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PROPOSAL FOR DEVELOPMENT OF GRAVITY INDEPENDENT GAS EXCHANGE SYSTEM

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Proposal for Development of Gravity Independent Gas Exchange System

1. Background Information

The use of photosynthesis as a means of regenerating oxygen from carbon dioxide in space cabins has been shown to be biologically feasible. As a working component in a sealed cabin, the photosynthetic gas exchanger requires development. This proposal is concerned with one of the engineering problems associated with a practical model. The problem to be studied involves growing algal cultures in contact with air for prolonged periods of time in the absence of an effective gravitational field.

Engineering analysis and preliminary experimentation indicated that a device employing the use of a semi-permeable membrane to create a controlled gas-liquid interface between air and algal suspension can be made to function. Its operation might be thought of as that of a kind of "reverse lung".

The Space Medicine Section, Martin-Denver, has completed a pilot study which confirms the validity of the basic assumptions. A description of the research accomplished to date follows.

2. Experimental Procedure

Figure 1 is a drawing of the device with which we have been working. A 3/8 inch thick sheet of plexiglas 15 in. x 18 in. is milled with a 1/4 in. continuous groove back and forth in the long direction. The grooves are separated by 1/16 in. lands except for two wider lands used for bolt holes. The channel is approximately 60 feet long. It is connected to the outside of the panel by holes through the edge at each end of the channel. A second panel is grooved as a mirror image of the first. A sheet of the film to be tested is placed between the two panels which are greased around the edges and on the bolt lands with stopcock grease. The assembly is held together by a series of bolts around the edge and in the bolt lands. In effect, the assembly represents two 1/4 in. square channels 60 feet long separated by the membrane material. The volume of each channel is approximately 700 ml. This device was designed to test the principle of gas exchange through membranes; and to serve as a test facility for a variety of films under the limiting conditions of temperature and pressure imposed by the biological material in the liquid phase. The collection of data from this device is aided by a number of instruments which feed information to a multi-channel strip chart recorder. Figure 2 is a diagram of the overall system as it was constituted when these experiments were done.

The algal suspension is pumped through the channel by means of a small centrifugal pump. About 50 cc. of the suspension is contained in a tube which contains a thermistor and an extra outlet for sampling any gas that accumulates in the liquid phase of the system. Air is pumped through a 500 cc. ballast bottle into the panel by means of a diaphragm pump. From the panel, the air passes through a liquid trap having a capacity of one liter and through a water cooled condensor which is maintained at 10° C. The purpose of the trap is to catch the algal suspension if the membrane ruptures. The partially dried air is passed to the pump through a CO_2 analyzer which consists of a veco temperature compensated thermal conductivity cell in a bridge circuit. A separate loop continuously feeds air from the ballast bottle through a flowmeter and a Beckman oxygen analyzer. Potentiometric type pressure transducers are connected to both high and low pressure sides of the air system.

The high temperature Sorokin strain of Chlorella pyrenoidosa was grown in urea medium in 2.5 liter chambers internally illuminated with daylight fluorescent lamps. Cells were harvested by centrifugation, washed in urea-free medium and resuspended in fresh medium containing from 0.5 to 1 gram of urea per liter. The final concentration of algae was approximately 1% volume per volume.

This suspension was introduced into the liquid channel of the gas exchanger and all gas bubbles were eliminated from the liquid phase, to provide hydraulic continuity. The panel was illuminated with a bank of 10 fifteen watt fluorescent lamps. In these experiments, the temperature of the algal suspension was controlled by a fan moving air across the lamps and around the panel. At the beginning of each experiment, the gas phase consisted of air enriched to approximately 14% with CO_2.

3. Results

The two most promising membrane materials tested to date are polyethylene and oriented polystyrene. The results of an experiment in which 0.5 mil polyethylene was used as a membrane and one with 1.5 mil polystyrene are shown in Figure 3. These results represent an oxygen transfer rate of approximately 43 cc. per hour for the polyethylene and approximately 11 cc. per hour for the polystyrene. The very thin polyethylene works comparatively well insofar as gas exchange capability is concerned. However, it is not satisfactory from the mechanical standpoint. The film ruptured after only a few hours service, allowing the algal suspension to be drawn into the air channel.

1.5 mil oriented polystyrene was substituted because of the superior mechanical characteristics of this material. The rate of gas transmission is lower than that of polyethylene. With this film in the panel, a significant amount of gas collects in the liquid phase. This gas is trapped in the small tube in which the thermometer is mounted. Samples withdrawn at this point contain no carbon dioxide and from 50 to 70% oxygen. Figure 4 is a drawing of the cross section of a modification of the panel. The panel was rebuilt to accommodate two sheets of film by milling 1/8 in. deep grooves in both sides of a third sheet of plexiglass. These grooves terminate in common outlets. The grooves in the center panel serve as the liquid channel and the grooves in the two outside panels are connected in series to serve as the gas channel. The liquid volume is the same as in the previous model, but the area of film is doubled. Data from an experiment conducted with this device employing 1.5 mil polystyrene are compared with those from the experiment with a cingle area of polystyrene in Figure 5. The rate of exchange is about twice that observed for the single area panel being 11 cc. per hour in that case and 23.5 cc. per hour with double the area.

