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SPACE FLIGHT ECOLOGIES

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SPACE SCIENCES LABORATORY
GENERAL ELECTRIC
MISSILE AND SPACE VEHICLE DEPARTMENT

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SPACE SCIENCES LABORATORY

SPECIAL PROJECTS OPERATION

SPACE FLIGHT ECOLOGIES

By

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MISSILE AND SPACE VEHICLE DEPARTMENT

GENERAL ELECTRIC

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I. INTRODUCTION

The physiology of man demands that a certain minimum quantity and quality of water and nutrition be supplied him for his survival. When man is in his natural environment, on the earth's surface, the ecology existing there supports him with little effort on his part. However, should man attempt to leave the relative security of the earth's surface, it becomes necessary to provide an environment that closely resembles the life cycle he is leaving behind. Hence, it is mandatory that the daily requirement of food, oxygen, water, plus a relatively clean inert carrier gas be present in addition to a means for the disposing of his wastes. In this concept, man's wastes include such factors as exhaled breath, containing water and carbon dioxide, odor, perspiration, urine, fecal matter and flatus containing toxic material.

Considerably increased effort has recently been devoted to the field of the life sciences, particularly in attempting to devise life support systems for man during space flight missions. It is well established that the time-of-flight to a great extent dictates the type of life support system that is necessary. For example, for a reasonably short term flight similar to the Project Mercury concept a system in which man's necessities are regenerated by application of the physical or biological sciences does not appear to be necessary. Obviously, the simplicity of the system and its weight make the prestored techniques attractive for flight times of a few days. However, as the flight time increases over perhaps one man month or some other threshold value, it then becomes desirable to look into regenerative techniques in order that weight savings may be effected. For the extremely long-term space flights perhaps the planetary station concept of semipermanent station keeping, it appears highly desirable to devise and put into use a completely closed ecological system. This paper concerns itself with the latter two systems, viz:

1. Regenerative - partially closed ecology
2. Regenerative - completely closed ecology.

II. AREAS OF INTEREST

Life Support studies is a field of investigation within the overall technology called Bioastronautics within the framework of the Life Sciences. It can be channeled into six distinct categories as follows:

1) Air purification
2) Oxygen supply
3) Water supply
4) Food supply
5) Temperature and pressure maintenance and control
6) Power supply

Each of these six subject areas have been under investigation for varying lengths of times for various purposes other than the problem associated with placing man in space. It might be generalized here that with the exception of food supply all are amenable to solution by application of known principles.

In particular, the control of temperature and pressure can probably be accomplished with the avialable hardware or at best some further development of this hardware. The power supply problem is being actively investigated based upon several relatively new techniques for the conversion of solar, thermal, or nuclear energy, into more useful forms. As a result in this paper we will deal only with the first four items because they relate particularly to bioastronautics. In addition, we will define a feasible partially closed ecological system which can be made ready for space application within a short time period. Following this we will speculate upon a completely closed system useful for indefinite flight durations.

III. PREVIOUS WORK

A. AIR PURIFICATION

The removal of carbon dioxide, water vapor, odor, and other toxic or trace or trace contaminants from the air is a reasonably well understood technology. However, assuming the necessity for a regenerative life support system wherein the raw material needed for processing must come from man's wastes a new specification is added to the selection of the techniques for the extraction of these materials from the contaminated air.

This specification concerns the recovery of the adsorbed wastes so that they may be treated to yield the necessary vital materials. Obviously, the requirement exists for a low energy input system and also for a reasonably simple procedure. For example, in the Mercury program (short term flight) the use of lithium hydroxide has proven satisfactory for the removal of carbon dioxide from the air. If a requirement existed for the recovery of the CO_2 and the reuse of the lithium hydroxide a problem should arise. It is a difficult task to remove the CO_2 from the lithium carbonate, which is formed by the reaction of CO_2 and LiOH, and then to reconstitute the LiOH. Therefore, another material should be found which will give up its adsorbed CO_2 more readily. Such a material is the molecular sieve. The sieve, while not particularly efficient as an adsorber of CO_2, is desirable because of the low energy input necessary to drive off the CO_2 and to have the molecular sieve available for further adsorption.

There are several techniques available for removal of moisture from the contaminated air which have been proven successful in previous applications. For example, the dessicant, lithium chloride is desirable because by heating this material to about 150 degrees C the moisture can be driven off and the material itself returned to its original state. Other successful techniques include dewpoint condensation and freezing. These are useful because a manned vehicle cabin must contain a cooling system for maintenance of the proper ambient temperatures. To do this, some type of heat exchanger is a necessity. This exchanger will obviously have at least one surface which will be sufficiently below the ambient temperature to permit the moisture in the air to condense upon it. Alternately, if that temperature is sufficiently low, the moisture may then freeze.

The removal of odor from the air is a problem which may be resolved by the use of an adequate supply of activated charcoal. Information obtained from the literature recommends that one pound of charcoal per year is suitable for odor control of toilets having a volume ranging from 100 to 1,000 cubic feet and from chemical plants with a volume ranging from 50 to 500 cubic feet. By extrapolating and remaining on the conservative side, perhaps 5 pounds of charcoal should be adequate to remove all predicted odors.

If additional treatment is necessary it is suggested that the dried, odorless air be passed through a high temperature zone in order to destroy the trace contaminants which have not been entirely eliminated by the charcoal. If these trace contaminants are presumed to be hydrocarbons or organic molecules it seems likely that passing through a high temperature zone will decompose these materials into their basic constituents, carbon dioxide and water. Since the quantity of these contaminants will be quite small, the trace amounts of CO_2 and H_2O introduced to the air as a result of these reactions would be minute. The need for this further purification will be known only after further testing.

B. OXYGEN RECOVERY

Considerable study and experimentation has been devoted to the problems concerned with the recovery of oxygen from carbon dioxide. In general, these techniques fall into two categories, the physico-chemical and the biological.

The biological approach makes use of the photosynthetic ability of chlorophyll containing plants to synthesize food and oxygen from carbon dioxide and water in the presence of sunlight or other light in the visible region of the spectrum.

This technique is sound and in principle, feasible. However, the present state of the art regarding photosynthetic gas exchangers still lags behind that of the physico-chemical technique. Potentially, however, the approach has great merit because of its apparent ability to duplicate (on a smaller scale) the earth's ecology. Consequently, it is described in greater detail later wherein it becomes the core of the completely closed ecological system.

The other general approach to the recovery of O_2 from CO_2 concerns the reduction of the latter by its reactions with hydrogen, the alkali metals or catalytic dissociation.

Many reactions appear in the literature in which carbon dioxide is reduced by its reaction with hydrogen. The reduction products always include water plus graphitic carbon or a carbon-containing compound. Water, since it contains oxygen, is the important product in these reactions.

