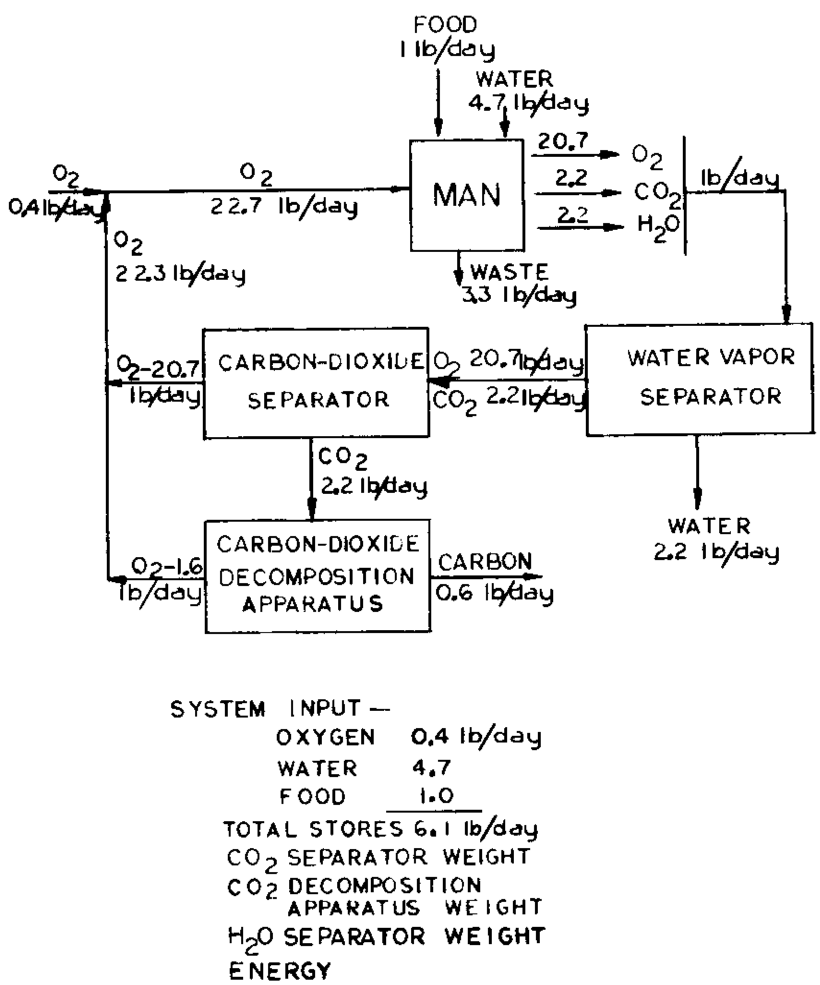

Figure 3. Improved Closed Respiratory System

This system requires a life giving substance input of 0.4 pounds of oxygen per day, 1 pound of food per day, and 4.7 pounds of water per day. It utilizes carbon-dioxide and water vapor separtaors, carbon-decomposition apparatus, and a conditioning system for the recycled oxygen. A comparison of this system and the other two systems must include not only the theoretical oxygen weight savings, but again reliability and the energy-weight requirements of the component equipment. Assuming system reliability, the improved closed respiratory system is more advantageous than the other two systems when its total system energy-weight requirements are less than theirs. Again such a comparison is dependent upon mission duration.

Another source of oxygen from man's physiological processes will be considered here. That is, the the recovery of oxygen from excreted water.

Such a system utilizing this oxygen recovery is shown in figure 4, and can be called the completely closed system.

