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# Controlled Ecological Life Support System

## *Life Support Systems in Space Travel*

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*XXV COSPAR meeting*
*Graz, Austria*
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# Controlled Ecological Life Support System

## *Life Support Systems in Space Travel*

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# PREFACE

Space travel by humans depends upon the reliable operation of life support systems. The life support systems in general use today are reliable and predictable, and are appropriate for small crews on relatively short missions. In essence, food, water, and oxygen are launched with the crew; during the flight, carbon dioxide is removed from the atmosphere by reaction with lithium hydroxide, and waste materials are stored for the duration of the flight.

To reduce the need for resupplying life support materials for longer missions, various methods of partially regenerating consumables have been developed: oxygen can be scavenged from carbon dioxide, and waste water can be purified for subsequent reuse. The technology used for these processes is well developed, and it is anticipated that they will be available for use on the space station during the next decade.

As space habitats get farther from Earth, resupply of life support materials will become increasingly difficult and expensive. Complete regeneration of life support materials then becomes of interest; the most reliable and efficient means of replacing used materials is bioregeneration. This process centers on the use of a primary biological process, photosynthesis, as part of a physical/chemical system which is capable of continously supplying the food, oxygen, and potable water required by a crew, and of removing all of the waste materials, including carbon dioxide, from the crew's environment.

The seven papers presented in session F.6 of the XXVth COSPAR Meeting, held in Graz, Austria, (1) review the problems of life support and discuss the fundamental concepts of bioregeneration (MacElroy and Averner); (2) review and discuss the technology associated with physical/chemical regenerative life support (Schubert et al.); (3) project the break-even points for various life support techniques for several conceived space missions (Olson et al.); (4) discuss the problems of controlling a bioregenerative life support system (Babcock and Auslander); (5) present data on the operation of an experimental algal/mouse life support system (Averner and Moore); (6) review a German industry's concepts of bioregenerative life support (Skoog); and (7) review Japanese concepts of bioregenerative life support and associated biological experiments to be conducted in the Space Station (Ohya et al.).

Together, these papers illustrate the wide ranges of thought, experiment, and design that constitute the thrust toward the development of future methods of life support for humans in space. Individually, the papers illustrate the dedication of scientists, engineers, industries, and nations to exploring the future, and to making human concepts into practical realities. However, without the forum for presentation, the XXVth COSPAR Meeting, the diverse mix of multinational sciences and engineering demonstrated in this session could not have occurred.

Robert D. MacElroy
Harold P. Klein

October 15, 1984

# INTRODUCTION

The papers collected here were presented as a topical session at the XXVth COSPAR Meeting held in Graz, Austria, during July 1984. They review various aspects of Bioregenerative Life Support (CELSS) research in Japan, The Federal Republic of Germany, and the United States. These papers, and all others presented at the COSPAR meeting, will be published for the Congress by Pergamon Press.

# CURRENT CONCEPTS AND FUTURE DIRECTIONS OF CELSS

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## ABSTRACT

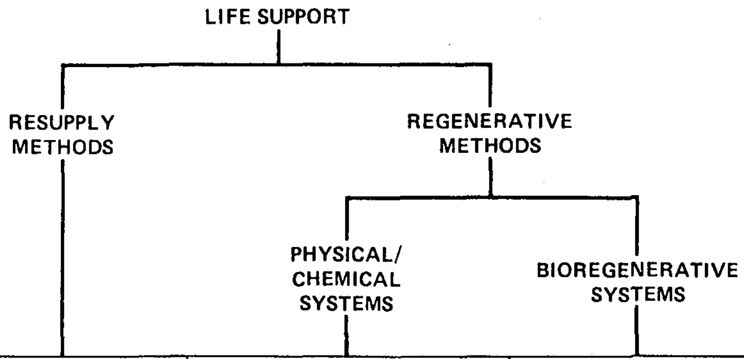
Studies of bioregenerative life support systems for use in space indicate that they are scientifically feasible. Preliminary data suggest that they would provide cost- and weight-saving benefits for low Earth orbit, long duration space platforms. Concepts of such systems include the use of higher plants 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 $O_2$ and removal of $CO_2$ 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/.



| | | | |
|---|---|---|---|
| $O_2$ | STORED | FROM $CO_2$ | FROM PLANTS |
| $CO_2$ | LiOH ADSORBED | 1. AMINE ADSORBED<br>2. CONC./REDUCED | TO PLANTS |
| $H_2O$ | STORED | 1. DISTILLATION<br>2. MEMBRANE/EVAP. | PLANT TRANSPIRATION |
| FOOD | STORED | STORED | PRODUCED |
| WASTE | STORED | STORED | RECYCLED |

Fig. 1. Comparison of crew life support options.

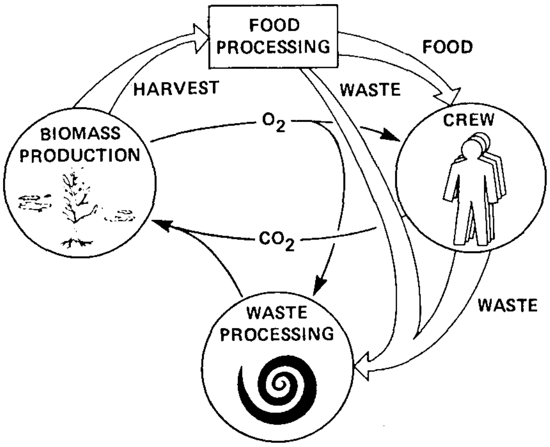


Fig. 2. Material cycling within a bioregenerative life support system.

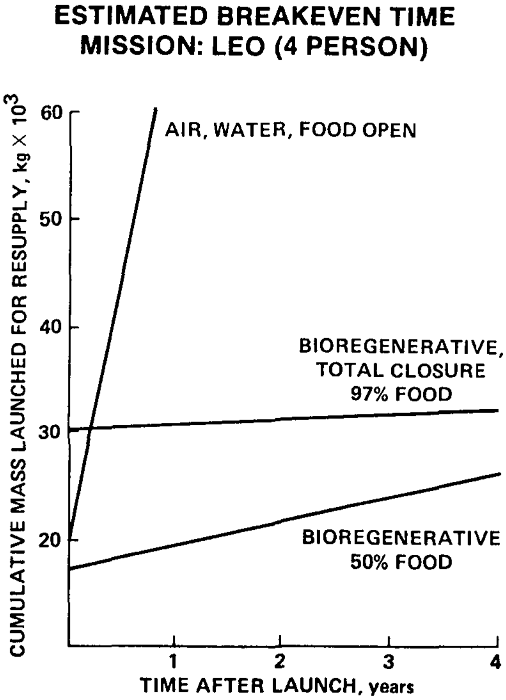


Fig. 3. Cumulative mass launched vs. mission time for life support options.

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. $CO_2$, $H_2O$, $NH_3$, $SO_4$, 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 Absorbtion

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, $CO_2$ absorbtion, 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 $CO_2$ gas is bubbled to provide carbon. Some other way of dissolving $CO_2$ 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 $CO_2$ 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 $CO_2$ and water. The CELSS program is currently sponsoring work on direct synthesis of methanol from $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 disolved, 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 $CO_2$, and a source of $O_2$. 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 $O_2$ 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 $m^2$ of land surface on earth there are about 1250 $m^3$ (STP) of atmosphere that can act as a reservoir of gases and volatiles needed by the organisms occupying 1 $m^2$. 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 $m^2$ and a volume of about 95 $m^3$. 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 $m^2$, 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 $cm^2$ (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 $m^2$ (in China) /5/ to 25,000 $m^2$ in the USA or the USSR. It is likely that intensive, controlled agriculture in space will require less than 25 $m^2$ 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 $m^2$ 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 accomodate 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)<br>200 $m^3$ (crew area)<br>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 $10^7$<br>(21,000) | 750<br>(1) |

Using the atmospheric $CO_2$ 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 $CO_2$ 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 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 $m^2$ exposed to light (approximate volume: 25 $m^3$) 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 $m^2$ (approximate volume: 13 $m^3$) /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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# SURVEY OF CELSS CONCEPTS AND PRELIMINARY RESEARCH IN JAPAN

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## ABSTRACT

Many agricultural and other experiments relating to the development of a Controlled Ecological Life Support System (CELSS) were proposed by scientists throughout Japan in the fall of 1982. To develop concrete experimental concepts from these proposals, the engineering feasibility of each proposal was investigated by a CELSS experiment concept study group under the support of the National Aerospace Laboratory. The conclusions of the group were described in two documents, /1/, /2/. Originally, the study group did not clearly define necessary missions leading to the goal of an operational CELSS for spaceflight. Therefore, the CELSS experiment concept study group met again to clarify the goals of CELSS and to determine three phases to achieve the goals. The resulting phases, or missions, and preliminary proposals and studies needed to develop a CELSS are described herein.

## INTRODUCTION

Since 1982 a study group in Japan examined proposals for the development of a CELSS, and the problems regarding the stability of the CELSS experiment model /2/. The general conclusions from the discussions were as follows:

1) The final targets of three necessary phases, or missions, should be more clearly defined to provide guidelines for technology development.

2) A water recycle system for urine and waste water purification should be developed to save water transportation costs.

3) A gas recycle system, containing gas separation capabilities, gas reservoirs, and pressure regulators, should be introduced to maintain air composition and pressure.

4) Waste management systems should reduce methane gas and organic sludge produced from a microbial waste management system. Therefore, incineration and wet oxidation methods are preferable to other methods as the primary waste processor for CELSS systems.

Based on these considerations and on an assessment of state of the art, three phases, or missions, are suggested, /1/, /2/.