The several reactions are listed which are currently under investigations:

$$CO_2 + 2H_2 \longrightarrow C + 2H_2O \qquad (1)$$

$$CO_2 + H_2 \longrightarrow CO + H_2O \qquad (2)$$

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \qquad (3)$$

Each of these reactions requires a catalyst. They are exothermic once the reaction has begun. These hydrogenation reactions separate the oxygen from the carbon dioxide by replacing the carbon molecule with hydrogen. Thus, in order for the oxygen to be made available in a gaseous form, electrolysis of water must be employed. In this manner, total energy requirement becomes large even though the basic reactions shown in Equations 1, 2 and 3 are exothermic.

Reaction (1) has been studied experimentally wherein it has been found that over an iron catalyst, the reaction proceeds well at a temperature level of about 600 degrees C. The products include CH_4, C_2H_2, CO in addition to those shown by the equation.

Reaction (2), the reverse water gas shift, requires a high temperature (approaching 1600 degrees C) before the reaction will proceed from left to right as represented by the arrow. Below this temperature, the equilibrium is such as to go in the reverse direction.

Reaction (3), the Fischer-Tropsch Synthesis, has received considerable attention. The reaction proceeds well at reasonable temperatures (200-500 degrees C) depending upon the material selected as the catalyst. The methane produced as a byproduct necessitates further treatment to make available the hydrogen required for the basic reaction. The decomposition of methane requires a large energy input at high temperatures ($\sim$1400 degrees C). As a result, the overall process necessary to obtain oxygen becomes complex because of the need for a) electrolysis of water, b) the decomposition of the methane in order that the hydrogen be made available, or c) the storage of hydrogen with its attendent weight and space penalties.

In addition, the total energy input is high because of the two decompositions required.

Another reaction appearing in the literature concerns the dissociation of carbon dioxide at reduced pressures and is shown below in Equation (4).

$$2CO_2 \longrightarrow 2CO + O_2 \tag{4}$$

Reaction (4), the thermal dissociation of carbon dioxide at reduced pressures, has been reported in literature by Nernst, Von Wartenberg, and Langmuir. It has been demonstrated that high yields may be obtained by passing carbon dioxide through a heated zone at reduced pressures. Ordinarily, the dissociation of carbon dioxide by application of high temperatures is quite low; however, by reducing the ambient pressure, the reaction is greatly accelerated towards completion. The results show that the amount of dissociation per pass is a function of pressure at any temperature and is about 53 percent at a pressure level of 0.01 atmosphere.

This reaction results in the production of gaseous oxygen and carbon monoxide. Obviously, since the oxygen is already in the form which may be immediately used by man, this technique is more desirable than a reaction in which the oxygen is obtained only after a further decomposition of some by-product, for example, water.

Pursuing this approach further appears promising since the other product, carbon monoxide, can be treated in a straightforward fashion to obtain carbon and water or carbon dioxide. These reactions are:

$$CO + H_2 \longrightarrow C_{(g)} + H_2O \qquad (5)$$

$$2CO \longrightarrow C + CO_2 \qquad (6)$$

Reaction 5, in which the monoxide reacts with hydrogen to form carbon and water, is a relatively simple and well known reaction and would result in the need for the electrolysis of water so that the oxygen is made available.

However, the advantage to this would be that the hydrogen, also made free by the electrolysis, could be reused in the basic carbon monoxide reaction. The reaction shown in Equation 6 requires a Fe_3C catalyst. The reaction proceeds at approximately 450 degrees C for a maximum yield of carbon dioxide. (It is of interest to note that the carbon deposited out during this reaction speeds the catalytic reaction.) The carbon dioxide obtained by this catalysis is then passed back into the original reaction chamber for dissociation.

Calculations based on the energy requirements for this overall dissociation reaction indicate that the total energy input is approximately one-third less than the energy required for the other hydrogeneration reaction. Secondly, an important fact is that the total number of reactions necessary to obtain all the oxygen from the carbon dioxide is less than the number of reactions necessary for the hydrogenation processes. As a result this approach appears less complex than the other methods shown earlier. The conclusion is reached, therefore, that the thermal dissociation reaction of carbon dioxide at a reduced pressure is the ranking method for the recovery of oxygen of the four reactions described above.

Table I entitled, "Computed Ranking" presents the calculated energy requirements of each of these reactions referred to above.

C. WATER RECOVERY

Several investigators have studied the feasibility of water recovery from urine by distillation. Although it is generally stated to be feasible, data were presented based on experimental evidence that only 50 percent of the water recovered from urine by distillation alone is suitable for further treatment which may make it potable. Studies have been conducted concerning several other techniques such as freezing, electro-osmosis, and ion exchange. In each approach it is probable that potable water could be obtained; however, no experimental evidence was offered.

More recently, publications have appeared indicating the successful recovery of potable water from urine. Three general approaches have been found to be satisfactory, acid distillation, lyophilization and distillation followed by the catalytic oxidation of the toxic volatiles. The acid distillation technique included adding H_2SO_4 and $KCrO_4$ to the raw urine then boiling out 85 percent of the initial volume which was then poured over a column of

TABLE I

COMPUTED RANKING, OXYGEN RECOVERY TECHNIQUES

THEORETICAL ENERGY REQUIREMENTS

Equation	Technique	Remove O_2 from CO_2 K cal/man day	Obtain O_2 gas K cal/man day	Total K cal/man day	Complexity Factor	Ranking
4	Dissociation	1390	1250	2640	1	1
3	Fischer Tropsch Synthesis	-874	4600	3726	2	2
2	Reverse Water Gas Shift	-1402	4600	3198	2	3
1	Hydrogenation	-880	4600	3720	2	2

moistened, activated charcoal. The freeze drying of the urine was then using a methyl cellosolve and dry ice mixture. The frozen material was then vacuum dried. Recovery of the sublimate yielded almost all of the original water content. The third technique in which the vaporized fractions of the urine are treated to a catalytic oxidation reaction has been under investigation at the laboratories of the author and has proven highly successful. This technique is of great interest because it does not require additives, is simple, and assuming the utilization of the vacuum and the solar energy existing in space, does not require other energy input. This approach uses a two-step purification technique because both nonvolatile and volatile toxic materials are contained in urine and they require different treatment for their elimination. The former are characterized by salts, primarily sodium and chloride and by urea and pigment. The latter, principally by ammonia and phenol. Many of these materials are toxic in various degrees and as such must be eliminated. Distillation alone is an ineffectual means for obtaining potable water from urine as previously discussed. In general, the material produced is odorous and alkaline and contains many constituents which make it unfit for human consumption. Further treatment such as chlorination, ion exchange or filtration improves the quality. Other chemical additives such as acids or oxidizing agents also improve the quality sufficiently in some cases to permit the water to be judged potable. However, a severe weight penalty is incurred because a specific quantity of treatment material must be prestored prior to take-off. The amount being a function of flight time and number in the crew. This, of course, is a far cry from a true regenerative system. Further study of the water recovery problem resulted in a simple approach that takes advantage of the distillation technique for separating and leaving behind the nonvolatile materials and color and then as a second stage destroys the volatile toxic materials by oxidizing them in the presence of a catlyst at high temperature. Vacuum oxidation offers a method of accomplishing the destruction of volatile materials simply and does it nonselectively. The breakdown of the relatively complex materials of unknown effects to simple molecules is a major benefit of this particular technique.

