

CURRENT CONCEPTS AND FUTURE DIRECTIONS OF CELSS

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ABSTRACT

Studies of bioregenerative life support systems for use in space indicate that they are scientifically feasible. Preliminary data suggest that they would provide cost- and weight-saving benefits for low Earth orbit, long duration space platforms. Concepts of such systems include the use of higher plants and/or micro-algae as sources of food, potable water and oxygen, and as sinks for carbon dioxide and metabolic wastes. Recycling of materials within the system will require processing of food organism and crew wastes using microbiological and/or physical chemical techniques. The dynamics of material flow within the system will require monitoring, control, stabilization and maintenance imposed by computers. Future phases of study will continue investigations of higher plant and algal physiology, environmental responses, and control; flight experiments for testing responses of organisms to weightlessness and increased radiation levels; and development of ground-based facilities for the study of recycling within a bioregenerative life support system.

INTRODUCTION

Support of a crew in space, whether in an orbiter or on the surface of a planetary body requires that oxygen, potable water and food be supplied, and that waste material be removed. The means for doing these tasks must include explicit recognition of astronaut health, safety and system stability. Figure 1 relates various approaches to crew life support. Resupply methods, such as those used by NASA and the Soviet space program at this time, become uneconomical as the number of crew members and the duration of flight increase. Regenerative methods, in contrast, can drastically reduce resupply requirements. Partial regeneration of O₂ and removal of CO₂ can be accomplished by physical-chemical methods; however, complete regeneration can be achieved with a combination of biological and physical techniques.

Manned stations, in orbit or on the Moon, are likely to use life support systems that minimize the consumption of supplies in order to reduce operating costs. The first steps taken in this direction will probably be confined to physico-chemical methods of on-board water purification and air regeneration. Such systems are discussed elsewhere in these proceedings /3/. As cost pressures continue, and operations such as Space Station become permanent, there will be incentives to move in the direction of bioregenerative life support.

Figure 2 illustrates schematically the kind of material recycling that will be involved with bioregeneration for life support. In some ways a bioregenerative system resembles an ecological system; however, the system required for life support in a location isolated from the Earth cannot rely on the same kinds or reservoirs and buffering mechanisms. This problem will be discussed more extensively herein. Based upon conservative estimates of biological productivity, equipment weight and power requirements, preliminary studies, indicate that a bioregenerative life support system for a low Earth orbit vehicle, such as Space Station, will begin to be cost effective after its second month of operation, compared to the costs of resupply /1/. (Figure 3). A more extensive discussion of the methods used to determine this kind of data, and of comparisons to non-bioregenerative systems are discussed elsewhere in these proceedings /1/.