## THREE MISSIONS

The most essential parts of CELSS are the systems for food production and for gas conversion from carbon dioxide to oxygen by plants and algae through photosynthesis. However, data on the morphogenesis and physiology of higher plants and algae in the space environment are not complete at the present time. Three missions are suggested to establish an operational CELSS for spaceflight.

The first mission should be conducted during 1991-1995. The purpose of this phase is to evaluate plant and algae cultivation methods and to summarize available data about the stability of photosynthesis in space. The problems of propagation in a microgravity environment is also to be studied during this phase.

The second mission, a CELSS-dedicated mission, should be conducted during 1995-1998. The purpose of this phase is to check the feasibility of a micro closed ecology using animal and aquatic subjects instead of human beings. In this mission, non-biological waste management and recycling systems should also be tested and evaluated in the space environment.

The third mission should demonstrate the feasibility of a complete CELSS system. This phase should be conducted in a CELSS-dedicated module after 1999 and is intended to develop the future technology needed for construction of a lunar base or an advanced space station. In this mission, the main food supply and gas conversion from $CO_2$ to $O_2$ for one man will be based on the photosynthesis of plants and algae. Necessary animal protein could be produced by small animal and fish breeding colonies. A microbial waste management experiment, an immobilized-enzyme bio-reactor experiment, and plant cell (or tissue) cultivation experiments for future food production should also be conducted in this dedicated module. Plant species which grow well and are stable should be selected for the third mission from the results of the first and second phase missions.

## ARCHITECTURE OF EACH MISSION

### The First Mission

Two kinds of experimental equipment: (1) A phytotron (for plant cultivation), and (2) an algae cultivator (for algae cultivation), are essential to conduct the first phase, or mission. (Fig. 1). In addition, an artificial light supply system is needed to maintain control over light intensity and duration, and thereby control photosynthetic productivity. Other equipment such as a data management system, an enclosed work bench (a zero-gravity fume hood), a refrigerator, and a solar light supply system are required for this mission. This equipment is also required for other life science missions.

### Second Mission

In this phase a closed ecological system experiment should be composed of gas and water recycling systems, in addition to the algae cultivator, and the phytotron for cultivation of higher plants.

1) In the zero-gravity field small animals, plants and algae will be used as the bio-species in the micro ecology system (Fig. 2-A). A sufficient food supply for animals may not be possible by plant cultivation. However, this experiment should require complete gas recycling between the respiration of small animals and the photosynthetic gas conversion of algae and plants. Feces and urine will be processed by the waste management and water recycling systems. Food will be supplied from outside the experimental system.

2) In an artificial gravity field produced by a rotating drum, higher plant cultivation equipment (a phytotron) should be installed for investigating the behavior of plants. (Fig. 2-B).

### The Third Mission

To demonstrate the one-man life support capability of CELSS, a large area is required for food production by a plant cultivator. Therefore, a large-scale facility in a CELSS-dedicated module must be used for this mission.

For this demonstration (Fig. 3), a waste management system will be added with gas and water recycling systems in the environment control section of the module. The biological species section of the module will contain a large-scale plantation facility, algae cultivation equipment, and small-animal and fish vivariums. Solar light can supply the light source for photosynthesis.

The experimental and support equipment and systems for each of the three missions are listed in Table 1.

TABLE 1 Devices Required for Each CELSS Mission

| | |
|---|---|
| Mission 1 | Phytotron<br>Algae Cultivator<br>Data Management System (including TV/VTR Equipment)<br>Artificial Light Supply System |
| Mission 2 | Phytotron<br>Algae Cultivator<br>Fish Breeding Equipment<br>Small Animal Vivarium<br>Rotating Drum<br>Data Management System (including TV/VTR Equipment)<br>Solar Light Supply System (possibly)<br>Waste Management System<br>Water Recycle System<br>Gas Recycle System<br>Enclosed Work Bench<br>Refrigerator |
| Mission 3 | Large Scale Rotating Plantation Facility<br>Callus Cultivator<br>Algae Cultivator<br>Fish Breeding Equipment<br>Small Animal Vivarium<br>Human Subject<br>Rotating Drum<br>Data Management System (including TV/VTR Equipment)<br>Solar Light Supply System (possibly)<br>Waste Management System<br>Water Recycle System<br>Gas Recycle System<br>Microbial Waste Management Equipment<br>Immobilized Enzyme Bioreactor<br>Galley<br>Shower<br>Toilet |

## PRELIMINARY DESIGN WORK AND SYSTEM INTEGRATION FOR EACH MISSION

The requirements for experimental devices and systems were deduced by the CELSS concept study group considering the developmental steps of CELSS technology and the need to limit initial development costs. Based on these requirements, systems were designed by four manufacturers: Hitachi Ltd., Mitsubishi Electric Ltd., Kawasaki Heavy Industry, and Mitsubishi Heavy Industry. These companies were asked to determine the measuring instruments required on the mission, and to estimate the weight, size, shape and electric power requirements for each experimental device or system.

The experimental equipment should be installed and integrated in the experimental module as easily as possible. Therefore the location of each device must be determined with the following considerations in mind:

1) Experimental procedures

2) Functions of each device

3) Weight of each device

4) Power consumption

5) Size of each device.

An example of equipment integration in a typical Spacelab or space station module is shown in Fig. 4.

## PROPOSALS AND PRELIMINARY STUDIES MADE BY INDIVIDUAL RESEARCH GROUPS

The following is a summary of CELSS-related studies in Japan.

1) An example of a biological recycling system is shown in Fig. 5. This system, proposed by Prof. Yatazawa of Nagoya University, consists of various living organisms and a number of biological subsystems (S/S). Attention should be paid to the inclusion of the following:

a) Biological nitrogen fixation by Azolla-Anabaena symbiosis (S/S 2)

b) Sodium extraction by edible halophytes, plants native to salt marshes or alkaline soils (S/S 5)

c) Cellulolytic food production by mushroom fungi (S/S 4).

2) Dr. I. Endo of the Chemical Engineering Laboratory, Institute for Physical and Chemical Research, has proposed the use of algae (Spirulina sp.) for the production of oxygen and foods. Dr. Endo and his collaborators have carefully considered zero gravity and other environmental conditions in the space station. His system includes many experimental and measuring devices requiring very few operators for control. Computer hardware and software has been developed for monitoring cultivation of Spirulina sp. A computer model has calculated the size of a fermentor, the volume of the gas reservoir, the size of the tank for the medium, the size of the waste water tank, methods for cultivation, light supply characteristics, fermentor agitation, separation methods for algae, methods of oxygen removal, and the characteristics of automatic monitoring and control of the system. One of the most difficult problems is contamination by bacteria in a space environment. These studies are continuing with the collaboration of the Institute of Physical and Chemical Research and the National Aerospace Laboratory.

3) To study the suitability of various crop species and their nutrient balance, scientists affiliated with Japan's Ministry of Agriculture and the Departments of Forestry and Fisheries have investigated a wide range of crop species for nutrition and ease of planting in space. As an example, the relative advantages of growing the sweet potato in space follows.

The sweet potato provides a lower moisture content and greater food energy than the white potato. Two kg of sweet potato supplies 2400 Kcal; various nutrients such as 24 g protein, 4 g fat, 600 mg calcium, 10 mg iron, 0.2 mg carotine, 2 mg Vitamin B1, 1 mg Vitamin B2, 600 mg Vitamin C, and about 1400 g of water. Although protein, fat and carotine vary with species variety and cultivation methods, it may be possible, through selective breeding in space, to increase the nutritive value of the crop.

The sweet potato also has the advantage of having edible leaves and vines, as well as the tuber. If a variety of sweet potato with good cultivation characteristics under the weightlessness of low gravity can be selected, it may well become the "First Crop in Space."

4) As a possible life support system in space, a biochemical oxygen and carbon recycling apparatus has been proposed by Prof. T. Oshima of Tokyo Institute of Technlogy. This apparatus is intended to replace living plants or algae. The first unit in the bioreactor is for photoreaction and oxygen generation. It is composed of a chloroplast suspension (a film of immobilized chloroplast particles), used to produce molecular oxygen, ATP and NADPH under sunlight. The second unit is composed of immobilized enzymes, or possibly whole cells which fix $CO_2$ into organic compounds using the supply of ATP and NADPH from the first unit. The advantages of the bioreactor system over living organisms are:

a) Bioreactors are easier to control and more stable than living organisms

b) Weightlessness may not seriously affect the reactors.

In cooperation with Mitsubishi Electric Company (Drs. S. Isoda and M. Maeda), a model experiment is being designed for space station. Fig. 6 shows a rough sketch of the bioreactor system.

Production of oxygen and reduced compound(s), especially molecular hydrogen, from chloroplast particles has been studied by many researchers, Therefore Dr. Oshima and his colleagues have focused their attention on the second reactor in the system. Based on stabilized enzyme systems from thermophilic algae (Synechococcus lividus), isolated from a hot spring and grown at 55°C, is immobilized in an agarose matrix and then treated at cold temperatures to damage the cell envelopes. The immobilized cells are incubated in the presence of ATP, NADPH and carbonate ion. Theoretically, glucose will be produced from 18 ATP and 12 NADPH according to the following formula:

$$6CO_2 + 18NADPH + 12H_2O \rightarrow C_6H_{12}O_6 + 18P_i + 12NADPH + 6H^+$$

Hydrogen bacteria, especially a thermophilic strain, is also considered as an enzyme source for the second unit. A preliminary design for this bioreactor is shown in Fig. 7.

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2. Preliminary Concepts of Space Station Missions. MS-SS-02. Report -- CELSS Experiment Concept Study Group, National Aerospace Lab., Tokyo, Japan. 1981.