Some general remarks can be made regarding the experiments with all the films successfully tested to date. These are first, with the volume of algal suspension and level of illumination employed, the CO_2 diffusion rate across the membrane is the limiting factor in the overall photosynthetic rate. Secondly, the diffusion of oxygen proceeds at a lower rate than does oxygen evolution by the algae. Finally, with the non-wettable films such as polyethylene and polystyrene, transfer of water vapor is so low as to be almost negligible. Theoretical prediction of the potential rate of exchange of oxygen can be made from the data provided by the film manufacturers. For polyethylene, the oxygen permeability is given as 430 cc./24 hrs. x 100 sq.in. x mil thickness x atmosphere. For oriented polystyrene, the figure is 210 cc. in the same unit.

The pressure differential was not accurately measured, but can be roughly estimated. In experiments with both films the absolute pressure in the gas phase averaged approximately 620 mm.Hg. With an average of 23% O_2 this represents an estimated average pO_2 of 143 mm.Hg. In the experiments with the polyethylene, the pressure in the liquid phase remained close to ambient, that is, approximately 620 mm.Hg. It is assumed that the gas on the liquid side of the film was essentially 100% O_2. Thus, in these experiments the pO_2 is estimated to be 620 - 143 = 477 mm.Hg. In the experiments with polystyrene, there was a significant increase in the absolute pressure in the liquid phase. Only one attempt was made to measure this pressure with a mercury manometer (differential to ambient) and this determination cannot be considered to be necessarily representative. The reading was equivalent to an absolute pressure of 846 mm.Hg. A rough estimation of the pO_2 would then be 846 - 143 = 703.

The predicted exchange rates are then

for 0.5 mil polyethylene:

$$\frac{430 \text{ cc.}}{\text{day}} \times \frac{180 \text{ sq.in.}}{100 \text{ sq.in.}} \times \frac{1 \text{ mil}}{0.5 \text{ mil}} \times \frac{477 \text{ mm.Hg.}}{760 \text{ mm.Hg.}} \times \frac{1 \text{ day}}{24 \text{ hr.}} = 40.5 \text{ cc./hr.}$$

for 1.5 mil polystyrene:

$$\frac{210 \text{ cc.}}{\text{day}} \times \frac{180 \text{ sq.in.}}{100 \text{ sq.in.}} \times \frac{1 \text{ mil}}{1.5 \text{ mil}} \times \frac{703}{760} = \frac{9.75 \text{ cc.}}{\text{hr.}}$$

In both cases, the predicted rate agrees fairly well with, but is less than observed. The discrepency is probably due to failure to accurately measure the pO_2 in the system. Future experiments will be designed to overcome this difficulty. The results obtained so far have established the validity of the principle that a gravity independent gas-liquid interface can be established across a semi-permeable medium in such a manner as to allow for appreciable exchange of CO_2 and oxygen while limiting the transfer of water vapor.

4. Statement of Work

Future development of this project will involve studies in two areas. The first of these will be concerned with efforts to improve the area to volume ratio and the second will involve study of other semi-permeable materials.

Some as yet untested materials which have possible application in this type of device include irradiated polyethylene, porous teflon, silicone rubber, woven stainless steel cloth and Corning porous Vycor glass. Acetate film and cellophane have been tested and both are characterized by excessively high rates of water transmission and generally poor mechanical characteristics. Mylar even as thin as 0.25 mil while mechanically superior is characterized by very low permeability to both CO_2 and O_2.

Four of the untested materials have been obtained but not evaluated. The non-film type materials to be tested are woven stainless steel mesh and porous Vycor glass. The steel mesh will be tested in a panel similar to the one described above. The porous glass was obtained as tubes 9 mm. in diameter with 1 mm. thick walls. The total length of tube obtained is approximately 5 meters providing a total area of approximately 1400 $cm.^2$ or about 217 sq.in. This compares favorably with the surface of 1160 $cm.^2$ characteristic of the single panel described above. On the basis of the data provided by Corning, the predicted rate of exchange for O_2 through a thickness of 1 mm. having an area of 217 sq.in. is between 3000 and 5000 cc. per hour, some 100 times that predicted for the same area of the polyester films. However, one major difference is the physical characteristics of the film and the glass alter this prediction drastically. The polyester films are non-wetting and their action in this application appears to be essentially a diffusion phenomenon. By contrast, preliminary experiments indicate that the porous glass is extremely hygroscopic. It will absorb as much as 25% of its weight of water (as compared to less than 1% for the polyester films). For this reason, it is expected that the exchange of oxygen through this material will be largely a function of rate of solution and dissolution of O_2. One possibility for improving this situation might be to coat the glass with some hydrophobic substance which would serve to prevent saturation of the glass with water without altering the gas permeability.