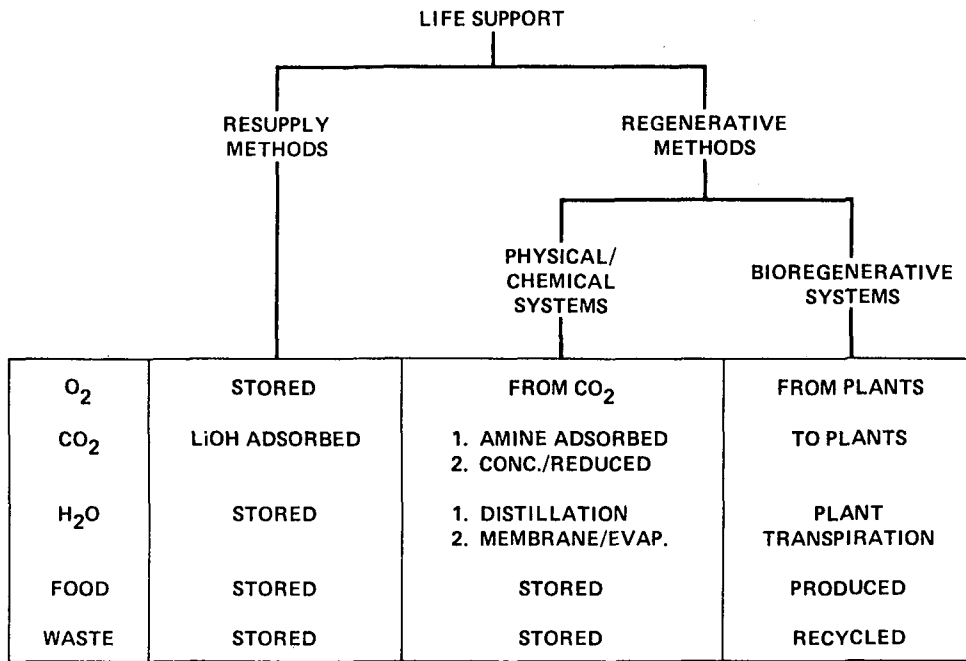


Fig. 1. Comparison of crew life support options.

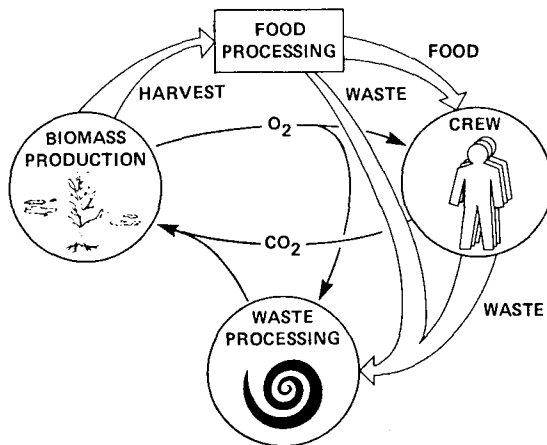


Fig. 2. Material cycling within a bioregenerative life support system.

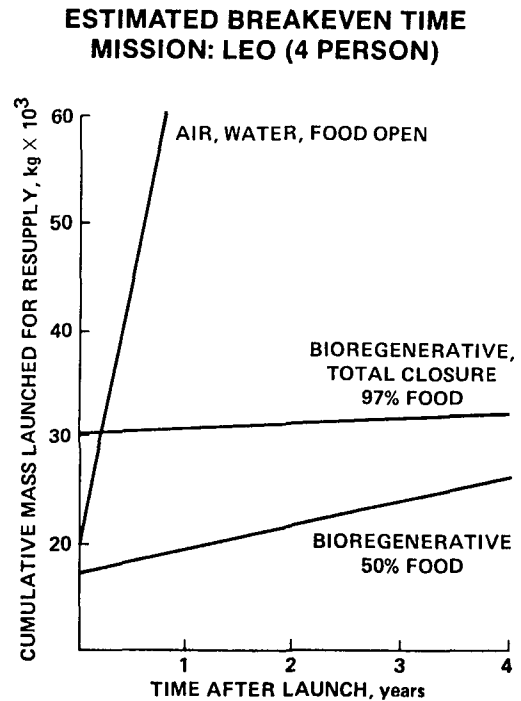


Fig. 3. Cumulative mass launched vs. mission time for life support options.

The decision to use bioregenerative techniques to support people in space for long periods will depend on many factors. Some of the most important factors are the feasibility of recycling essential life support materials in space; the operating efficiency and the practicality of such a system; the mass launched to orbit to set up and operate a bioregenerative system; the amount of work, and the cost, of developing a reliable bioregenerative system; the psychological response of astronauts to the operation and products of a bioregenerative system (water, oxygen, food); and the relative cost, and work involved, in developing and incorporating new concepts of life support.

This paper is intended to describe the components of a bioregenerative life support system, and to discuss the requirements for system control. As part of the discussion of system control, bioregenerative life support in space is contrasted to terrestrial ecological concepts to focus on the specific problem of reservoirs and buffers. Finally, some of the future directions of the NASA CELSS program are outlined.