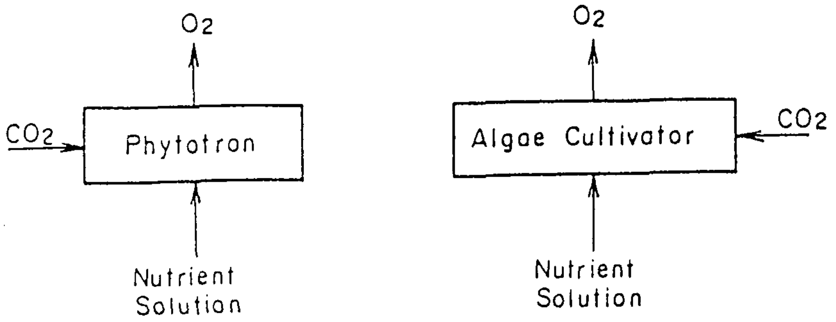


Fig.1. First phase experimental concept

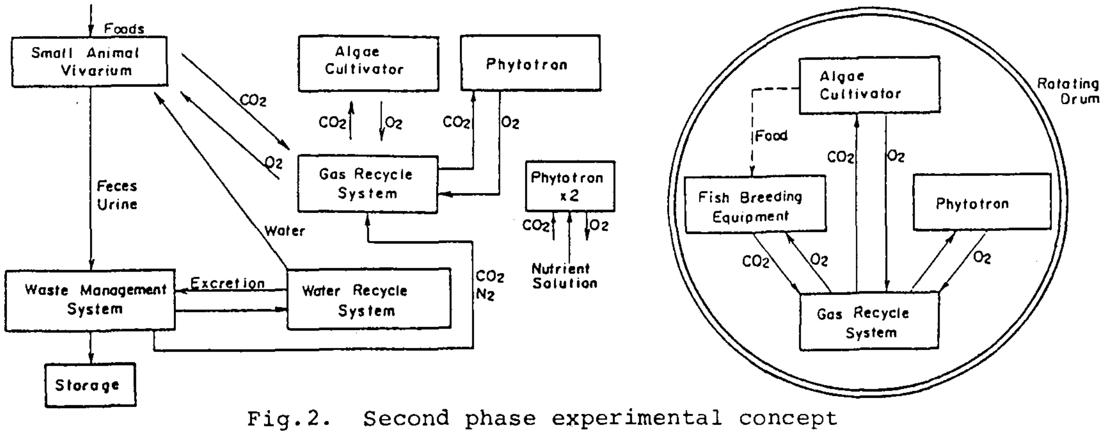


Fig.2. Second phase experimental concept

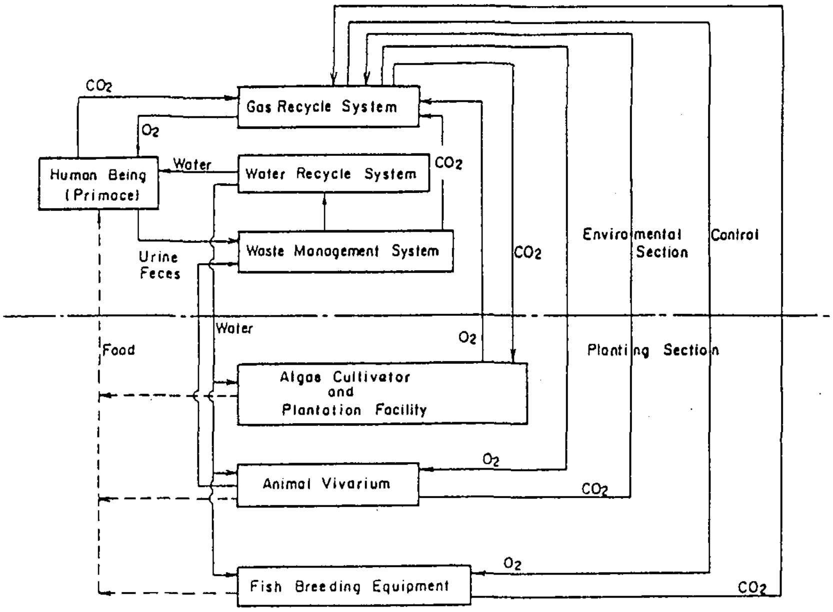


Fig.3. Third phase experimental concept

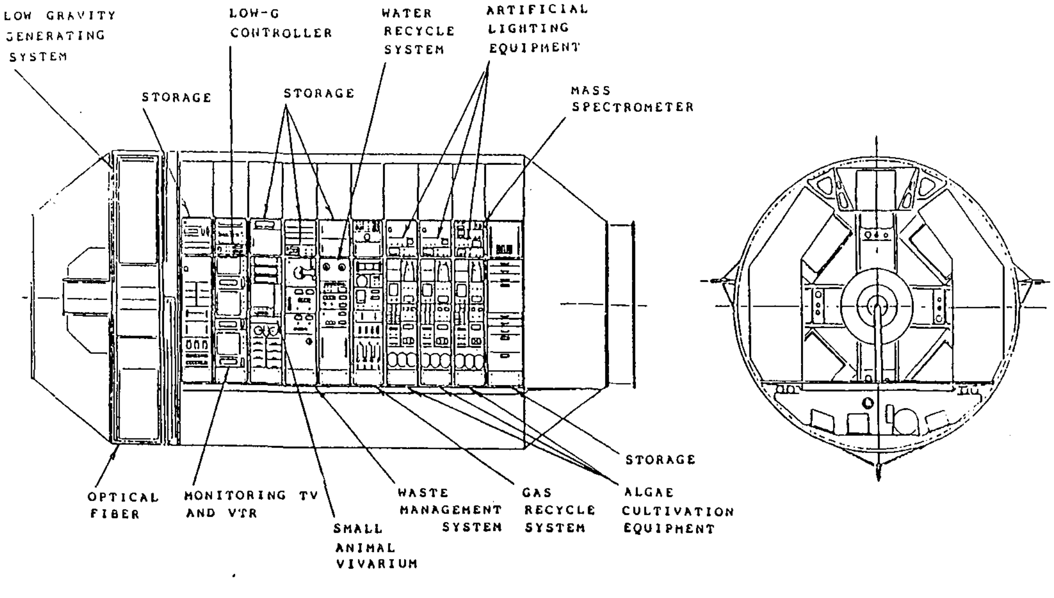


Fig.4. The second time phase mission experiment integration

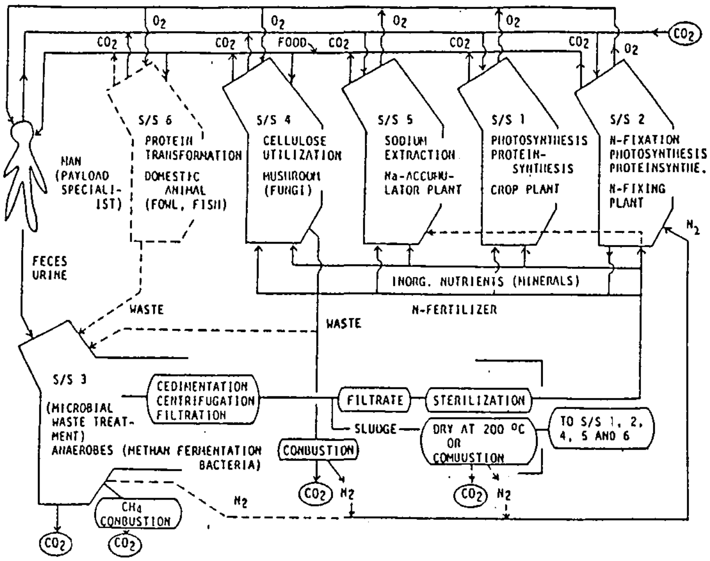
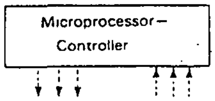