D. FOOD SUPPLY

The supply of food in any life support system constitutes a logistic problem. From a practical point of view the present as well as the advanced state of the art ordinarily proposed by informed workers prescribes storing the proper quantities of this material. However, a basic research area exists in the study of the photosynthetic mechanism as a means for not only supplying oxygen to man but also food.

The two equations below represent in their simplest form the operation of the earth's ecological system in which life is supported on a very large scale through the action of an approximately closed cycle involving a great complexity of biological material.

$$\text{Food} + O_2 \longrightarrow H_2O + CO_2 \text{ and Wastes} + E_1 \qquad (7)$$

$$\text{Wastes} + H_2O + CO_2 + E_2 \longrightarrow \text{Food} + O_2 \tag{8}$$

when E_1 = Energy in form of heat

E_2 = Solar energy

Equation 8 represents the photosynthetic process of growing plants while equation 7 is the means by which animals carry out metabolic processes and as such is the reaction used by man to obtain energy for his activities. Although a man's energy requirements are about equal to the energy received by a square-foot of surface normal to the sun's rays at the earth's distance, the efficiency with which he can collect and utilize this energy with the help of present technology is quite low. Directly or indirectly he must utilize the second phase of the above-mentioned cycle. A field of corn, for example, utilizes on a year-round basis less than 0.10 percent of the solar energy incident upon it. Recent studies using simple biological types of algae have indicated the possibility of achieving an efficiency exceeding 10 percent of the solar enegy utilization. One might solve much of the weight problems associated with prolonged space flight by utilizing a small short-cycle closed ecological system in which all the food requirements except perhaps a few of the more complex types, e.g., certain vitamins, are provided. The weight requirements of such a system would certainly have to be several orders of magnitude less than that of the system on earth in which man is now nourished.

Since algae are presently being considered as a source of oxygen for the crew it therefore becomes of great importance economically as well as scientifically to devise means by which the organic material produced by the algae (additional cells) could be treated in some manner to form a palatable, nutritious diet for the astronaut.

IV SYSTEM LESCRIPTION

A. PARTIALLY CLOSED ECOLOGICAL SYSTEM

As a result of the investigations presently underway and/or concluded on the four subjects concerned with supporting life in space it becomes apparent that sufficient information is available concerning each of the recovery techniques such that a partially closed ecological system may be selected.

1. Air Purification

The removal of the odorous material from the air by the use of activated charcoal appears to be the most direct and lightweight method.

Moisture control can be affected by one of the several techniques described earlier. However, it is believed that the dessicant, lithium chloride, appears to offer the maximum promise. The regeneration of lithium chloride requires a temperature of about 150 degrees C and the total of 1600 BTU's per pound of water is required. By this means the water is recovered and the lithium chloride is returned to its original state so that it may continue to serve its function of adsorbing the water vapor from the atmosphere.

The use of a recycling molecular sieve cartridge appears highly desirable for the task of removing carbon dioxide from the atmosphere. Experiments have indicated that the sieve may be regenerated by either heating to a temperature of approximately 95 degrees C with a heat input of 450 BTU's per pound of CO_2 plus 650 BTU's per pound of carbon dioxide as sensible heat or the application of low pressures. Here experiments have been conducted at a pressure of approximately 15 mm Hg and with a heat input just sufficient to maintain the molecular sieve at approximately room temperature. The second method is suggested as the most desirable primarily because of the availability of the vacuum of space.

2. Oxygen Recovery

The oxygen supply is obtained by a combination process wherein the initial oxygen results from the catalytic dissociation of carbon dioxide at reduced pressures and the remainder of the oxygen is obtained by the electrolyis of water. The dissociation reaction shown as Equation (4) earlier is feasible and appears to be quite desirable from the point of view of

a) the low energy requirements

b) the availability of the space vacuum

The by-products, carbon monoxide and oxygen, are directly useable as shown on Figure 1 which is a schematic flow diagram of the selected oxygen recovery system.

The decomposition of water by electrolysis is a process that has been long understood and practiced. The General Electric Company has been active in the development of a fuel cell that combines oxygen and hydrogen to produce energy with water being the by-product. This cell is unique in that it contains a hydrophylic resin membrane containing a molecularly anchored ionically active functional group as the electrolyte. This permits an essentially self-regulating action. In addition, the electrolyte cannot be leached from the membrane by the water. Reversing the action of this ion exchange solid membrane electrolytic fuel cell results in an electrolysis cell having certain advantages. For instance, since the electrolyte is incorporated into the membrane, pure water may be decomposed by electrolysis with no additional substance added to improve conductivity. Secondly, the membrane also serves as the dividing wall for the hydrogen and oxygen chambers. Thirdly, the energy input is considerably below that of a standard type of laboratory model electrolyzing cell. Test data yielded an energy input of 8.14 kilocalories per liter of oxygen compared with an input of 24.79 kilocalories per liter of oxygen required by the laboratory unit.

3. Water Recovery

The technique described earlier as the distillation followed by the catalytic oxidation of the toxic volatiles has been selected as the means by

OXYGEN RECOVERY SUBSYSTEM

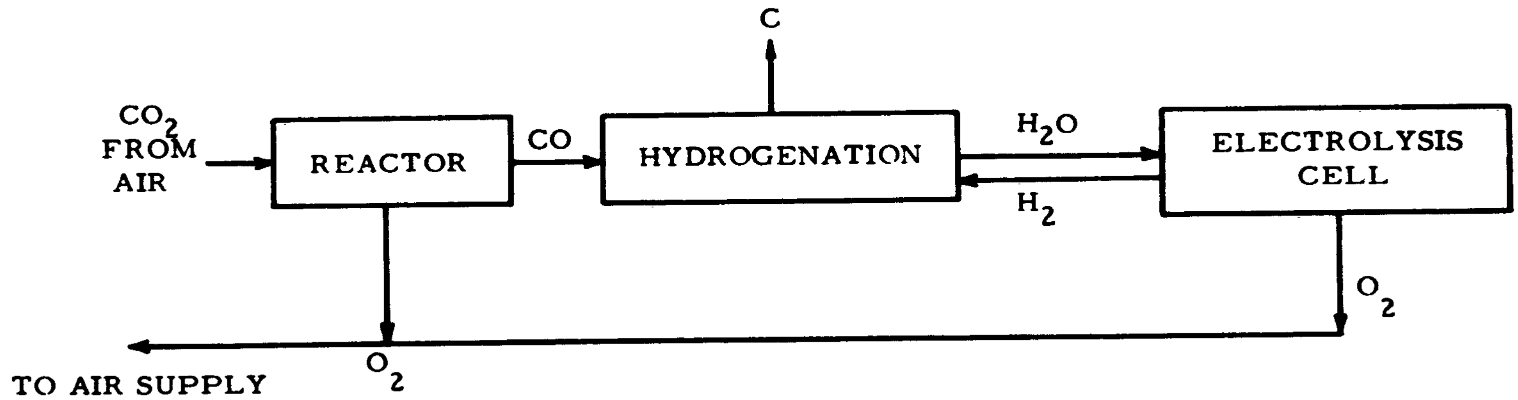

FIGURE 1

which potable water will be obtained from urine and fecal matter in this system. Several reports have been published concerning the results of the study of this technique and it has been demonstrated that the recovered product has consistently been adjudged potable in accordance with the U.S. Public Health drinking standards. Figure 2 is a schematic flow diagram illustrating the principle of the regeneration technique. Table II and Figure 3 illustrate the results that have been obtained using this technique.