Samples of 0.5 mil teflon and of 5 mil silicone rubber are available. On the basis of diffusion data supplied by the manufacturer, it is expected that these will be superior to those already tested. The predicted diffusion rates in the experimental prototype are 160 cc. per hour for the teflon and 1600 cc. per hour for the silicone rubber. The later figure is extremely promising. Provided the observed rate equals the predicted rate, the exchange rate per unit area will be higher than the maximum rate of O_2 produced per unit area at solar levels of illumination. In other words, if the mechanical characteristics of silicone rubber film prove to be as good as predicted, then membrane permeability will not be the limiting factor in the design of the gravity independent photosynthetic gas exchanger.

Specifically, the following phases will be accomplished.

Phase I

1. Experimentally determine the exchange characteristics of the Corning glass, stainless steel mesh, and the teflon and silicone films as well as any other promising semipermeable materials that can be obtained. This will include attempt to treat the glass to prevent wetting and retain the diffusion characteristics predicted for the dry material.

2. Conduct a design study aimed at increasing the surface to volume ratio in devices using semipermeable films and to increase pO_2 in the systems. Excessively high partial pressures of O_2 in the liquid phase of the system are expected (on the basis of reported experiments) to decrease the photosynthetic rate. An optimization problem is evident here.

3. Select and test from commercially available equipment (pumps, heat exchangers, illuminators, algal harvest apparatus, water recovery apparatus, etc.) necessary to a complete gravity independent system. Where commercially available equipment is not available, design criteria for procurement will be developed.

Phase II

1. Design, construct and operate a test model gravity independent photosynthetic gas exchange system capable of producing not less than 350 liters (STP) of O_2 per day. This model will not represent airborne capability with respect to the weight and volume parameters. It will be used in design studies for airborne models.

2. As a result of operational test of the test model, develop, design criteria for an airborne gravity independent photosynthetic gas exchanger.

Laboratory Facilities

The Space Medicine Laboratory is presently housed in an air conditioned building. The area assigned to primary laboratory use comprises approximately 900 square feet. The same building contains a small animal room and a combination shop and glass-blowing facility. Approximately 2700 additional square feet of laboratory space will be provided in a new Engineering Development Building. Occupancy has been initiated and is scheduled for completion about/or during December 1959.

The Space Medicine group will take delivery about 1 October 1959 on a small animal space cabin simulator. The inner chamber on this unit is nominally 4 feet long and 2½ feet in diameter. The outer chamber is 11 feet long and 6 feet in diameter. Provisions have been made for closed cycle operation with respect to the atmosphere. A complete instrumentation capability is being assembled in conjunction with a complete, modularized environmental conditioning system.

The unit will serve a two-fold purpose. It will be used to study physiological effects of artificial atmospheres, reduced pressures and atmospheric toxicants; and it will serve as a test bed for environmental conditioning hardware developed under the direction of the Space Medicine group.

Present laboratory equipment includes those major items shown in the attached list as well as all necessary minor equipment, glassware, and supplies required for complete physiological, biochemical, and microbiological research. An additional $80,000 in major laboratory equipment has been budgeted to add additional capability in the new laboratories.

Major Equipment

Martin-Denver
Space Medicine Laboratory

1 Beckman DU Spectrophotometer

2 9 Position Rotary Warburg Apparati

1 B & L Spectronic Colorimeter

1 Serval SS-4 Centrifuge with Continuous Flow Attachment

1 International Clinical Centrifuge

1 Bacteriological Incubator

1 Castle Automatic Control Autoclave

1 Freezing Microtome

2 Drying Ovens

1 Muffle Furnace

1 Research Microscope

1 Beckman Oxygen Analyzer

1 Leeds and Northrup CO_2 Analyzer

1 Bristol 12 Channel Strip Chart Recorder

3 Ionaire Ionizers

2 Ionaire Ion Collectors

1 Ainsworth Analytical Balance

2 Chemical Balances

2 Scholander Gas Analyzers

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Present Position:

Specialist Human Factors, Chief of Ecology Unit, Space Medicine Section.
The Martin Company, Denver Division

Education:

University of New Mexico, 1939-42, 1946-47, B.S. (Biology), 1947

Stanford University, 1953-55, M.A. (Biological Sciences), 1955
Major Professor: E. L. Tatum
Thesis Title: The Metabolism of Protocatechuic Acid by Neurospora

Stanford University, 1955-57, Ph.D. (Biological Sciences), 1957
Major Professor: S. R. Gross
Thesis Title: The Lethal Effects of Gamma Radiation on Neurospora Conidia

Experience:

1955 - 1958 School of Aviation Medicine, USAF
Research Biologist working on problems of the biological effects of ionizing radiation and on problems of closed ecological systems for manned space operations.

1958 - present Space Medicine Section, The Martin Company, Denver Division. Responsible for directing program of biological research in support of the space medicine program. General areas of interest include problems of cultivation of microbial populations of potential benefit to manned space flight, and control of microorganisms of potential danger to manned space flight.

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Professional Societies:

American Astronautical Society
Sigma Xi
Society of American Bacteriologists
American Association for the Advancement of Science
Southwestern Branch, Society for Experimental Biology and Medicine