Fig.5. Proposed scheme of controlled ecological life support system



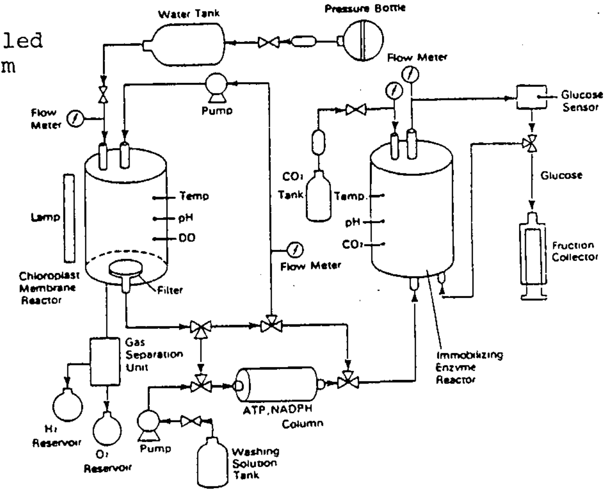


Fig.6. Schematic diagram of a bioreactor system using immobilized enzymes

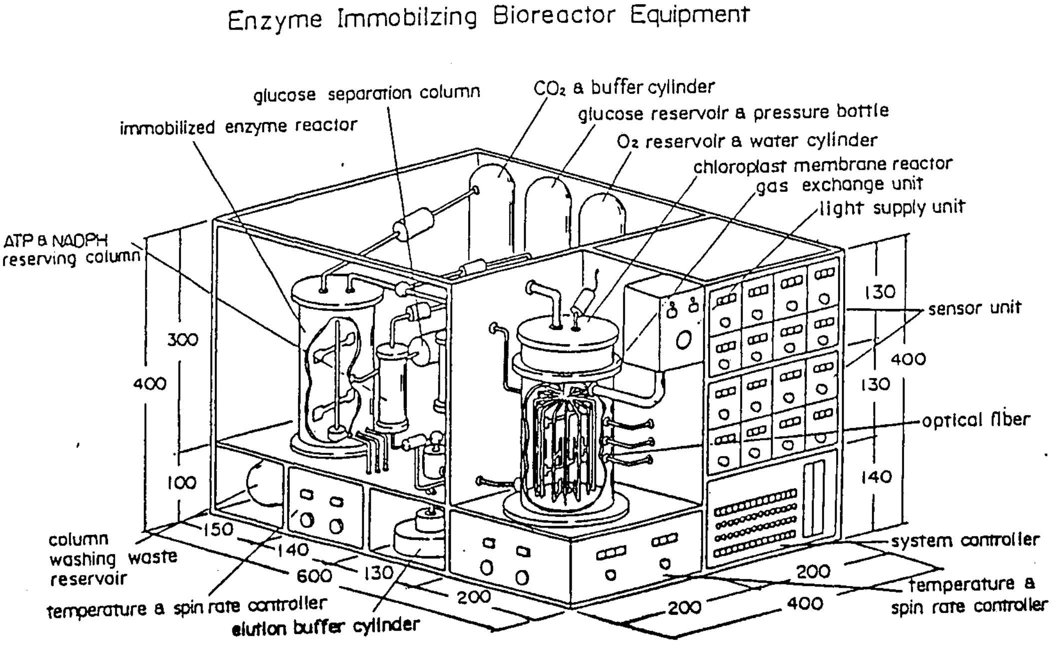


Fig. 7. A proposed design for the bioreactor experiment using immobilized enzymes.

# BLSS: A CONTRIBUTION TO FUTURE LIFE SUPPORT

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## ABSTRACT

For extended duration missions in space the supply of basic life-supporting ingredients represents a formidable logistics problem. Storage volume and launch weight of water, oxygen and food in a conventional non-regenerable life support system are directly proportional to the crew size and the length of the mission. In view of spacecraft payload limitations this will require that the carbon, or food, recycling loop, the third and final part in the life support system, be closed to further reduce logistics cost. This will be practical only if advanced life support systems can be developed in which metabolic waste products are regenerated and food is produced.

Biological Life Support Systems (BLSS) satisfy the space station environmental control functions and close the food cycle. A Biological Life Support System has to be a balanced ecological system, biotechnical in nature and consisting of some combination of human beings, animals, plants and microorganisms integrated with mechanical and physico-chemical hardware.

Numerous scientific space experiments have been delineated in recent years, the results of which are applicable to the support of BLSS concepts. Furthermore ecological life support systems have become subject to intensified studies and experiments both in the U.S. and the U.S.S.R. The Japanese have also conducted detailed preliminary studies.

Dornier System has in recent years undertaken an effort to define requirements and concepts and to analyse the feasibility of BLSS for space applications. Analyses of the BLSS energy-mass relation have been performed, and the possibilities to influence it to achieve advantages for the BLSS (compared with physico-chemical systems) have been determined. The major problem areas which need immediate attention have been defined, and a programme for the development of BLSS has been proposed.

## INTRODUCTION

A new era of space exploration, utilization, and research is developing as man extends his time in extraterrestrial activity. It is expected that orbital activities, such as research and satellite servicing, will become routine. Potential uses for manned space stations include facilities for space astronomy, materials processing, biological research, and earth resources research. In these and other future space station activities, man with his unique mobility, work dexterity and adaptive decision-making capabilities will play an essential role. However, for extended duration missions in space the practical supply of basic life-supporting ingredients represents a formidable logistics problem. The weight at launch and the storage volume in weightlessness of water, oxygen and food in a conventional non-regenerable life support system are directly proportional to the crew size and the length of the space mission. In view of spacecraft payload limitations, the inescapable conclusion is that extended-duration manned space missions will be practical only if advanced life support systems can be developed in which metabolic waste products are regenerated and food is produced.

Only a Biological Life Support System (BLSS)*, which not only satisfies the space station environmental control function requirements, but also closes the food cycle, can meet all the expected requirements. A BLSS must be a balanced ecological system, biotechnical in nature and consisting of some combination of human beings, animals, plants and microorganisms integrated with mechanical and physico-chemical hardware /2/.

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*Biological Life Support System (BLSS) is synonymous to Controlled Ecological Life Support System (CELSS) in this paper.

The final BLSS functional requirements for space application can be summarized by:

- Atmosphere maintenance,
- Waste water reclamation,
- Solid waste reclamation, and
- Food production.

Some basic factors of human/plant/microorganism cohabitability are understood, but additional research to provide basic knowledge in a number of technologies remains necessary.

Numerous scientific space experiments have been delineated in recent years, the results of which are applicable to the BLSS concept. To ensure that the efforts expended by various international bodies aim toward a common goal, the coordination with existing Spacelab and Shuttle utilization programmes is of major importance to avoid duplication of effort, and to gain early access to valuable data as early as possible. The analysis reported here is a result of a cooperative effort undertaken by Dornier System and Hamilton Standard in recent years to define requirements and concepts, and to analyze the feasibility of BLSS for space applications.

## STATE OF THE ART

The development of manned space activities will most likely continue along the evolutionary lines that have so successfully guided the space programme to date. Along with progressively growing crew sizes, mission duration and complexity have increased dramatically since the first orbital flights in 1961-1962. Mission duration has progressed from the one to three orbits of the first Vostok and Mercury flights to the 84 days of the third Skylab flight and the 211 days of Salyut. From the initial, single objective of survival, mission objectives have increased to the achievement of major experiments, and the accomplishment of major operational missions, such as satellite launch, deployment, capture, repair and redeployment.

The Space Transportation System (STS), Shuttle Orbiter and Spacelab, are opening up the future expansion of manned space activities. The baseline STS capability is a seven day on-orbit mission.

Future use of space stations and larger scale operations are forecasted to continue in a progressive manner /1/. In concert with the evolution of man's activities in space, the technology to support these activities will require progressive development of today's space systems. Of major importance is the life support system. The latest U.S. and European manned space vehicles, the Space Shuttle Orbiter and the Spacelab, contain the same life support systems with expendable supplies, such as the systems used on the earlier manned space flights. However, the next phases of manned space flight development will provide substantial impetus to improve life support technology, and to reduce the dependency upon these expendable technologies. Figure 1 shows how improvements in life support technology might be implemented in conjunction with the mission growth scenario.

The life support systems for pre-Shuttle space missions evolved very little from the initial systems of Mercury to the present ones; the evolution to today's systems was largely one of technology refinement, as opposed to the technology replacement forecasted for the future. The only exception to this generalization was the $CO_2$ control system of Skylab, in which a regenerable molecular sieve system was used due to the extended duration of the mission.

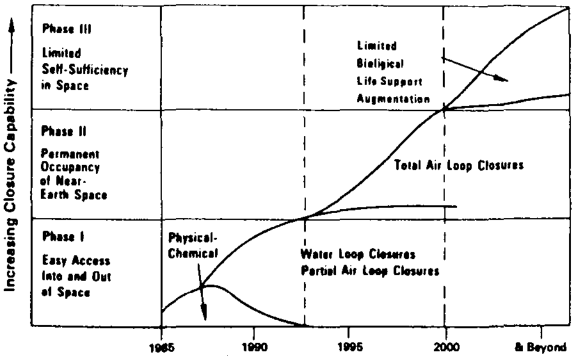

Fig. 1. Prospective evolution of life support systems /1/.

The next U.S. and European manned space objective is likely to be a space station. This permanently manned facility will presumably be resupplied on 90-day intervals and have a crew size of 4-8 astronauts. Such an on-orbit system is envisioned to have a large role in the commercialization of space activities, as well as playing a key role in continued development of space technology, primarily in the area of in-orbit operations. Because resupply from Earth of metabolic expendables ($O_2$, clean $H_2O$, food) incurs a high launch cost the space station life support system is expected to regenerate water and oxygen.

Beyond the initial space space station, future manned space missions include various missions that require large teams of humans working and living in space for extensive periods of time in permanently-inhabited large space stations. These space habitats will require the carbon loop to be closed to further reduce logistics costs. This recycling of carbon will only be partical if advanced life support systems can be developed in which metabolic waste products can be used to produce food (Figure 2).

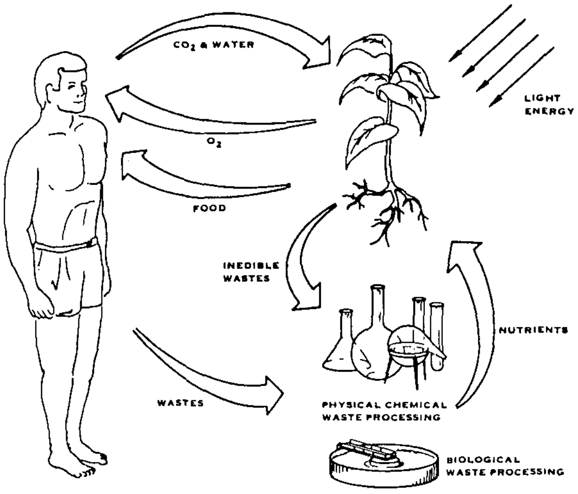

Fig. 2. Principal Biological Life Support System (BLSS).