SCHEMATIC FLOW DIAGRAM
WATER RECOVERY TECHNIQUE

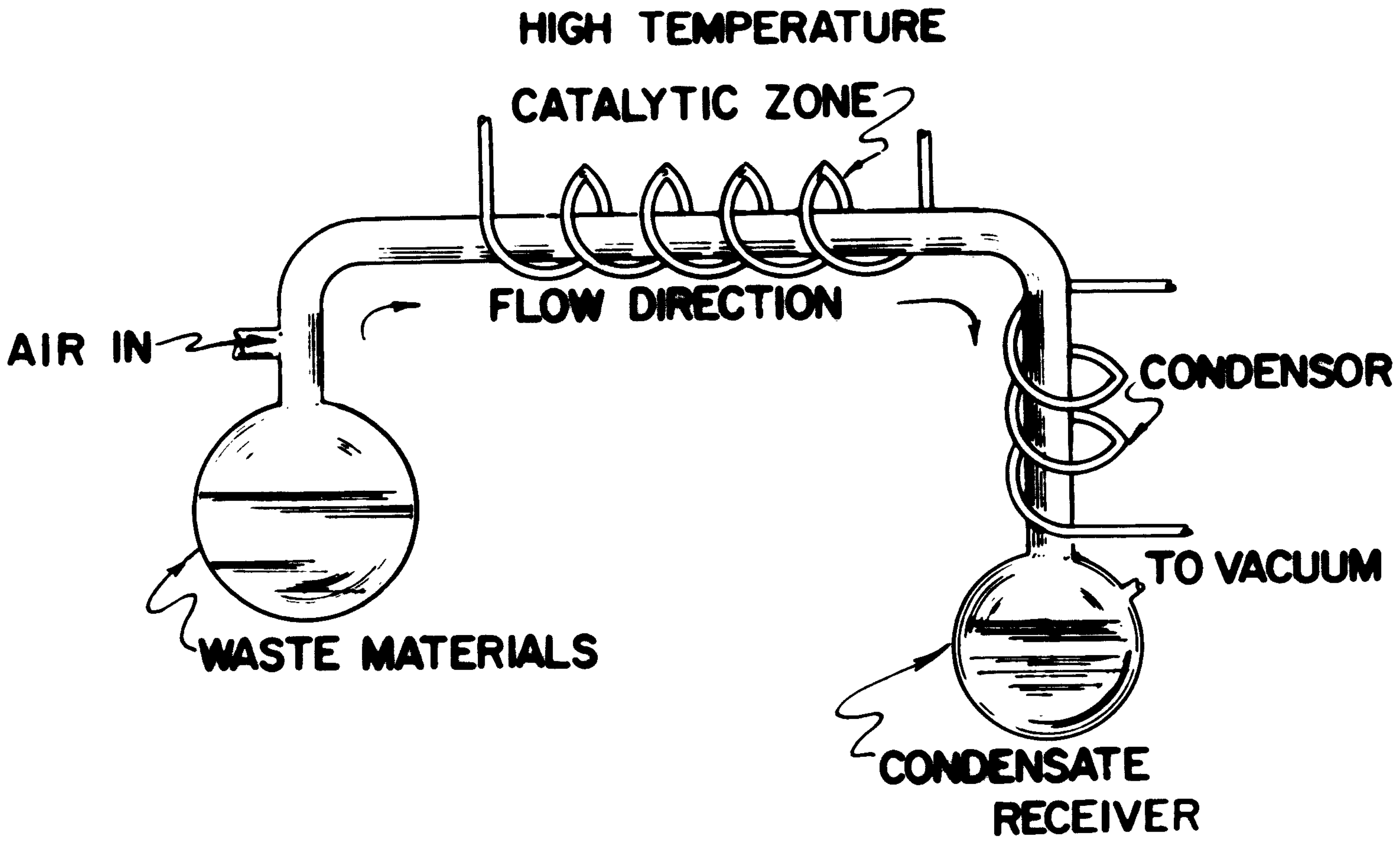

FIGURE 2

TABLE II

WATER RECOVERY
CHEMICAL ANALYSIS OF CONDENSATE TO POTABILITY

	Urine Only fully treated	Urine & Feces fully treated	Urine & Feces (10B) distilled only
Ammonia as N, ppm	0.10	35	1250
Total Hardness	2	0	1
Chloride, ppm	0.5	2	14
pH	6.8	8.8	10.10
Nitrate as NO_3, ppm	0.05	0.025	0.025
Nitrate as NO_2, ppm	0	0	138
Color units	0	0	7
Phenol, ppm	0.0	0.0	3.25
Odor (intensity)	None	None	Strong Pungent
Total Solids	14	54	168
Phenolphthalein Alk. as $CaCO_3$, ppm	0	20	4670
Methyl Orange Alk. as $CaCO_3$, ppm	2	86	5810
Specific Conduct. (micro-ohms)	3.4	180	1400