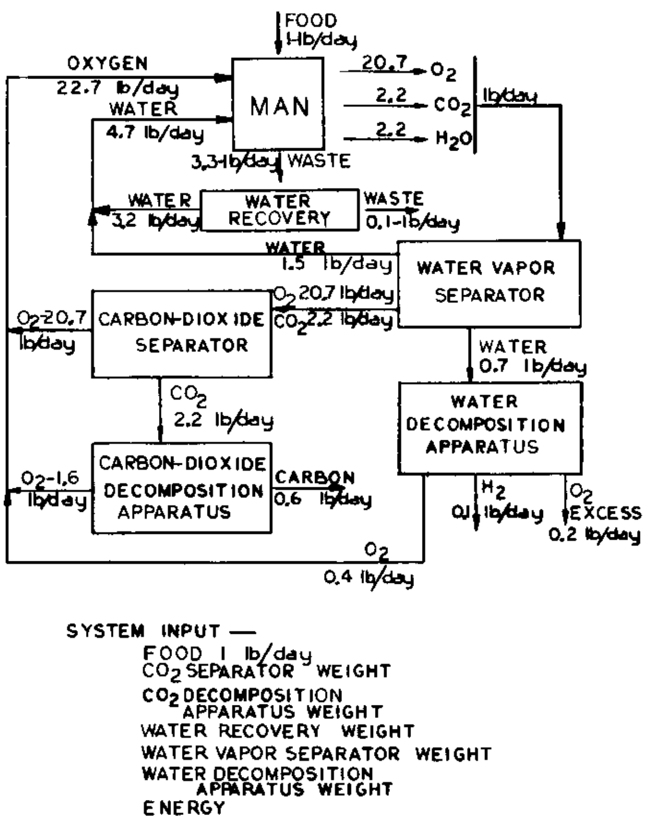

Figure 4. Completely Closed System

The total water of excretion is composed of water from respiration, urine, and feces. As in the preceding analyses perspired water is disregarded for the purpose of simplification.

Water is collected in this system from the exhaled breath, urine, and feces. Water recovery from urine yields 3.0 pounds per day whereas that from the feces yields 0.2 pounds per day. It is interesting to note here that due to the combustion of food, the body excretes more water than it requires as a life giving substance input. A portion of the collected water can then be conditioned and recycled to the man as the total water input while the remaining portion can be decomposed into the components of oxygen and hydrogen. Part of this oxygen is recycled so that the total recovered oxygen is conditioned to supply the total oxygen life giving substance input. The remaining oxygen of water decomposition is considered an output product.

Such a system is completely closed and only requires one pound of food per day as the total life giving substance input. A comparison of this system and the other three systems must include not only the theoretical life giving substance weight savings, but again the energy-weight requirements of the component equipment and reliability. Assuming system reliability, the completely closed system is advantageous than the other three systems when its total system energy-weight requirements are less than theirs. Again, such a comparison is dependent upon mission duration.

In general for missions of "A" duration and shorter, the open ecological systems should be utilized. Closed respiratory systems should be utilized for durations between "A" and "B" hours. Improved closed respiratory systems should be utilized for durations between "B" and "C" hours. The completely closed system should be utilized for mission durations longer than "C" hours. The relative mission durations can be expressed as

$$O < A < B < C.$$

The preceding analysis of various life support systems has been theoretical and highly idealized. Whenever a living organism is introduced into any system, many independent and dependent variables influence the function of that system. The efficiencies of the system components as well as the reversibility and completion of chemical reactions affect the entire system and its function.

Although the previous theoretical analysis must be considered highly idealized, it illustrates the fundamental concepts of closed ecology.

Design Parameters (ref. 6)

To satisfactorily design sealed closed ecological environments for space vehicles, the engineer must be aware of certain design parameters. These parameters will be presented in this section.

Of the gases man breathes, the most important to him is oxygen. He breathes approximately 22.7 pounds of oxygen per day, and his actual oxygen consumption is approximately 2 pounds per day. A conservative oxygen consumption design figure can be chosen as 0.1 pounds per hour.

As the altitude increases, the partial pressure of oxygen within the ambient atmosphere decreases. If man were to ascend to high altitude without proper protection, this decrease in oxygen pressure (sometimes referred to as oxygen tension) would lead to hypoxia. Hypoxia is a deficiency of oxygen in the cells of the body marked by fatigue or nausea, and in the extreme hypoxia condition, convulsions, unconsciousness, and finally death. On the other hand, an over abundance of oxygen partial pressure leads to a deleterious condition known as oxygen toxicity.

The designer of breathing systems must consider the effects of oxygen partial pressure and design accordingly to maintain the proper oxygen partial pressure within the alveoli of the lungs so that sufficient oxygen will be absorbed in the blood to keep the physiological process in balance.

The recommended oxygen partial pressure is 160 mm Hg, since man is accustomed to this partial pressure at ground level.