Initial efforts to investigate advanced life support systems of the ecological/biological type to close the carbon loop (food supply), Figure 3, have been undertaken in the U.S. (Controlled Ecological Life Support Systems, CELSS) and in Europe (Biological Life Support Systems, BLSS) in recent years. During this decade, continuing efforts will concentrate on feasibility studies, investigations of specific development issues, and flight experiments to prove the viability of selected detailed designs or to provide basic scientific information in preparation for large scale testing on board a space station in the 1990's. As indicated in the literature, intensive experimental studies concerning BLSS are also being conducted in the U.S.S.R. and Japan as well. Both terrestrial and space experiments are being planned or performed.

The benefit of BLSS is primarily an economic one, because the cost of launching supplies into orbit to support manned space activities can be reduced by the use of a BLSS. The first, and relatively near potential application for BLSS is on a space station in a low earth orbit (LEO). An estimated systems trade-off between a non-biological (physico-chemical) regenerative system and a biological system with ∿ 80 % food closure is given in Figure 4.

Depending on the mission type and crew size the pay off varies from 6-7 years for a 4-man crew to about 1 1/2 year for a 100-man crew in LEO.

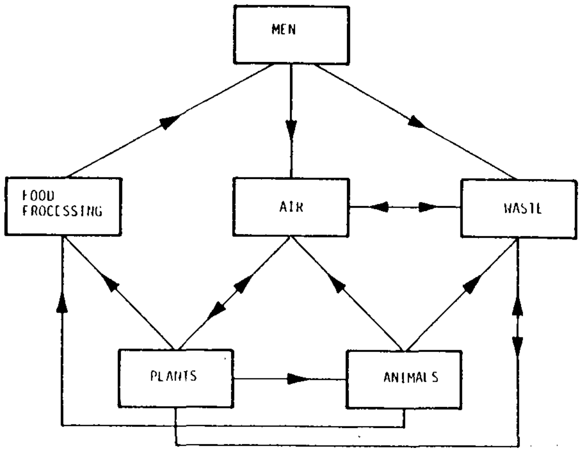

Fig. 3. Principle carbon mass flow in a closed system (BLSS).

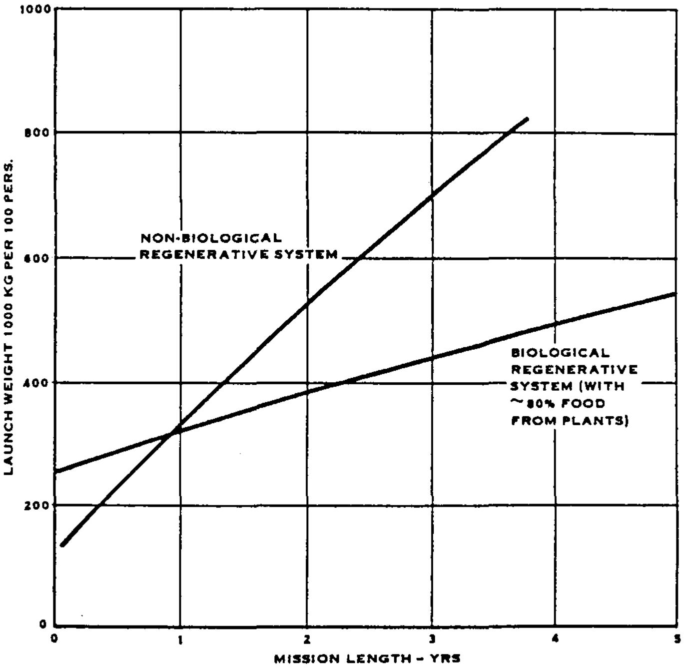

Fig. 4. Estimated systems trade-off for life support system alternatives.

## BLSS REQUIREMENTS

In defining BLSS characteristics, it is important to consider potential space applications, which dictate BLSS functional requirements. A permanently manned space station or base has been used as the model for the following BLSS discussions, because this application embodies the essential complexities of most BLSS uses. As BLSS will represent only one of many subsystems integrated to form the space station, the BLSS design must take into account all potential inputs (e.g., gases, chemicals) from other subsystems if the resulting space station ecology is to be balanced and stable.

Space station life support functions can be more definitively specified as:

- Oxygen Production
- Carbon Dioxide Control and Reduction
- Contaminant Gas Control
- Two Gas Control and Pressure Regulation
- Humidity Control
- Thermal Control
- Solid Waste Reclamation
- Waste Water Reclamation

- Radiation Protection
- Illumination
- Artificial Gravity
- Food Supply (production and supply).

Ultimately, BLSS functional requirements for space application will be to supply oxygen, water and food for support of human life on a continuous basis, while maintaining a balanced, stable spacecraft ecology. The BLSS must satisfy both the Environmental Control and Food Production functional requirements of the space station listed above. While the precise BLSS components will be highly dependent on the space mission, it will probably consist of human, animal, plant and microorganisms integrated with other supporting physico-chemical components.

In an ideal scenario, a BLSS would be capable of perfect:

- metabolic balance between man's oxidative process and plants regenerative process,
- waste water reclamation, and
- mass-balanced regenerative food/waste cycle.

The closed system as presented in Figure 5 would represent this case. In a closed system, where the food supply might include both animal and plant species, no unusable residues would be produced. That is, a perfect regenerative balance of input and output quantities from human, animal and plant species would be maintained. In practice, however, total BLSS closure will not be achievable. At best, BLSS closure will be approached incrementally and only after intensive biological research effort. Representation of a partially closed BLSS is shown in Figure 6. Note the requirement for supplements to replace generated unusable waste products.

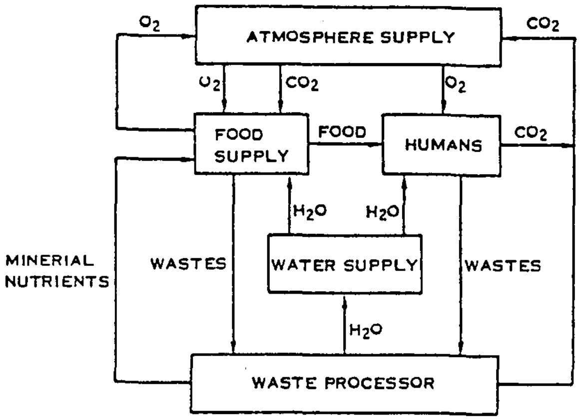

Fig. 5. Closed BLSS.

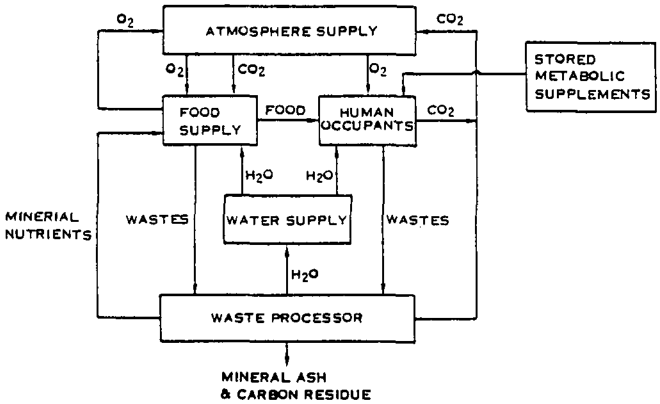

Fig. 6. Partially closed BLSS.

To expand upon the concepts introduced above, the BLSS must be balanced in the sense that proper proportions of $CO_2$, $O_2$, biomass, water, food reserves, etc., are maintained. The precise nature of this balance relates directly to BLSS's regenerative ability to convert waste products to usable products. In any practical BLSS, supplement additives to the system will periodically be required to maintain the desired ecological balance, because some unusable waste residues will always be produced. Such BLSS systems are said to be partially closed. Even if a closed BLSS could be achieved, the space station would still only exhibit limited self-sufficiency because resupply of consumables such as medicines, propellant fuels, clothing, replacement equipment, film, filters, etc., would be periodically required. Finally, even the simplest experimental closed biological systems, exposed to the same light and heat required by constituent species when in the earth's large open biosphere, eventually degrade in performance and die. Although this phenomenon is not entirely understood, it is believed to be linked to what has been defined as buffering capacity. Since space ecosystems are not expected to be self-regulating, an artificial buffering capacity, provided in the form of physico-chemical subsystems and a degree of human intervention, will be required to maintain stable biological processes.

Assessing the required life support functions (oxygen supply, food production and water reclamation) for a BLSS indicates that the food production requirement is the design driver for higher plants. A system sized for food production will be in the position to handle the other life support functions without an increase in size. Analyses of the BLSS energy-mass relation have been performed, and it appears possible to achieve advantages using the BLSS compared to physico-chemical systems. At equal energy consumption for a BLSS and a physico-chemical system, the break-even point of mass is in the order of 7 years. If the phototrophic efficiency could be increased over the 2 % used in this analysis the energy consumption would be higher for the BLSS, but it would show a weight advantage for shorter mission durations.

## BLSS GENERAL DEVELOPMENT

The development of an operational biological life support system for space requires dual development paths /2/. In parallel to the selection of species plants and animals, the improvement of culturing methods and of waste treatment by experimental investigations, and mathematical models will be needed to decrease development risks of the prototype BLSS.

The development process (Figure 7) starts with the specification of the human diet and the vitamin and trace mineral requirements. Compatible with these human requirements and the environmental conditions of a space station, the next step would be to select the plant and animal species required. This selection will be reevaluated and retested as the development of a BLSS makes progress in the following areas:

- higher yield of cultures,
- waste treatment, and
- control mechanisms.

Many single experimental investigations in various disciplines will be necessary for the evaluation of the biological, chemical and technical basis for these areas before they can be integrated into subsystems, whose functional coupling and reliability under working conditions can be tested.