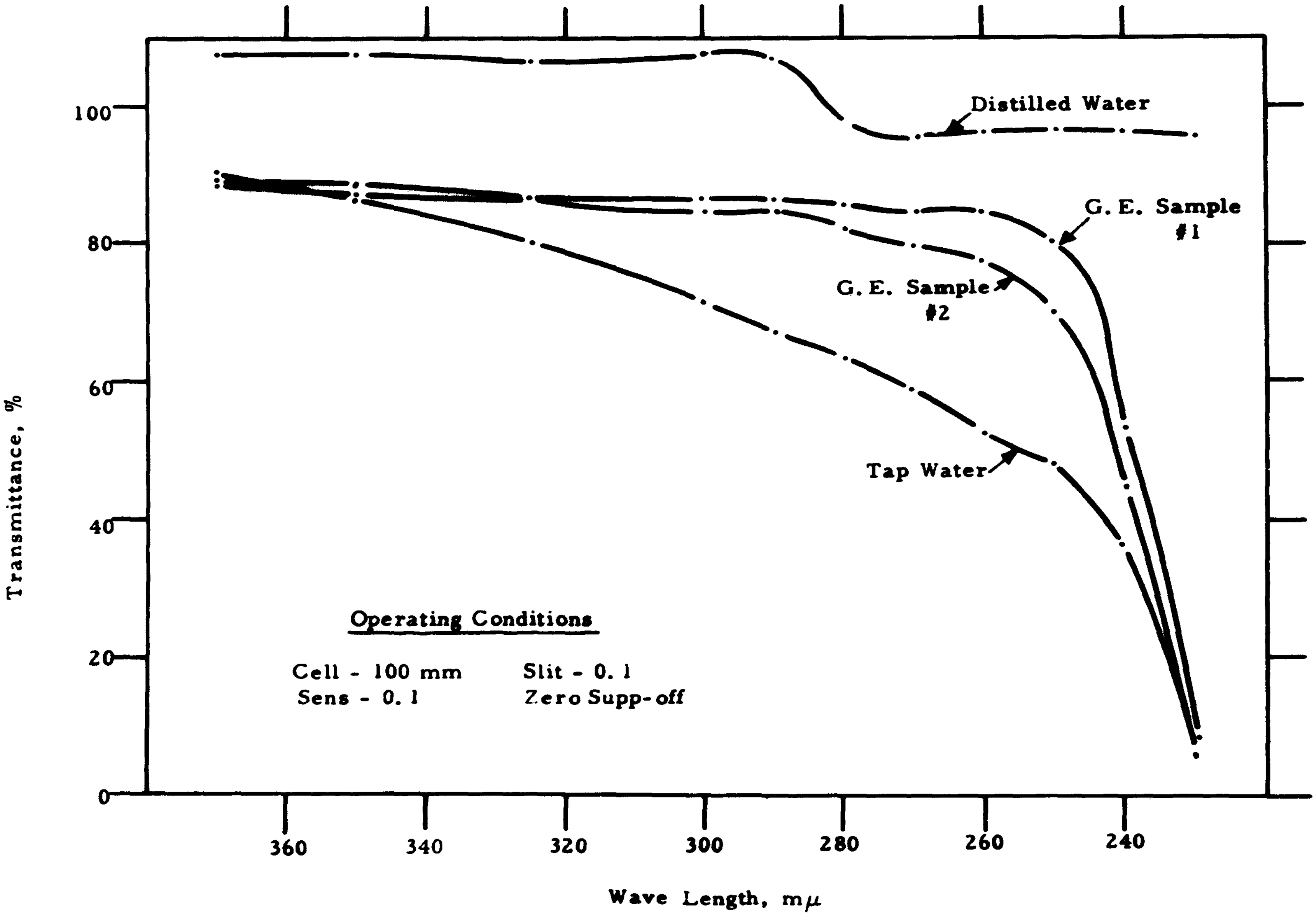

FIGURE 3 U.V. TRANSMITTANCE (DISTILLED WATER REFERENCE)

4. Food

The production of food in space for this particular partially closed system is considered uneconomical primarily because of the probable use of scientifically prepared dehydrated food containing all of the necessary constituents in their proper proportions. As will be shown later in this paper it has been estimated that such a scientifically prepared food will weigh of the order of one pound per day per man. Simple computations indicate that for a flight duration of one man year a total of only about 400 pounds (including container weight) will then be necessary. This weight is sufficiently low to warrant prestorage of food.

5. System Concept

By the methods described above, it can be seen that we now have a system in which the spent air is initially purified dehydrated and oxygen is injected to revitalize it. At the same time the carbon dioxide removed from the air is decomposed into carbon monoxide and oxygen. The oxygen, of course, is used to revitalize the air whereas the carbon monoxide is hydrogenated forming water and carbon. The water is electrolyzed thus obtaining the additional oxygen requirement and the hydrogen is led back to the hydrogenation reactor. In this fashion we have a regenerative recycling system in which the only by-product not immediately used is carbon. The overall imbalance in this reaction occurs in the fact that carbon is lost. It has been suggested that this material be activated and be used for odor control; however, it appears that the quantity of carbon that is formed per day will be considerably greater than the need for activated charcoal.

PARTIALLY CLOSED ECOLOGICAL SYSTEM

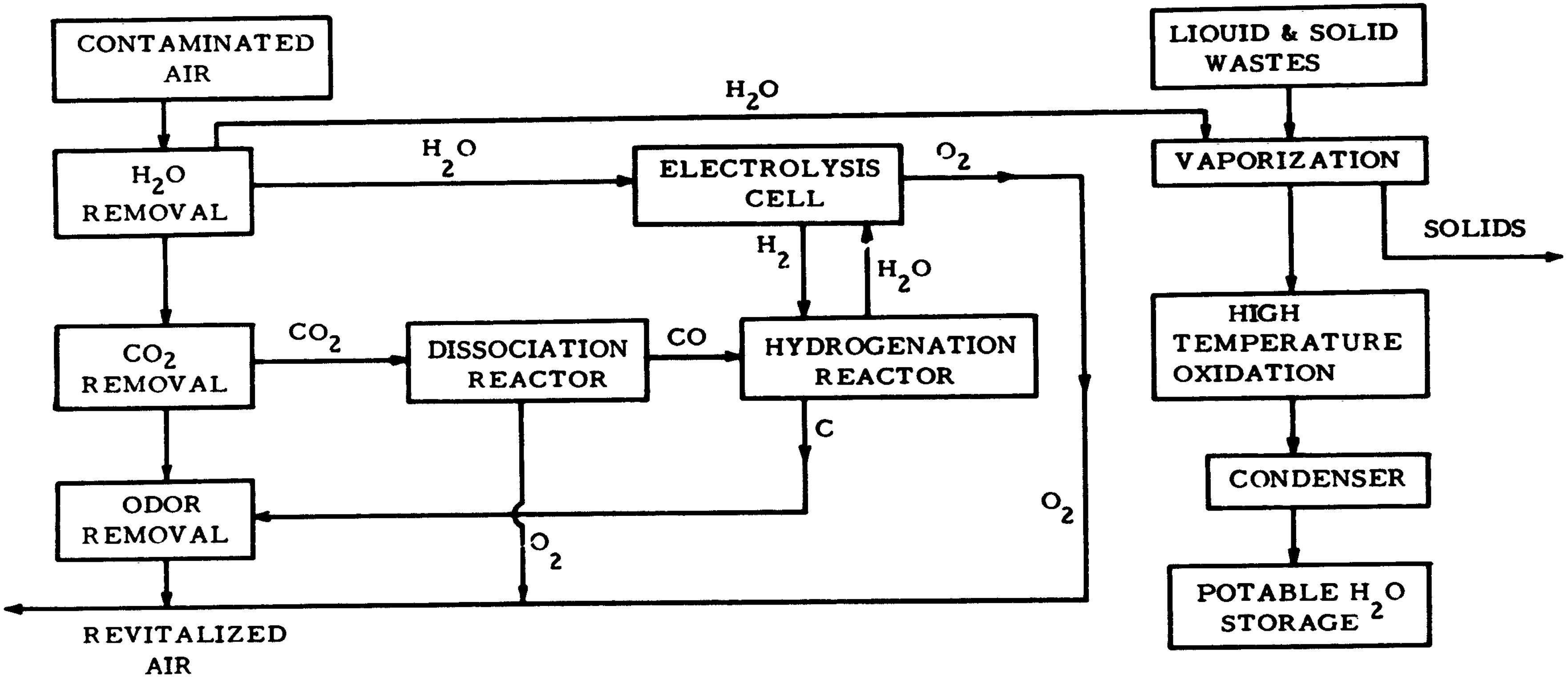

FIGURE 4

As a result, an imbalance will exist. It might be pointed out here that this imbalance is due to the fact that we are not completely reusing all of the products, and as a result we have a partially closed - not a completely closed system.