The total pressure of gases within the space vehicle is also a decisive factor in closed ecological system design. At first glance, designing space vehicles to maintain the internal pressure as low as physiologically possible would appear highly desirable, because a decrease of internal vessel pressure decreases the vessel weight if the internal vessel volume is kept constant. However, the skin of the vehicle must be thicker than that calculated using classic pressure vessel equations, because the space vehicle must bear its own weight on the launch pad and withstand launch forces. The thicker skin will be able to withstand pressures in excess of 14.7 psia. Man cannot tolerate excessively low ambient pressures because of the expansion of air and gases in his body requiring a counteraction of his own internal pressures. A total pressure of 140 mm Hg (equivalent to 40,000 feet altitude) should be considered the minimum ambient pressure condition man can withstand without counterpressure.

Other advantages of low cabin pressure cannot be overlooked. A relatively low total sealed environment pressure would reduce the pressure differential between the sealed environment and outer space, thus lessening the problem of explosive decompression, and minimizing cabin leakage to outer space.

As the engineer redesigns for lower cabin pressure, maintaining the oxygen partial pressure at the recommended value, the oxygen concentration is increased within the environment until high and even 100 percent oxygen concentrations must be maintained. This constitutes a fire hazard. The physiological effects of breathing oxygen at increased concentrations, using the recommended oxygen partial pressure, for prolonged periods of time are not completely known. However, at the AF School of Aviation Medicine an experiment has been performed sustaining two men in a sealed environment for approximately 17 days at 33,000 feet altitude, and at 96 percent oxygen by volume. The effects of an inert gas such as nitrogen within the closed environment may be of importance even though the toxic effect of oxygen is specifically determined by the oxygen tension. Various studies have indicated tolerance limits to prolonged respiration of pure oxygen may be dependent on the oxygen pressure only.

Man lives in a gaseous environment on earth. He physiologically adapts to this environment and would have no difficulty in adjusting to any environment which closely resembles his natural environment. The philosophy of the engineer of closed respiratory systems should ultimately be to provide conditions resembling those on earth to which man can accustom himself.

The designer of closed ecological systems must be fully aware of those noxious and sometimes toxic factors that vapors and gases may affect the occupants of closed respiratory systems as well as the other factors which might present new problem areas.

Carbon-dioxide is not a harmless by product of respiration, but rather a lethal gas. It must be dealt with as such and not allowed to build up to a toxic level in the breathable environment.

The primary purpose of respiration is to supply oxygen to and remove carbon dioxide from the tissues and blood. The automatic process of respiration is apparently stimulated directly by the presence of carbon dioxide in the lungs and indirectly by the oxygen presence. Thus, the body does require a certain portion of carbon dioxide to stimulate breathing.

A severe limit of allowable carbon dioxide concentration must be set so that the astronaut does not die of carbon dioxide poisoning. It has been determined that 3 percent carbon dioxide by volume produces a human bi-phasic reaction consisting of a period of excitation followed by depression. A carbon dioxide concentration of 0.5 to 1 percent by volume is the suggested maximum limit as determined from field tests carried out on submarines during war patrols and in confined environmental tests.

This maximum limit was determined from experiments involving ambient atmospheric air of 14.7 psia. The maximum concentration of 0.5 to 1 percent by volume corresponds to a carbon dioxide partial pressure of roughly 3.8 to 7.5 mm Hg at ground level.

The maximum allowable concentration of carbon monoxide in ambient atmospheric air of 14.7 psia, is recommended as 0.01 percent, or 100 ppm. This lethal gas will occur primarily as the result of smoking.

The astronaut excretes other trace substances which remain undetected until a buildup condition exists in the closed ecological environment. At present trace substance build up rates in closed ecological systems are not known.

The engineering - physiological requirements presented in section are those intimately concerned with the closed ecological system. The closed ecological system designer must also consider the external environmental conditions such as weightlessness, acceleration, noise, vibration, nuclear radiation, and design accordingly.

Designing Closed Ecological Systems

Once the design parameters are established, the designer may then proceed with the design of closed ecological systems.

The designer's purpose is to design a system which provides and maintains a physiologically adequate environment for man in a sealed cabin for definite mission durations. In achieving this purpose he must be certain the system fulfills the design goals of reliability, low weight and bulk, and low energy input.