The theoretical approach, going hand in hand with the experimental one, will use mathematical models. These mathematical models should describe the functional couplings between all system components as well as their dynamic behaviour. The models should also define system stability and eventually form the basis for computerized control and management of the system, including problem prediction, trend analysis, crop forecasting, and logistical requirements predictions.

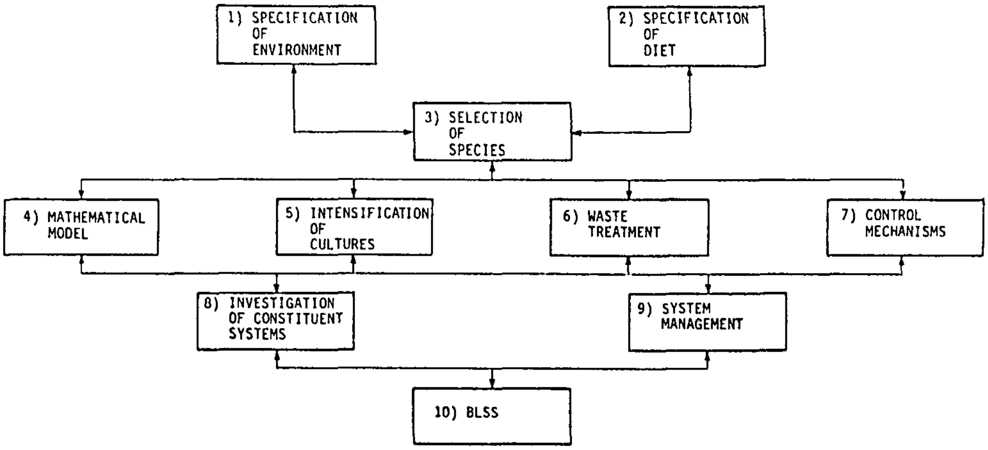

Fig. 7. Idea of the development process of a BLSS.

## BLSS DEVELOPMENT APPROACH

The early state of development of the BLSS system is reflected by the large number of issues yet to be resolved in the definition of an operational system. Table 1 summarizes some basic developments yet to be undertaken in the areas of environment control, agriculture, aquaculture, food synthesis and processing, diets, and waste conversion. A development programme as outlined in Figure 7 is envisioned to sequentially address these issues in the development of a BLSS system /2, 3/.

TABLE 1 Basic BLSS Development Issues

| REQUIRED BLSS SCIENTIFIC AND TECHNOLOGY DEVELOPMENTS |
|---|
| Environment<br>- Materials selection<br>- Atmosphere selection<br>- Gravity selection<br>- Radiation shielding requirements and methodology<br>- Ecosystem tradeoff studies<br>- Chemical analysis and control of contaminants and toxicants<br>- Illumination requirements<br>- Solar reflectors and filters |
| Management and Control<br>- Critical biological performance parameters<br>- Biological sensor development<br>- Definition of biological stability criteria<br>- BLSS mathematical models<br>- BLSS management and control philosophy |
| Agriculture<br>- Plant culture and physiology in space environments<br>- Concepts to reduce spatial requirements<br>- Equipment concepts for cultivation and harvesting<br>- Radiation effect on genetic drift germination<br>- Plant growth without soil<br>- Forced growth effects on plants<br>- Plant cycle photosynthesis efficiency<br>- Plant hormone activity in micro-gravity<br>- Plant production of toxic gases |
| Aquaculture<br>- Food-producing ecologies based on waste conversion<br>- High yield, high nutrition plant production and harvesting<br>- Photosynthesis process |
| Food Synthesis<br>- Acceptable microbiological sources and production methodology<br>- Acceptable chemical synthetic production of protein and carbohydrates |
| Food Processing<br>- New concepts for food preparation processing, storage, and distribution to reduce equipment and resource requirements<br>- Improved food preservation and packaging methods |
| Diet Planning<br>- Human nutritional requirements<br>- Food and food-source selection criteria<br>- Nutritional equivalency of various food sources<br>- Physiological and psychological acceptability aspects of nonconventional diets and food sources<br>- Definition of crop/plant scenarios<br>- Digestive tract adaptability |
| Waste Conversion and Resource Recovery<br>- Physico-chemical processes, particularly mineral separation and recovery<br>- Microbiological processes<br>- Regenerative chemical filters<br>- Chemical separation methods<br>- Auxiliary non-food products from wastes (e.g., paper and tools)<br>- Plant waste byproduct processing. |

Within the large list of BLSS issues to be resolved, there are a number of early technology tasks that can be performed in an initial test and development programme to lay a technological foundation for the eventual BLSS system evolution. These early key tasks are listed in Table 2.

These problems have to be subdivided into ones that absolutely require studies in space, and ones that can be studied and solved in terrestrial research programmes. Furthermore, priorities should be set as to whether the problem is relevant in the very near future (short-term relevance, pre-pilot type) or not (long-term relevance, pilot type).

TABLE 2 Problems to be Studied in Early BLSS Development

| TASK | Pre-Pilot Type | | Pilot Type | |
|---|---|---|---|---|
| | Terrestrial | Space | Terrestrial | Space |
| 0-g influence during cultivation | x | x | | x |
| 0-g influence on culture-methods | x | x | | x |
| Solar radiation in PAR region impact on biological material | x | | x | x |
| Cosmic radiation | X | X | | |
| Optimization of biological material | X | (X) | X | |
| Optimisation of cultivation methods | X | (X) | X | |
| Optimization of harvesting methods | (X) | (X) | X | X |
| Energy recycling | X | | X | |
| Waste recycling | X | | X | |
| Monitoring and Control | X | X | X | X |
| Improvement of mathematical modelling | X | | X | |
| Selection of diet | X | | X | |
| Development of large area windows for PAR and IR | X | X | X | X |
| Refined theoretical model | X | | X | |

( ) = need for exp. still to be defined
PAR = Photosynthetic Active Region
IR = Infrared

Generally speaking, only those problems need to be studied in space, which:

i) require a micro-gravity environment, and/or
ii) are cosmic radiation dependent.

As to i), perhaps problems arising in the micro-gravity environment of a BLSS may be solved on earth by studying the problems under increased g-force levels and directional attitudes of gravity, and then extrapolating the results to 0-g. This approach, in connection with sophisticated mathematical modelling, might be successful. If experiments have to be conducted under micro-gravity, it seems possible that only verification experiments may be necessary.

As to ii), it is clear that the simulation of cosmic radiation on earth is very difficult, and that appropriate experiments may have to be performed in space. However, the composition of cosmic radiation and its distribution in space is relatively well known, so that first order approximations are possible for certain experiments.

For all experimental activities, a prerequisite is that they focus on the applicability of certain biological features for BLSS. Therefore, questions concerning problems of basic life science are not to be studied, but results of such experiments might provide answers to certain questions relevant to BLSS.

## Pre-Pilot Studies

Pre-pilot studies should center around the problem of providing the crew with a certain amount of fresh greens. The culture methods are characterized by the use of prepared beds or pots which contain a medium either in the form of solid fertile 'soil' (agar plate) or sponge-like substances. The interface of the BLSS with the spacecraft and with outer space (sunlight) should be as simple as possible. Direct sunlight would be preferred from an energy point-of-view, but because of multiple light-dark periods during each 24-hour day in low earth orbit, solar powered artificial light may be required.

The harvesting process should take place by cutting plants during their vegetative period. Species able to perform vegetative reproduction should be selected to shorten the duration between the harvesting periods; that is, the generative period during growth should be bypassed. Vegetative reproduction is usually supported by the method of stem-cutting. This method is also less crew-time consuming than sprouting from seed.

Below is a suggested listing of pre-pilot studies aimed at providing fresh greens:

Terrestrial activities.
(a) Test of stem-cut method for the following species:leek, dill, cabbage, endive, chicory, cress, parsley, and spinach.
All of these species grow leaves, which constitute the edible part of the biomass, hence the generative phase of growth can be bypassed.

(b) Optimization of the fertile soil with respect to the production of large amounts of biomass.

(c) Studies of the growth (orientation and propagation) of roots and sprouts under different intensities and directions of gravity forces.

(d) Studies of the effect of very high PAR (photosynthetic active region) intensities (up to 600 $Wm^{-2}$ as is the case in low earth orbit) on photosynthetic efficiency and yield.

(e) Studies of the compatibility of species when cultivated simultaneously in the same greenhouse-like facility.

(f) Studies concerning the possibility of stimulating growth (yield) by hormones.

Activities in space.
(a) Verification of the results obtained in terrestrial growth studies if no unique interpretation of terrestrial experiments is possible.

(b) Study of the impact of cosmic radiation on biological material. BIOSTACK-like experiments with a window-like shielding of a material thought to be optimal for greenhouse windows in space.

(c) Production of certain species of edible greens in small scale to gain experience in cultivation and harvesting. These experiments will also fulfill the purpose of providing a certain diet variety by fresh vegetables.

Pilot Studies

Pilot studies focus on the design and testing of a terrestrial reference system which simulates the life support system with its biological subsystems intended for flight application. Reference systems have in the past been designed and tested along with the development of physico-chemical subsystems.

Whereas in pre-pilot studies principle aspects of BLSS are experimentally investigated, the aims of pilot design and testing of a reference system is to verify the selected principles for the closure of the water, atmosphere and carbon loops as a system. The successful experimental work performed to date with such systems led to the conclusion that the concept of a reference system is valid. Pilot studies should include both terrestrial and space activities.

Terrestrial activities. The major part of the work should only begin after careful analytical studies of subsystems and the complete system. On the other hand, with the broad spectrum of problems in mind, the terrestrial reference system should, as far as practical, be designed as a multipurpose and multi-user facility to allow the study of different approaches suggested by various disciplines of science and engineering before the determination of the flight configuration of the BLSS. The terrestrial investigations performed with a reference system constitute the indispensable basis for the development of a BLSS for flight application.