Functional Description of a Bioregenerative System

The operation of a bioregenerative life support system will depend on the integration with the crew's living space of at least two processing components, and a control system. The two processing components are: 1.) one or more systems for using energy to convert simple materials (e.g. CO₂, H₂O, NH₃, SO₄, etc.) into oxygen and complex organic materials for human consumption; and 2.) one or more systems for converting oxygen and the complex materials in organic wastes into the simple materials for plant, and possibly, human consumption. The control, or regulatory component, is a computer capable of sensing the condition and location of materials to continue the stable operation of the system as a whole. The fourth general element of a bioregenerative system is the crew, whose demands of health and safety completely control the system.

Food and Oxygen Production, and Carbon Dioxide Absorption

Three alternative approaches are under investigation for primary production of raw materials in food systems: a.) Higher plants, possibly supplemented by animals and/or chemical processing to convert normally inedible biomass into assimilable forms; b.) Photosynthetic algae; c.) Non-photosynthetic microbial food production processes, using substrates that are either synthesized chemically or naturally available in the waste stream. The food production subsystem in an optimized bioregenerative life support system may incorporate elements of all three approaches, since it must satisfy a complex mixture of constraints imposed by spacecraft system considerations as well as by human dietary requirements.

Growth of Higher Plants

In developing concepts of a plant growth subsystem the main features will be minimization of size, weight and power consumption; extensive use of automatic monitoring and environmental controls; automated manipulations to eliminate human labor; and selective breeding of plants to provide optimum performance under artificial conditions. Hardware development for a large space station plant growth subsystem is within the resources of existing technology.

For a large subsystem, some of the most important biological questions concern the transport of nutrients to the plant roots. Plants absorb different nutrients at different rates, and their roots exude various products and slough off dead material. Because of this, it will be necessary to arrange flows of water both to transport nutrients to the roots and to carry off depleted solutions and waste materials. Conventional hydroponic culture techniques will be undesirably heavy, however, because they use large amounts of water. Novel methods, such as aeroponics and misting, must be developed to minimize the amount of water used while allowing normal root development and avoiding damage to the fragile parts of the root system. A detailed understanding of how roots interact with their aqueous environment will be needed to devise alternatives to conventional hydroponics.

The chemical form of nutrients supplied to the plants will be important for bioregenerative life support system definition because requirements in this area largely determine what products the waste management subsystem must supply. Nutritional "programs" that obtain optimum performance from the plants must be developed with due regard for their impacts on the rest of the system.

Finally, adequate environmental controls must be developed and long-term ground based tests conducted to verify that plants can develop normally through their whole life cycles and be propagated for several successive generations in a system like the one contemplated for space use. Before a plant growth subsystem becomes a permanent part of spacecraft life support, it will be necessary to reproduce successive generations in a space based experimental plant growth chamber.

Algal Cultures

The possibility of using algae in a bioregenerative life support system will be evaluated on the basis of their efficiency in producing all of the life support elements of interest in the system: oxygen, CO₂ absorption, potable water and food. Algae also exhibit an additional capability, that of nitrogen fixation, that will be considered in evaluating the efficiency of the organisms in a life support system. However, because the potential of algae as a food source is of considerable significance in the bioregenerative life support system, it will be most extensively investigated.

The most difficult problem in using algae as food is the conversion of algal biomass into products that a spacecraft crew could actually eat over a long period of time. Algae have been considered only as a diet supplement in the work that has been published so far, and work in the area of food processing has been largely confined to developing powdered products that are inoffensive when added to other foods. If algae are to be considered seriously as a primary food source, however, it will be necessary to determine that they can be converted into a wide enough range of palatable forms to make an acceptable complete diet. Development of processing techniques will be intimately associated with the selection of species to be used and characterization of their compositions for manipulation in culture.

Algae are normally grown in relatively dilute water solutions, through which CO₂ gas is bubbled to provide carbon. Some other way of dissolving CO₂ efficiently in water must be devised for space operations, since gas bubbles will not rise through the liquid in weightlessness. Probably the problem will be solved by using surface tension and capillary forces to maintain the water in a configuration with a high surface-to-volume ratio (either suspended droplets or films adhering to extended surfaces) in contact with a flowing CO₂ gas stream.