Figure 4 is a flow diagram of this partially closed ecological system. It illustrates the interdependence of the processes upon one another for the raw materials required in order that the regeneration/recycling techniques continue. For example, following the flow lines concerned with air purification, it can be seen that the water is adsorbed, released by heating whence it is passed into the electrolyzing zone, and reduced to oxygen and hydrogen. The hydrogen is then passed over to the hydrogenation zone where it is reacted with the carbon monoxide forming additional water and carbon. Of course, the water is then passed back into the electrolyzing cell. It can now be shown that by judicious selection sufficient quantities of raw materials (waste products) are available in a closed system which after processing, will support the donor.

As a basis for this comment, consider first man's metabolic process. Assuming a 2500 kilocalorie diet, containing 52% carbohydrate, 32% fat, and 16% protein is suitable, then the weight of this dehydrated food becomes 454 grams (1 lb.). By simple manipulation a hypothetical food molecule may be derived from this combination of C-H-O-N. This hypothetical food molecule has the form of $C_{23}H_{43}O_{11}N$.

The trace elements, i.e., S, Fe, I. P, etc., have been ignored in this analysis since their total weight is small in comparison with that of any of the major constituents. Now since the process of metabolism is basically one of oxidation (or combustion) we may write equation (9) from which we obtain the stoichiometric oxygen requirements and also the quantity of carbon dioxide and water produced.

$$\begin{array}{llccccc}
 & C_{23}H_{43}O_{11}N + 28\text{-}1/4\ O_2 & \longrightarrow & 23\ CO_2 + & 21\text{-}1/2\ H_2O + & 1/2\ N & (9) \\
\text{Wt (g)} & 454 + 806 & = & 903 + & 345 & + 12 & \\
\text{Wt (lb)} & 1.0 + 1.78 & = & 1.99 + & 0.76 & + 0.03 & \\
\text{Vol. (liters)} & 565 & \longrightarrow & 456 & & &
\end{array}$$

$$RQ = \frac{CO_2\ (\text{vol.})}{O_2\ (\text{vol.})} = \frac{456}{565} = 0.81$$

903 grams of CO_2 contain 656 g of O_2 and 345 g of H_2O contain 306 g of O_2. Therefore, if it is possible to extract all of the O_2 contained in these two compounds a total of 962 g is made available for respiration. This quantity is greater than the required amount derived from equation (9) because the O_2 contained in the food molecule is converted to CO_2 and H_2O and subsequently recovered.

The dissociation reaction shown in equation (4) yields the following material balance:

$$903\ \text{g}\ CO_2 = 575\ \text{g}\ CO + 328\ \text{g}\ O_2$$

and from equation (5)

$$575\ \text{g}\ CO + 41\ \text{g}\ H_2 = 246\ \text{g}\ C + 370\ \text{g}\ H_2O$$

electrolyzing the H_2O yields

$$370 \text{ g } H_2O = 41 \text{ g } H_2 + 329 \text{ g } O_2$$

In this manner, it is seen that the total O_2 recovered is 328 g + 329 g = 657 g. The hydrogenation reaction (equation 5) is self supporting since the 41 g of the H_2 are recovered by electrolysis.

The remainder of the required O_2 (803g-657g = 146 g) is obtained by electrolyzing a portion of the metabolic H_2O formed during metabolism as shown in equation (9).

$$165 \text{ g of } H_2O = 19\text{g } H_2 + 146\text{g } O_2$$

the remainder of the water (180g) is used for drinking purposes.

Now letting the average daily water turnover be 2600 ml (5.73 lbs.) then the water balance can be shown as follows:

Urine and fecal output	=	1335 ml
Perspiration	=	920 ml
Respiration	=	345 ml
Total Output	=	2600 ml
Intake	=	2255 ml

The difference (345 ml) results from the production of metabolic water.

Assuming that 90 percent recovery of potable water from urine and feces can be achieved (as has been demonstrated consistently in the laboratory) then the water supply problem is resolved as follows:

90 percent recovery - urine and feces	=	1201 ml
100 percent recovery - perspiration	=	920 ml
Remainder of metabolic water	=	180 ml
Total Water supply	=	2301 ml

It is thus shown that an excess of about 45 ml of H_2O is recovered assuming that the predicted yields can be achieved.

Calculations have been made based upon available experimental results and theoretical considerations to derive the overall energy requirements. These values are shown on Table III and total 5590 K cal/man day (22,360 Btu or 6.55 Kwh).

B. COMPLETELY CLOSED ECOLOGICAL SYSTEM

As noted earlier, considerable effort has been expended in attempting to define and construct a photosynthetic gas exchanger capable of maintaining man. To a great extent, partially successful experimental models have been evolved. Problems still exist, of course, however, these should be resolved in time assuming sufficient research and development activity is applied. Consequently, it would appear that we may, by speculation, devise a completely closed ecological system with only a slight advance in the state of the art which will perform the required tasks of maintaining man in space for indefinite periods of time.

TABLE III

PARTIALLY CLOSED ECOLOGICAL S STEM APPROXIMATE ENERGY REQUIREMENT

SUBSYSTEM	TOTAL ENERGY PER MAN-DAY K CAL
H_2O FROM LiCl	1350
CO_2 FROM MOLECULAR SIEVE	550
H_2O FROM URINE, FECES, AIR	1050
O_2 FROM CO_2 AND H_2O ELECTROLYSIS	2640
TOTAL	5590

Referring to equation (8) it is seen that this is the photosynthetic reaction and represents the plant kingdom contribution to the closed ecological system existing on earth. Man requires the oxygen which results from the plant's metabolic process and the plant requires the carbon dioxide produced by man as a biological waste product. Here then is the connection between an algal culture and man. In its very broad sense, we can show that the food produced by equation (9) may be either eaten directly by man or consumed by some intermediate biological specimen which, in turn, is eaten by man. As a result, the application of the photosynthetic mechanism presents an extremely interesting concept for the closed ecology.

In order that man and the algal culture be at equilibrium several aspects of the overall problems must be considered. One of the important and useful parameters for describing this equilibrium exists in the concept of the respiratory quotient. In equation (9) representing a simplified version of man's metabolic process, it was demonstrated that the respiratory quotient (the ratio of the volume of CO_2 evolved to the volume of oxygen taken up) was equal numerically to 0.81. This is an average value for man, although it varies roughly from 0.8 to 0.85. Now in describing the respiratory process for plants the animal RQ is replaced by the plant assimulatory quotient, (AQ) defined as a ratio of the volume of carbon dioxide taken up by the plant to the volume of oxygen evolved. Values ranging from less than 0.7 to 0.9 have been measured with algal cultures. In fact, it has been demonstrated that the AQ of the alga is a function of the form in which nitrogen is supplied to the unicellular organism.