Activities in space. Although pilot studies are fairly well advanced in character, space activities in connection with these studies are to a certain extent equivalent with prepilot activities already defined. A typical example may be the micro-gravity testing of new promising species.

It is only in the final stage of the development of BLSS that pilot studies will occur in space. At this stage of development, complete biological subsystems are flown, possibly as some kind of parallel system to physico-chemical subsystems, activated only during a certain phase of the mission. Such a mission will occur before complete BLSS are implemented as the main life support system.

## DEVELOPMENT OF BLSS EXPERIMENTS

The BLSS studies have indicated two blocks (pre-pilot and pilot type) of experiments and analysis which are required for the support and promotion of the development of BLSS (Table 2). The development of specific flight experiments should follow the generalized flow diagram (Figure 8). This approach takes into account the known typical BLSS design parameters for different types of species, and can also be used for the definition of new BLSS flight experiments and to evaluate modifications to planned experiments. A preliminary programme has been proposed indicating some potential BLSS experiments. These experiments investigate those areas with immediate impact upon the successful integration of a regenerable life support system into future manned space activities.

Tasks of immediate importance from a life support system development point-of-view are:
- investigations concerning micro-gravity,
- investigations concerning cosmic radiation,
- development of large area windows for radiation in the PAR-region,
- investigations concerning harvesting and cultivation in micro-gravity,
- monitoring, control and sensor technology, and
- waste processing.

Cosmic radiation studies are already planned, but those experiments dealing with micro-gravity and PAR-windows are only partly defined. Any efforts related to the PAR-windows should include systems analysis studies in the areas of:
- the correct wavelength needed for optimum growing conditions,
- avoidance of excessive heat load into the spacecraft, and
- use of day/night growing cycles.

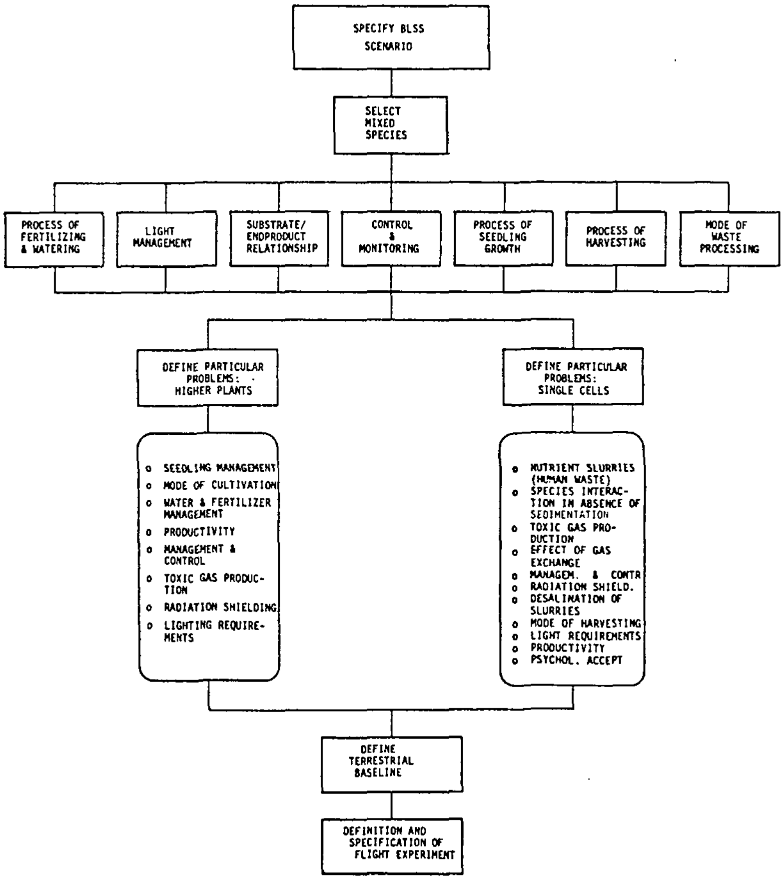

Fig. 8. Development of flight experiments for BLSS.

Concerning the cosmic radiation investigations, advanced experiments are planned and, in this case, the interpretation of results, and the subsequent influence on species selection are the major tasks in the BLSS development.

New experiments should have the dual goal of advancing the basic scientific research while meeting the BLSS requirements.

## EUROPEAN ROLE

Due to the interdisciplinary character of BLSS, it will be necessary to engage many scientists of various disciplines in research and basic development of BLSS. The disciplines required, but not limited to, include:

- all kinds of biology,
- biochemistry,
- chemical engineering,
- ecology,
- cybernetics,
- physiology,
- medicine, and
- agriculture.

The development of new advanced life support systems on an ecological basis has just been initiated in different parts of the world (U.S., U.S.S.R., Europe, Japan). These systems can be tested and implemented on a space station towards the end of this century. The present life sciences and life support activities in Europe permit a projection of future activities until the end of the century (Figure 9). Europe has a strong position in many of the scientific disciplines relevant to this development activity (e.g. agriculture, botany, genetic engineering, biochemistry, physiology, ecology) and could become an important partner in the development of future life support systems for a permanent human presence in space.

The scientific and technology tasks to be performed to establish the basis for the design of an ecological life support system for space applications are very extensive and also well suited for international cooperation.

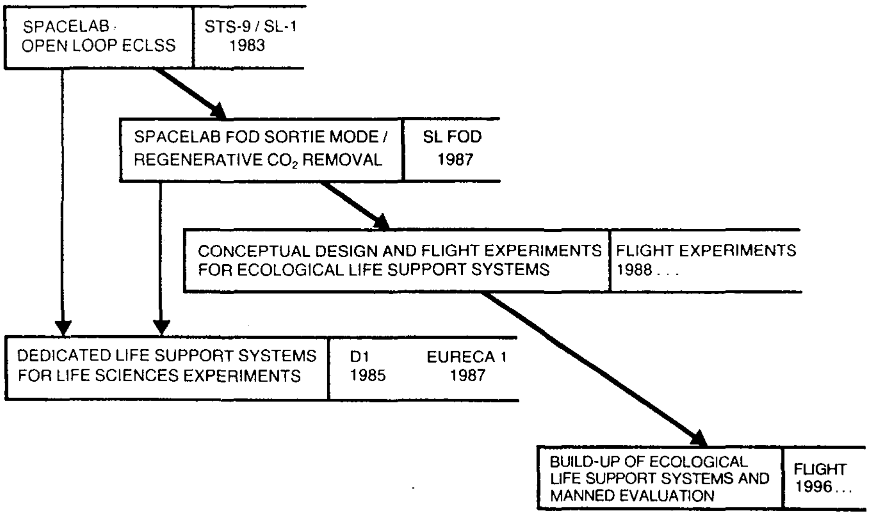

Fig. 9. Anticipated life support system development activities in Europe. (D1 refers to the first West German Spacelab flight; Eureca is an unmanned retrievable carrier.)

## CONCLUSIONS

Several studies have revealed the benefits of a biological life support system to a space station by food production on-orbit from metabolic waste products. Problem areas requiring experimental and analytical investigations necessary for the development of BLSS have been identified. The nature of these problems allows for the classification into near-term (pre-pilot) and long-term (pilot) studies, and into terrestrial and space research programmes.

The knowledge of planned European and U.S. space experiments allows for a coordination with existing Spacelab and Shuttle programmes to avoid duplication of research efforts. The Japanese also plan biological experiments on Spacelab in 1988. Coordinating our efforts should provide answers to certain BLSS relevant questions.

Major areas which need immediate attention are:

- micro-gravity effects,
- cosmic radiation effects,
- use of PAR-radiation and high energy particle radiation protection, and
- monitoring and control (including sensor technology).

Relevant problem definitions and potential contacts with advisers in the scientific community are available. This allows for detailed definitions, tasks descriptions and programme planning as the next step in the development of BLSS.

## ACKNOWLEDGEMENT

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# ADVANCED REGENERATIVE ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS: AIR AND WATER REGENERATION

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## ABSTRACT

Extended manned space missions will require regenerative life support techniques. Past U.S. manned missions used nonregenerative expendables, except for a molecular sieve-based carbon dioxide removal system aboard Skylab. The resupply penalties associated with expendables becomes prohibitive as crew size and mission duration increase. The U.S. Space Station, scheduled to be operational in the 1990's, is based on a crew of four to sixteen and a resupply period of 90 days or greater. It will be the first major spacecraft to employ regenerable techniques for life support. The paper uses the requirements for the Space Station to address these techniques.

## INTRODUCTION

The need and requirements for a low earth orbit Space Station have been studied and defined. It will provide for the U.S. and other free world countries a comprehensive capability to exploit and explore the space environment. It will support and be part of a wide range of missions with objectives in science, applications, commercial activities and technology development. The Space Station will evolve by time-phased modular increments delivered and supplied by the Space Shuttle /1,2/. It will be capable of operating continuously manned and, under special circumstances, unmanned. A minimum useful lifetime of ten years is sought, but life cycle costs decrease continuously as the operating life increases beyond this minimum level.

## SPACE STATION SYSTEMS

The Space Station has been divided into 13 systems /1/. The current paper addresses just one of these: the Environmental Control/Life Support System (ECLSS).