Microbial and Chemosynthetic Food Sources

Some possibilities have been identified for food production by means other than growing algae or higher plants, but technology is much less well developed in these more speculative areas. The two main alternatives are: a.) To produce edible biomass using substrates chemically synthesized from spacecraft wastes, or b.) To use biological processes to convert waste materials into chemical forms that can be processed into food.

The most developed idea in the first category is to raise edible methylotrophic yeasts on methanol synthesized from CO₂ and water. The CELSS program is currently sponsoring work on direct synthesis of methanol from CO₂ and water by photocatalysis, which may prove to have advantages if catalysts with sufficient efficiency and stability can be developed. Alternatively, methanol can be produced by a two-step reaction between CO₂ and hydrogen (which would be obtained by electrolyzing water) at moderate temperatures and pressures. Although the energy efficiency of this process would be low, that disadvantage might not be decisive if the process heat could be supplied by an inexpensive solar energy collection scheme.

This method of food production and similar schemes would produce amounts of waste materials roughly comparable to their yields of usable human food. Rather than degrade these materials to CO₂ and water before re-introducing their elements into the food chain, it may be advantageous to reform them into usable human nutrients and let the crew's metabolism oxidize them while supplying energy.

Waste Management

Although the complete waste management function for a bioregenerative life support system is apt to be complex, much of it can probably be implemented by straightforward engineering. At present the major uncertainties in waste management concern processes to convert organic wastes to acceptable inputs for the food production subsystem without converting mineral nutrients into forms that are difficult to separate and recover.

The chief chemical inputs to any workable food production subsystem must be CO₂ and water, since these form most of the metabolic waste produced by the crew. Consequently, the main function of any waste processing subsystem must be the oxidation of organic wastes to these products. The subsystem must effect a complete, quantitative conversion of wastes from the food processing subsystem as well as from the crew, and ideally it should require no energy but what is released by the oxidation process itself. Both aerobic biological digestion and direct wet oxidation processes are being considered for this function.

Biological Digestion

Most of the animal wastes and plant biomass produced on Earth are recycled by microbial digestion: sometimes under human management in treatment plants, but for the most part without management in bodies of water and on the ground. In general the retention times for natural decay processes are long, and managed systems are used to obtain short retention times and correspondingly high rates of material throughput. Since economic factors have kept terrestrial sewage treatment plants from being designed for maximum achievable throughput rates, their performance is not an accurate guide to what could be done with a system optimized for space applications.

Aerobic digestion is potentially attractive for bioregenerative waste management because it is an efficient room-temperature oxidation process that does not degrade the soluble mineral nutrients required by plants, and it can be kept from producing toxic products. It does produce a residual sludge that would have to be disposed of by other means, but its efficiency could make it a desirable part of a composite system if the amount of residual material could be made acceptably small. Basically, the process consists of reducing incoming waste materials to a slurry, seeding it appropriately with aerobic bacteria, and maintaining proper aeration and mixing while the bacteria metabolize carbon in the mixture. When the digestion process reaches its endpoint, solids are removed by ultra-filtration, leaving sterile water containing dissolved minerals.

Inputs to the waste processing subsystem would comprise wastes from the food production process (typically cellulose from photosynthetic plants) kitchen wastes, household water, urine, and feces. In contrast to the practice in terrestrial waste systems, the several streams of incoming material might be kept separate until pre-treatment had reduced them to forms for maximally efficient digestion. For example, urine would be desalted before being added to the digestion reactor, and cellulose would probably be passed through an anaerobic fermentation step. In addition, the temperature, concentration of solids, and other significant parameters of the mixture in the digester would all be controlled to maximize the speed and completeness of digestion.

The techniques that work best for aerobic digestion will probably differ from techniques that optimize algal growth in space, because the physical requirements are likely to differ significantly between the waste mixture and the algal cultures. In addition, because oxygen (the gas to be injected into the mixture) is less soluble in water than carbon dioxide (the gas to be removed) it may be necessary to manipulate the temperature, pH, or other characteristics of the mixture to overcome this difficulty. If such manipulations are employed, rather than subdivide the digestion mixture into droplets, probably it would be more effective to use capillary forces to draw it into a configuration with a large surface area.