Mission duration dictates the choice of closed ecological system design. The system designed for relatively short mission durations is less complex and weighs less than that designed to provide life support requirements for long mission durations. In general the weight of closed ecological life supporting systems increases with mission duration until the long term duration is reached when the system weight no longer increases with an increase of mission duration, but remains constant. Such a system maintains a fixed weight and bulk requiring only an input of energy. The ultimate in design would be to achieve such a constant weight-bulk system employing the least weight, bulk, and energy input, and greatest reliability possible.

Closed respiratory systems should be utilized for relatively short mission durations. The intermediate mission duration dictates utilization of the improved closed respiratory system, where as, the relatively long duration dictates utilization of the completely closed system.

The closed respiratory system requires:

1. a method of storing oxygen.
2. a carbon dioxide separator.
3. a water vapor separator.
4. an oxygen conditioner.

The storage of oxygen may be accomplished by employing liquid oxygen convertors or extremely high pressure gaseous oxygen containers. The high pressure oxygen containing vessel is advantageous in some instances to liquid oxygen convertors because of its inherent small volume occupancy.

The carbon dioxide separator, however, presents a more difficult problem. Its purpose is to separate this lethal gas from the sealed environment without removing the life giving oxygen. Various separation methods may be employed such as freezing the gas out of its environment to separating it by chemical means.

Lithium hydroxide appears to be a good carbon dioxide solid chemical separator. Approximately 1.35 pounds of lithium hydroxide are required to absorb one pound of carbon dioxide. Although this chemical has a very desirable absorber-absorbent weight ration, it has an undersirable dusting characteristic which produces considerable tracheal irritation. This disadvantage can be overcome by employing suitable filters.

Another desirable carbon dioxide absorber is the solid chemical Baralyme. It has a higher absorber-absorbent weight ratio than lithium hydroxide yet its density is much greater. This chemical occupies approximately the same volume as would lithium hydroxide for a given amount of carbon dioxide to be removed. The weight of such a system separator would be greater, however, than using the lithium hydroxide separator system. This system does not require an extensive filter arrangement as does lithium hydroxide since it is relatively free of dusting.

The previously described chemical systems are difficult to regenerate. Thus, the system weight increases with mission duration for the chemical weight increases linearly. Regenerative carbon dioxide separators employing the usual weight, bulk, and energy design goals would be most desirable.

Water vapor separation can be accomplished by chemical methods similar to those used in carbon dioxide removal. Another method of separating the water vapor would be to cool the sealed environment air below its dew point temperature. The water vapor thus changes into the liquid phase and is easily separable from the gas flow. Such a system is "regenerative" in operation.

Some chemical compounds perform the unique function of storing oxygen, and removing both carbon dioxide and water vapor. Such a chemical is potassium superoxide. Water vapor and carbon dioxide cause liberation of oxygen as seen by the following equations:

$$4KO_2 + 2H_2O = 4KOH + 3O_2$$

$$4KOH + 2CO_2 = 2K_2CO_3 + 2H_2O$$

An oxygen conditioner is necessary to further purify the exhaled gas. It removes trace substances and odors by methods similar to those utilized in carbon dioxide removal, and supplies the correct humidity-temperature conditions.

As with this system and the others to be discussed, instrumentation plays a vital role. Oxygen, carbon dioxide, and trace substance partial pressure sensors, as well as, a total pressure sensor must be utilized along with regulating devices which function when the sensors detect particular limit values.

The improved closed respiratory system differs from the previously described system in that a regenerative carbon dioxide separator and decomposition apparatus are utilized. Obviously such a system is more complex and should only be utilized when its weight, bulk, and energy input requirements are more desirable than the closed respiratory system.

Carbon dioxide can be decomposed by many methods; for example, nuclear radiation, ultraviolet light, chemical breakdown by hydrogen, and photosynthesis.

Photosynthesis is the synthesis of chemical compounds with the aid of radiant light energy. Man is familiar with this process from his experiences of life surrounding him on earth. In simple terms man and his affiliates give off carbon dioxide to be used by the plants. The plants take on this carbon dioxide, along with other plant food and sunlight to give off oxygen. The oxygen is then breathed by man and the cycle is completed. The earth then is a closed ecological system where the earth's stores and the sun's energy are the only system inputs.