With nitrogen in nitrate form, the AQ ranges from 0.67 to 0.75 compared with a value in excess of 0.8 when nitrogen is supplied in urea and almost 0.9 using ammonia as a nitrogenous source.

Obviously, it is important in matching man with algae that the RQ equal the AQ. If this equality cannot be maintained, then either the oxygen or the CO_2 content will build up which in time will prove detrimental.

Drawing freely from the literature and, in particular, from Dr. Jack Myers of the University of Texas, if the nitrogenous supply to the culture is in urea and carbon dioxide and water are available in sufficient quantities, then the equation for the algal cell production becomes:

$$1/2\ (N_2H_4\ CO) + 5.5\ CO_2 + 4.55\ H_2O \longrightarrow C_{6.0}\ H_{11.1}\ O_{2.7}\ N + 6.68\ O_2 \qquad (10)$$

In this equation, the right hand side represents a) the algal cell production and b) the evolution of oxygen. The quantity of oxygen evolved in equation (10) must equal the quantity of oxygen required for man's metabolism as shown in equation (9) (565 liters per day). By substituting this value of oxygen into equation (10) the quantities needed to support one man for 24 hours have been computed and are shown in Table IV.

TABLE IV

Theoretical Material Input to Evolve Man's O_2 Requirement

Urea ($N_2\ H_4\ CO$)	113.2g	(0.25 lbs.)
CO_2	462.42l	(2.01 lbs.)
H_2O	308.9g	(0.68 lbs.)
Algae ($C_{6.0}\ H_{11.1}\ O_{2.7}\ N$)	530.7g	(1.17 lbs.)

The assimilatory quotient AQ thus becomes $\frac{462.4}{565} = 0.82$

Table V repeats some of the values listed in Table IV but presents them from another point of view so that it is immediately apparent that the small difference in AQ - RQ (0.01) will result in an important imbalance in the O_2-CO_2 relationships with increasing time

TABLE V

Material Imbalance Due to RQ - AQ Inequality (grams)

Man Eq. (9)		Algae Eq. (10)
806	O_2	806
454	Organic Material	530.7
903	CO_2	913
345	H_2O	309
12	Nitrogenous Material	113.5

The consequences of this small imbalance have been reported in the literature based on a study conducted with an experimental algal chamber designed to support four 30 gram mice on a continuous basis. During the test it was found that the algal AQ was lower than the mice RQ resulting in an atmospheric O_2 content of about 27 1/2 percent after 48 hours. Obviously, some means must be included in the system to maintain the oxygen content at its proper level.

Another unbalanced component in this hypothetical relationship is in the supply and production of nitrogenous material. The average daily urinary output of man is approximately 1200-1300 ml. Only about 30 grams of this is urea. Hence, man can only supply about 1/4 of the required urea to the algal culture from his urine. Of course, this holds only with the algae described by the molecular formula $C_6H_{11.1}O_{2.7}N$. If the protein-fat-carbohydrate composition is changed then the urea requirement will change. Basically, the problem can be approached by attempting to produce an alga whose molecular formula will be approximately the same as the hypothetical food molecule shown in equation (9). At the same time, latitude is present in the ratio of protein, fats, and carbohydrates ingested by man so that an important area of research is presented here in the equating of the molecular food formula with the molecular composition of the alga. The implications are great for by resolving this point not only does the cycle close from the input side, but man can then feed on algae completely and thus form in theory a closed ecological system. As a suggestion it is pointed out that the fecal matter contains a quantity of nitrogen which may be modified to permit to utilization by the cell.

Figure 5 proposes a closed ecological system based on existing technology and some speculated advances in the photosynthetic gas exchange technology. The recovery of potable water is accomplished in the same manner as in the partially closed system described earlier. However, the solids which remain in the stillpot after the volatile material is vaporized are treated as necessary and then are introduced to the algal culture rather than be discarded. This is done because these solids are rich in inorganic, mineral salts and nitrogenous material which serve as the nutritional requirements for the algae. On the other side of the flow diagram, the contaminated air is introduced directly to the photosynthetic gas exchanger where the carbon dioxide is assimilated by the cells and additional cells and oxygen are produced. The excess cells are removed on a continuing basis from the gas exchanger in order that equilibrium conditions will exist. The excess material is then fed into a centrifuge or some other type of separator where the cells are extracted from the supernatent.