The power required to run an aerobic reactor would be determined by the rate at which it oxidizes waste material, which in turn would be conditioned by how much of the biomass from the food production subsystem was used for food and how much went into the waste stream. Roughly speaking, one would expect the digester's oxygen demand to be no more than that of the crew members it served, and perhaps as little as half as much. A 50 to 100 liter reactor would probably also require between 100 and 200 watts of electrical power to run pumps and environmental controls.

Wet Oxidation

A particularly interesting method of waste processing is based upon a process generally termed wet oxidation. The process elevates the temperature of a slurry or solution of waste material to several hundred degrees, and exposes it to oxygen at high pressures. Under such conditions, organic material is oxidized rapidly to CO_2 .

A variation on this process that appears quite practical is a system that increases the reaction temperature to 400 to 700 degrees C, and the oxygen pressure to about 3000 psi. At these temperatures and pressures the dielectric constant of water falls from 80 to close to 0. As a consequence, insoluble materials, such as O_2 are readily dissolved, and normally soluble materials, such as NaCl, are precipitated from solution. Oxidation of organic materials occurs very rapidly (within seconds), and CO_2 is produced /2/. This work has been done by Dr. M. Modell at a private company (Modar, Inc.) under contract to NASA.

Management and Control of System Operation

Early high altitude balloon flights were possible because of the introduction of some of the same methods of human life support that are still used today in space flights: an absorber of CO₂, and a source of O₂. Space flights planned by NASA during the 1990's will involve an increase in the number of crew members, and the crew will be in space for extended periods of time. With the advent of space stations, interest in newer methods of life support have been generated. These methods are based upon the recycling of materials, most specifically of O₂ and water.

The concepts of bioregeneration appear well-founded. Except for certain problems that will be discussed below, the theoretical and practical basis of recycling is well understood. The application of the method, however, will depend upon answers to a series of practical questions. These concern the long term stability of such a system, and its operating efficiency. Such questions will be addressed during the next several years by NASA's Bioregenerative Life Support/CELSS program in a series of scientific investigations and practical demonstrations.

Terrestrial Reservoirs and Buffers

Support of people in space or on another planet, such as in a lunar base, requires the same materials, and attention to many of the same problems as support of people on Earth. However, while the analogy between life support on Earth and in space can be very useful, it can also result in conceptual problems unless detailed information on differences in scale are available. Significant differences exist in the sizes and the dynamics of the non-biological parts of terrestrial systems compared to small life support systems. The contrast between the characteristics of the terrestrial and man-made life support systems are instructive because it points to the kinds of problems that will have to be addressed.

The atmosphere and waters of the Earth are reservoirs for the materials that are needed for life; they are also buffers for specific materials, in the sense that they are so large that the movement of materials into and out of them make only very small changes in the concentration of any specific material. Moreover, physical and chemical activity in these enormous reservoirs can change the chemical composition of materials that are considered toxins and pollutants, and thus rapidly reduces their concentration.

Accompanying the dynamic activity of the gas and liquid reservoirs of the Earth, the metabolism of organisms living on the land and in the waters acts to change the state of essential elements from solids, to aqueous solution and to gas, and back. The net result of biological, geochemical and weather dynamics is a relative constancy of the environmental concentrations of many materials.

Bioregenerative Life Support: Some Theoretical Considerations

The concept of bioregenerative life support in space is, naturally, based upon life support on Earth. It has been suggested by Odum that life support in space must rely on terrestrial ecological principles /4/. However, the admittedly simplistic analysis that follows suggests, instead, that this is not the case. Realization of an artificial bioregenerative life support system will require the development of analogues to terrestrial weather, and to atmospheric chemistry and volumes. The most significant of these innovations will be attempts to mimic the terrestrial material reservoirs and buffering systems. The following is intended to give some concept of the enormous differences between the size of the Earth's reservoirs and those that will be available to space-based bioregenerative systems, and to provide some indication of the extent to which artificial buffering systems will be required.