The plants perform this amazing feat of decomposing carbon dioxide by utilizing sunlight as the energy source, and chlorophyll as the catalyst. Water is also oxidized in this process so that free gaseous oxygen results.

The design of such systems is remarkable indeed and it would appear foolhardy not to try to employ these already developed systems into man's scheme of space flight.

Controlled aqueous algae systems can be employed to remove the carbon dioxide from the exhaled gas and evolve oxygen. The input to such a system is primarily that of light energy. In general the algae multiply much faster than needed. Some of the algae can then be used as a food supplement, for various parts of the Orient have been accustomed to eating algae for years. Such photosynthetic gas exchangers then can remove carbon dioxide, supply oxygen, and even serve as a food supplemental source.

The weight and bulk for such a system approaches a constant value with respect to mission duration. Such natural systems are not necessarily limited to algae systems, but can be extended to small replicas of the earth itself. These space farms would then incorporate plant life to remove the carbon dioxide, supply oxygen, and utilize animal life to supplement the plant produce for food. Such a balanced ecology requires energy as the primary system input.

The completely closed system incorporates all aspects of the previously described improved closed respiratory system and utilizes oxygen recovered from excess system water obtained from the excreta.

Some methods of recovering water from the urine and feces are distillation, ion exchange, freezing, electro-osmosis, and through chemicals. Water can be recovered from the exhalation and perspiration by condensing it out of the gas stream.

Electrolysis and other methods can then be used to decompose the excess water. The resulting oxygen is then conditioned to be recycled.

Such a system can be considered completely closed the only input will be that of energy. It represents the ultimate system in closed ecological design, since it provides and maintains an adequate physiological environment for man in a sealed space vehicle for indefinite periods of time.

The fundamental concepts of closed ecology as well as the engineering-physiological requirements have been presented as fundamental truths which will not change with technology. The design of such systems will change, however, with further advancements in science. The design concepts presented are basic in principle and form a starting foundation from which the designer may proceed.

Closed ecological systems play a vital role in space flight, for they support the astronaut's life needs. Such systems satisfy certain engineering requirements by utilizing stored life giving substances and recovering usable portions of the sealed environment.

The degree of system closure is dependent upon system weight, bulk, energy input, and mission duration. For mission durations of indefinite length, closure is complete as other systems utilizing both stored and recovery principles would require excessive weight, bulk, and energy input.

Waste and trace substances which can not be economically broken down into life giving substances, for that particular mission duration, must be disposed of or stored within the space vehicle. This again is dependent upon economics of the design goals.

The designer must not be hesitant about designing redundancies into the closed ecological system. Whenever a man's life is concerned the safety factor of design must be increased without question.

The closed ecological system will support the astronaut's life needs in outer space which is void of any life giving substance. Such a system must function as designed and never fail.

BIBLIOGRAPHY

1. Schaefer, K.E., "Selecting a Space Cabin Atmosphere," Astronautics, Vol 4, No. 2, pp 28-39, 104, 106, February 1959.

2. Michel, E.L., R.W. Langevin, and C.F. Gell, Effect of Continuous Human Exposure to an Oxygen Tension of 418 mm Hg for 168 Hours, Air Crew Equipment Laboratory, Naval Air Material Center Naval Base, Philadelphia 12, Pennsylvania.

3. Myers, J., Study of a Photosynthetic Gas Exchanger as a Method of Providing for the Respiratory Requirements of the Human in a Sealed Cabin, Research Report 58-117, Air University, School of Aviation Medicine, USAF, Brooks Air Force Base, Texas, November 1958.

4. Dryden, C.E., Lit-Sien Han, F.A. Hitchock, and R. Zimmerman, Artifical Cabin Atmosphere Systems for High Altitude Aircraft, WADC Technical Report 55-353, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, November 1956.

5. Best and Taylor, Physiological Basis of Medical Practice, Williams and Wilkins, Fifth Edition.

6. Keating, D.A., Design Parameters for the Engineering of Closed Respiratory Systems, WADC Technical Report 59-766, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, December 1959.