CLOSED ECOLOGICAL SYSTEM

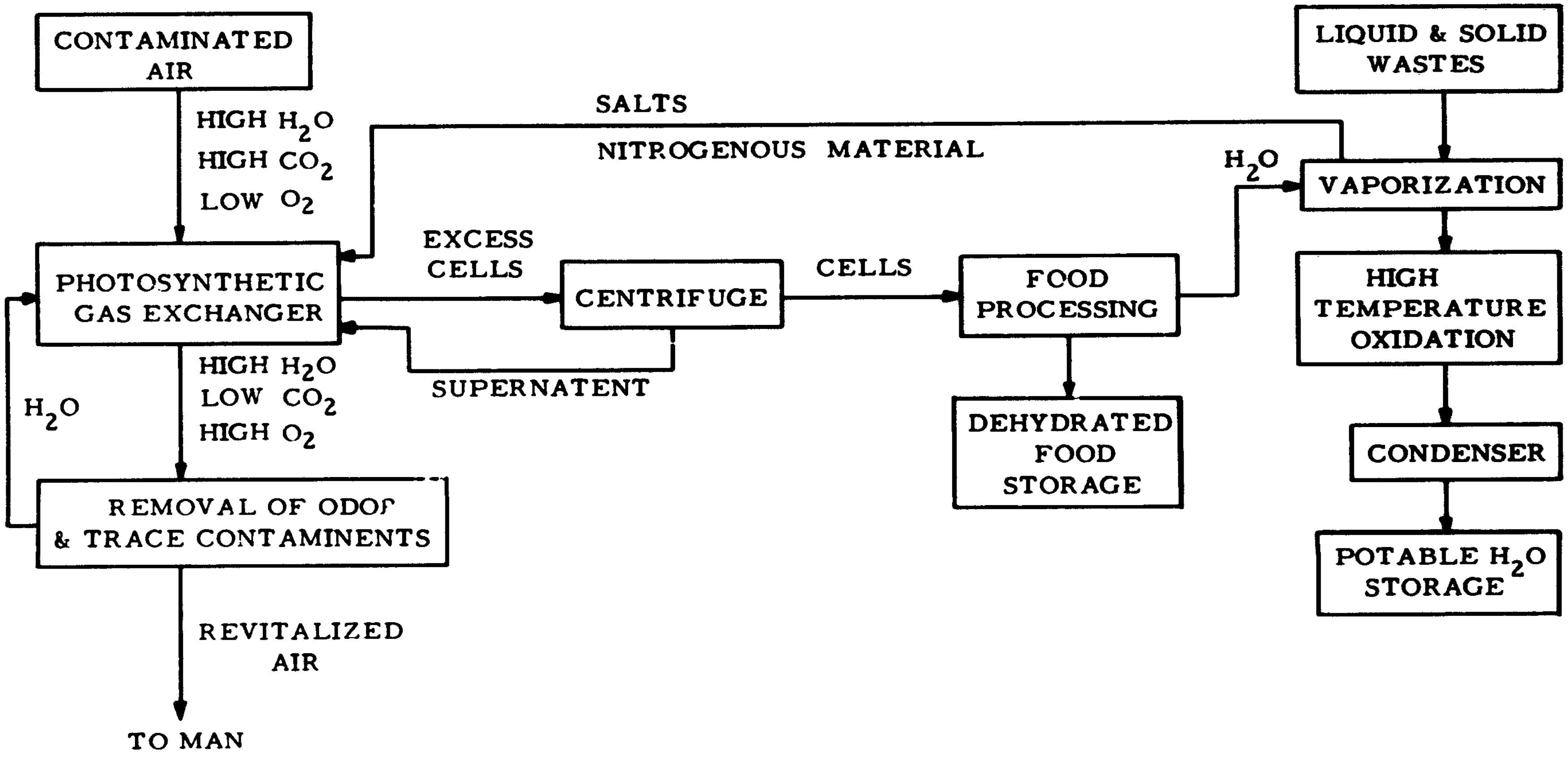

FIGURE 5

The supernatent is returned to the photosynthetic gas exchanger and the cells proceed to a food processing zone where they are dehydrated, decolored, and modified in some fashion to become palatable and nutritious to man. The gases, after leaving the photosynthetic gas exchanger contain a high percentage of water vapor, a low percentage of CO_2, and the proper quantities of oxygen. They are then sent through an air purifying system wherein the excess humidity is extracted as are the odor and trace contaminants. The purified air is then pumped back to man.

It must be remembered that this system has not been reduced to practice, although a number of the subsystems have been proved feasible by experimentation in the laboratories of the author.

Several problems of major importance still exist before this proposed system is reduced to practice. These include:

a) Energy considerations

It has been demonstrated by many investigators through relatively simple calculations that approximately 9900 kilocalories of energy are required per day to maintain an algal culture.

This is obtained as follows:

a) Burning an organic molecule in O_2 releases 112 Kcal corresponding to one gram atom of carbon, plus CO_2 and H_2O. Assuming this is a reversable process; then this is quantity of heat that must be supplied to the reactants CO_2 + H_2O to form the organic molecule.

b) Chemical composition of algae indicates that about 50 percent of the cell is carbon.

Thus:

$$E_1 = 0.50 \times \frac{112}{12} = 4.667 \text{ Kcal/g} \tag{11}$$

This is the theoretical minimum quantity of energy required to produce a gram of dry algae.

Taking the efficiency of photosynthesis to be 25 percent then the energy becomes

$$5.667/0.25 = 18.67 \text{ Kcal/g of dry algae.}$$

Table IV shows a requirement of 530.7 g of dry algae needed for a man balance, therefore the total energy per man-day becomes:

$$E_1 = 18.67 \times 530.7 = 9916 \text{ Kcal} \tag{12}$$

This is equivalent to 11.53 Kwh.

If solar energy is to be used as the source of light energy, remembering that only light in the visible region of the spectrum is useable by chlorophyll, we find that only 41 percent of the total energy available in the solar spectrum is useable. This works out to the requirement of a surface area of almost one square meter to supply a man equivalent algae culture based on a 24 hour exposure per day at the earth's distance from the sun. Obviously, as the vehicle moves away from the earth towards the sun or in the opposite direction the surface area requirements vary inversely with the square of the distance from the sun. For example, at the Mars distance the surface area requirement would be over two square meters whereas at Venus' distance the area requirements falls to less than one-half of a square meter.

If one proceeds to design the system using artificial light as supplied by say fluorescent lamps which are the most efficient form of light production in use today, we find that the energy requirements are greatly increased since the 20 percent conversion efficiency of the lamp raises the overall energy level to 49600 kilocalories per man day or 57.6 Kwh.

Another problem area of importance refers to the maintenance of equilibrium of the system and the waste management of the excess cells. The chart indicates a block for food processing of excess cells. Now it must be remembered that an algal culture is composed of living organisms. As such the algae, while assimulating the carbon dioxide and producing oxygen, are also producing additional algal cells. A predetermined quantity of oxygen is required from the photosynthetic gas exchanger. Based on calculations the quantity of algae needed to evolve this necessary quantity of oxygen can be precisely determined. Therefore, as additional algal cells are made they must be removed from the main culture. Hence, the waste management is very intimately associated with the equilibrium of the system. In order to have a closed system use must be made of the excess cells. Obviously, the first and most important use that could be made for these cells is to process them for the use as food. In so doing we would dehydrate the cell after lysing has been accomplished. The water removed by the dehydration of the cells should then be passed into the vaporization phase of the liquid and solid waste processing for the eventual recovery as potable water.

A third problem area relates to the balancing of the RQ with the AQ. Although some preliminary work has been done which indicates the dependence of the AQ upon the source of nitrogenous material for the cell considerably more study must be devoted to actively balance the system. It would appear that in addition to nutritional supplies for control, a physical or chemical system of gas adsorption and/or desorption may prove necessary as a backup design in order to maintain a given gas composition.

IV. CONCLUSIONS

Two systems have been described in this paper for the support of human life in sealed space vehicles. The first system, a partially closed ecology, has a number of important advantages:

1) It is composed of subsystems which have been found to be feasible by experimental methods.

2) As a result of this feasibility and the regeneration and recovery of man's metabolic waste materials, large weight savings can be effected over a finite flight time.

3) Since the subsystems comprise known reactions and to a great extent known yields from these reactions, the so-called lead time in assembling such a complete life support system should be relatively short. In fact, it is estimated that within perhaps one to two years a system of the type described could be assembled and tested. This latter point is of great importance when it is remembered that multi-manned cis-lunar flight experiments are currently being planned for the immediate future.

The second ecological system presented is a much more ambitious one and requires a considerable amount of research and development. Not only is research necessary with respect to the metabolism of algae, but appropriate equipment must be designed for such things as equilibrium maintenance, waste management and food processing. In addition, the very considerable problem concerning the utilization of light by the cell and the source of this light is of prime importance. It is ~~also essential~~ that the search continue to find better strains of micro-organisms or to optimize those strains that are now being used. Although a wealth of information is available, a considerable amount of cooperative effort must be expended between the biologist and the physical scientist. ~~However,~~ the system described appears to offer the greatest promise for the indefinite (planetary station) or extremely long flight time. As shown earlier many of the subsystems have been investigated with vigor and with partial success. Consequently, assuming at least the same amount of attention in the future there is no reason why this type of system cannot become fact within the next three to five years.

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