For every m² of land surface on earth there are about 1250 m³ (STP) of atmosphere that can act as a reservoir of gases and volatiles needed by the organisms occupying 1 m². The atmosphere is driven by energy that is first absorbed from the sun and subsequently radiated into space. Turbulence generated by the landscape mixes and distributes atmospheric gases relatively rapidly. Atmosphere dynamics also drive the water cycles, and provides for the mixing and distribution of water soluble materials.

In contrast, a proposed module for bioregenerative life support on the NASA Space Station might have an interior surface area of approximately 98 m² and a volume of about 95 m³. Scaled proportionally, the air volume in the module would be capable, on the Earth's surface, of acting as a reservoir for about 0.075 m², or a plot 27.5 cm on a side. Each square meter in a Space Station will thus have an atmosphere reservoir equivalent to an area 7.65 cm² (2.76 cm on a side) on the surface of the Earth. In addition, the chemical reactions and the movement of the terrestrial atmosphere will not be available in space unless specifically included.

Another comparison that can be considered is that of the density of biological activity on the Earth and in space. Accurate data for such comparisons are difficult to find, but considering only arable agricultural areas, the land areas used to grow food for the support of human populations varies from about 1300 m² (in China) /5/ to 25,000 m² in the USA or the USSR. It is likely that intensive, controlled agriculture in space will require less than 25 m² per person. The proposed bioregenerative life support module described above could therefore support at least 4 crew members. However, it is obvious that, in space, the intensity of plant cultivation (per m² of surface area), and therefore, of metabolic activity, will be at least 50 times greater than that generally practised on Earth.

If the environment within a Space Station module is to be made as constant and stable as that on Earth, some devices will have to be employed to accommodate the chemistry, movement and the volume difference between the terrestrial and the Space Station atmospheres, as well as the difference in agricultural intensity. These rudimentary calculations suggest that the available atmospheric volumes and projected agricultural densities will, in space, result in demands on the atmospheric reservoir that are at least 20,000 times more intensive than in normal terrestrial agriculture (Table 1). One objective of the Bioregenerative Life Support program's scientific research will be to determine how much buffering is in fact required in a closed system for the crew, the plants, algae and ancillary machinery that are required for life support in space.

Table 1 Comparison of Agricultural Intensity
Required for 4 People

	On Earth:	Bioregenerative System in Space:
Agricultural area for 4 people	5,200 m ²	98 m ²
Atmosphere reservoir for 4 people	6.5 x 10 ⁶ m ³	100 m ³ (agric. area) 200 m ³ (crew area) 300 m ³ (total vol.)
Approximate gas exchange rate for CO ₂ (or O ₂) by agriculture only /5/	0.4 m ³ /day	0.4 m ³ /day
Volume CO ₂ in atmosphere	1950 m ³	0.09 m ³
"Buffer ratio" (e.g. volume of atmosphere/volume CO ₂ absorbed)	1.6 x 10 ⁷ (21,000)	750 (1)

Using the atmospheric CO₂ exchange as an example, it is obvious that one mechanism of coping with the demands of the crew and of the agricultural growth unit is to ensure that over some small time interval the crew's production of CO₂ matches the photosynthetic demand, which is impractical. Further, a significant portion of the plant biomass is inedible. Considering the schedule for processing inedible material reveals another aspect of the overall control problem. As the time-dependent mismatch between demands of atmosphere stability, waste control, etc. becomes greater, more attention must be paid to projecting probable future demands, and preparing to meet them. Part of the approach to this problem will be to establish storage reservoirs for specific materials that have minimal weight and volume, sensing devices that can be used to collect data, and intelligent (or cybernetic) controls to create an active decision making buffering system.

Practical Considerations: Efficiency

The per capita consumption of grain in the United States and the Soviet Union for all purposes, including the growth of animals for human consumption, is approximately 750 kilos/year /5/ and the yield of grain is approximately 250 to 300 kilos/hectare /5/, or about 2.5 hectares used for grain growth per person per year. Obviously, development of a bioregenerative life support system for use in space would not be realistic if 25,000 square meters were required for each person.

The parameters that affect agricultural efficiency on Earth and in space are such factors as: the number of crops per year, the effect of uniform temperature and humidity, the amount of exposure to light, the density of growing plants, the effect of constant nutrient supplies on growth, the proportion of edible to non-edible material in a plant, and the nutritional value of the edible material.

Recent studies of the efficiency of potato growth by Tibbitts et al (7) suggest that an area of 77 m² exposed to light (approximate volume: 25 m³) is sufficient to supply food for one person in space /7/. In contrast, studies by Salisbury et al (8) demonstrate that sufficient wheat for one individual can be grown on a light-exposed surface of about 25 m² (approximate volume: 13 m³) /8/. These experiments were done under conditions that were well-controlled; however, a complete examination of all the parameters that can affect efficiency has not been done, nor is sufficient data yet available to suggest the effects of micro-gravity. It is likely that variation of atmospheric gas composition, nutrient composition and temperature will increase the rate of growth, thus decreasing the area required to sustain a single individual. Since the areas needed for growth in space can be translated into weight launched into orbit, changes in efficiency can be directly related to other methods of life support for comparison.

Another measure of efficiency is light use. Initial assumptions are that the light available for plant growth will be collected by solar power arrays, converted into electrical current that will be used to power lamps inside Space Station modules. An increase in the efficiency of light use by photosynthesis will translate directly to a decrease in weight for solar arrays, as well as for batteries that are required for lighting when the Space Station is in the Earth's shadow. At the present time, wheat is able to convert 14% of photosynthetically active radiation (PAR) into biomass, compared to a theoretical maximum of 18% /8/. Algal growth that utilizes approximately 16% of incident PAR has been reported by Radmer et al (9), suggesting that if some of the problems associated with using algae as food can be overcome, algal growth reactors might become part of a bioregenerative life support system.

CONCLUSIONS

Until now, the NASA program on bioregenerative life support has focussed on determining whether the fundamental concepts are appropriate and workable. This approach has resulted in many studies of the behaviour of higher plants and algae, and investigations into the responses of the organisms to environmental factors. It has also resulted in several studies about the efficiency and the potential need for such systems.

The results of these studies strongly suggest that bioregenerative systems can play a role in NASA's space efforts in the future, and that the concept should be examined further. For these reasons, during the next year the program will enter two new phases of activity. The two major new efforts will focus on integrating ground-based investigations, and on preparing flight experiments.

The goals of the new ground-based investigations will be to determine whether the results that have been obtained on a small scale in the laboratory can be reproduced in a larger, integrated system, and to investigate problems associated with recycling materials in a relatively closed system. For these purposes a laboratory scale facility will be constructed consisting of one or more plant growth units capable of maintaining any selected atmospheric conditions, an algae growth unit, a waste processing device, and a surrogate "crew", either based upon small animals or simulated by computer. The system will be maintained by computer, and an opportunity will be afforded to eventually utilize computer models to determine long-term strategy of operation.

Flight experiments will be designed to answer biological and technological questions about growing plants, algae and bacteria in a weightless environment. The higher plant growth devices used for these experiments will have controlled environments, and will be used to address questions concerning the growth patterns of plants, maturation rates, fruiting and plant nutrition. The devices for algae and bacterial growth will be designed to investigate problems of gas separation in 0 g, harvesting problems, and in the case of algae, methods for exposure to light.

It is anticipated that these new directions, in addition to fundamental ground-based research will allow preparation for longer term flights and more extensive experimentation on the Space Station. When the necessary results are available it will be possible to begin to plan for a complete experimental bioregenerative life support system for operation on Space Station, paving the way to eventual inclusion of such systems as central life support systems in space and, perhaps, on the lunar surface.

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