### Environmental Control/Life Support System

The ECLSS can be divided into six functional categories:

- Air Revitalization System
- Atmospheric Pressure and Composition Control System
- Cabin Temperature and Humidity Control System
- Water Reclamation System
- Personal Hygiene System
- Waste Management System

Each of these, in turn, are further subdivided, e.g., the Air Revitalization System into carbon dioxide ($CO_2$) concentration, $CO_2$ reduction, oxygen ($O_2$) generation, trace contaminant control and atmosphere quality monitor. The first three functional categories makeup the Atmosphere Management Group. The last three makeup the Water and Waste Management Group. A third group could be considered those functional elements needed to provide a safe haven capability.

**ECLSS Functions.** Table 1 summarizes the ECLSS functions. The functions include, for example, providing $O_2$ for metabolic consumption, Space Station leakage and airlock use. It is maintained or controlled by monitoring the partial pressure of $O_2$ ($pO_2$) in the atmosphere.

**ECLSS Performance Requirements.** Table 2 summarizes the ECLSS performance requirements /3/ being used on the Space Station studies. These requirements are close to those used for previous studies /4-7/. These requirements are further supplemented by such needs as sufficient $O_2$ and nitrogen ($N_2$) storage aboard the Space Station for one total emergency repressurization; atmospheric leakage to be less than 0.5 lb/day

TABLE 1 ECLSS Functions

| Functions[a] | Applications | Maintain Or Control |
|---|---|---|
| • Provide $O_2$ | — For Metabolic, Leakage, Airlock Use | $pO_2$ |
| • Provide $H_2O$ | — For Drinking, Cooking, Bathing, Dishes, Laundry | -- |
| • Remove $CO_2$ | — From Metabolic | $pCO_2$ |
| • Remove $H_2O$ | — From Respiration, Perspiration, Use of Handwash, Shower, and Washer/Dryer | $pH_2O$ (RH) |
| • Remove Trace Contam. | — From Crew, Equipment, Outgassing | Trace Contam. |
| • Provide $N_2$ | — For Leakage, Airlock Use, Purging, Pressure Reference | $O_2/N_2$ Ratio |
| • Provide Environment | — Temperature, Pressure, Relative Humidity | T, P |
| • Provide Facilities | — Handwash, Shower, Dishwasher, Clothes Washer/Dryer, Toilet, Trash Compactor, Air Ventilation/Filtration | -- |
| • Provide Bacterial Control | — Of Air, Water, Waste Solids/Liquids | Bacteria |

a. Provisions for food assumed part of Space Station Habitability and Crew Support System.

TABLE 2 ECLSS Performance Requirements

| PARAMETER | UNITS | OPERATIONAL | 90-DAY DEGRADED(1) | 21-DAY EMERGENCY |
|---|---|---|---|---|
| $CO_2$ Partial Pressure | mmHg | 3.0 Max. | 7.6 Max. | 12 Max. |
| Temperature | deg. F | 65 - 75 | 60 - 85 | 60 - 90 |
| Dew Point(2) | deg. F | 40 - 60 | 35 - 70 | 35 - 70 |
| Ventilation | ft/min | 15 - 40 | 10 - 100 | 5 - 200 |
| Potable Water | lb/man-day | 6.8 - 8.1 | 6.8 min | 6.8 min |
| Hygiene Water | lb/man-day | 12 min | 6 min | 3 min |
| Wash Water | lb/man-day | 28 min | 14 min | 0 |
| $O_2$ Partial Pressure(3) | psia | 2.7 - 3.2 | 2.4 - 3.8 | 2.3 - 3.9 |
| Total Pressure | psia | 14.7 | 10 - 14.7 | 10 - 14.7 |
| Trace Contaminants | — | 24 hr. Ind. Standard | 8 hr. Ind. Standard | 8 hr. Ind. Standard |
| Microbial Count | per $ft^3$ | 100 | — | — |
| Maximum Crew Member | Per Space Station | 8 | 8 | 12 |
| Maximum Crew Member | Per Habitat Module | 4 | 8 | 8 |

1. Degraded levels meet "Fail Operational" reliability criteria
2. In no case shall relative humidities exceed the range of 25 - 75%
3. In no case shall the $O_2$ partial pressure be below 2.3 psia, or the $O_2$ concentration exceed 26.9%

per module and 5 lb/day for the entire Space Station; exposure of ECLSS equipment to cabin pressure of 0 to 10 psia must not create hazard of cause damage; etc.

**ECLSS Average Design Loads.** The ECLSS average design loads are given in Table 3 /8/. Although similar to those used for previous studies, values often differ significantly in areas of importance to ECLSS designers.

## ECLSS CLOSURE OPTIONS

Current state-of-the-art ECLSS is based on an expendable or "open loop" system approach. Various options exist for the space ECLSS designer to reduce the resupply requirements and costs associated with expendables. Options range from an enhanced open loop in which only regenerable $CO_2$ removal is used to a completely closed ECLSS where food is regenerated aboard the space vehicle.

TABLE 3 ECLSS Design Average Loads

| | Space Station Values /8/ | SOC Value /9/ |
|---|---|---|
| Metabolic $O_2$ | 1.84 lb/man day | 1.84 lb/man day |
| Leakage Air | TBD | 5.00 lb/day total SOC |
| EVA $O_2$ | 1.32 lb/8 hr EVA | 1.22 lb/8 hr EVA |
| EVA $CO_2$ | 1.67 lb/8 hr EVA | 1.48 lb/8 hr EVA |
| Metabolic $CO_2$ | 2.20 lb/man day | 2.20 lb/man day |
| Drinking Water | 2.86 lb/man day | 4.09 lb/man day |
| Food Preparation Water | 3.90 lb/man day | 1.58 lb/man day |
| Metabolic Water Production | 0.78 lb/man day | 0.70 lb/man day |
| Clothing Wash Water | 27.50 lb/man day | 27.50 lb/man day |
| Hand Wash Water | 7.00 lb/man day | 4.00 lb/man day |
| Shower Water | 5.00 lb/man day | 8.00 lb/man day |
| EVA Water | 9.68 lb/8 hr EVA* | 9.68 lb/8 hr EVA |
| Perspiration and Respiration Water | 4.02 lb/man day | 4.02 lb/man day |
| Urinal Flush Water | 1.09 lb/man day*(a) | 1.09 lb/man day |
| Urine Water | 3.31 lb/man day*(a) | 3.31 lb/man day |
| Food Solids | 1.36 lb/man day | 1.60 lb/man day |
| Food Water | 1.10 lb/man day | 1.00 lb/man day |
| Food Packaging | 1.00 lb/man day* | 1.00 lb/man day |
| Urine Solids | 0.13 lb/man day | 0.13 lb/man day |
| Fecal Solids | 0.07 lb/man day | 0.07 lb/man day |
| Sweat Solids | 0.04 lb/man day | 0.04 lb/man day |
| EVA Wastewater | 2.00 lb/8 hr EVA | 2.00 lb/8 hr EVA |
| Charcoal Required | 0.13 lb/man day* | 0.13 lb/man day |
| Metabolic Sensible Heat | 7,010 BTU/man day | 7,000 BTU/man day |
| Hygiene Latent Water | 0.94 lb/man day | 0.94 lb/man day |
| Food Preparation Latent Water | 0.06 lb/man day* | 0.06 lb/man day |
| Experiments Latent Water | 1.00 lb/day | 1.00 lb/day |
| Laundry Latent Water | 0.13 lb/man day | 0.13 lb/man day |
| Waste Wash Water Solids | 0.44% | 0.44% |
| Expended Water Solids(b) | 0.13% | 0.13% |
| Air Lock Gas Loss | 2.40 lb/EVA | 2.40 lb/use |
| Trash | 1.80 lb/man day* | 1.80 lb/man day |
| Trash Volume | 0.10 ft 3/man day* | 0.10 ft 3/man day |

*Not cited in reference but taken from the Space Operations Center Study /9/.

(a) Cited reference identified urine, at 4.4 lb/man day, approximately combined total of urinal flush water and urine water.

(b) Assumed shower and hand wash.

### Alternatives

Cost-effective continuous operation of the Space Station requires use of some level of regenerative techniques. Table 4 presents a range of closure operations. Major ones include: a) Regenerable $CO_2$ removal; b) Regeneration of $O_2$; c) Reclamation of water and d) Regeneration of food. All of these are candidates for a 1990's in-orbit Space Station. Technology for closure of the food cycle, however, while currently under development, may not reach the maturity level needed to be a viable candidate when the initiation of the detailed Space Station design must start (projected 1987). Regeneration of $N_2$ is not under development, *but* a subsystem for on-board generation of $N_2$ from potential propellents (e.g., hydrazine, $N_2H_4$) is being developed.

### Open Loop Costs

The launch weight of a Space Station decreases as the $CO_2$ removal, water and $O_2$ loops are closed. This is illustrated in Figure 1. The level of launch weight savings, however, can vary depending upon many factors. This is illustrated in Figure 2 which shows the impact on launch weight for the initial launch (with 120 days of on-board storage) and for resupply every 90 days as function of crew size. The results are presented for three different levels of water allotment:

- A minimum level defined as only the water required for drinking, food preparation, hand washing and urinal flushing
- An acceptable level defined as the minimum level plus adding the water for a full body shower
- A full service level defined as the acceptable level plus adding the water for clothes washing and dish washing

The water requirements are based on the quantity of water per person day for the water uses cited in Table 5. Note, the water requirements from Table 3 have been included. There are, however, many less visible, but yet expensive hidden costs of an open loop, expendable driven Space Station design. Some of these are cited in Table 6.

## REGENERABLE ECLSS TECHNIQUES ARE AVAILABLE

Regenerable techniques are available and developed, for example, to close the $CO_2$ removal, $O_2$ generation and water reclamation loops. The technologies for food closure are under development.

### $CO_2$ Removal

Of the more than nine $CO_2$ removal concepts evaluated by NASA, two techniques remain as viable candidates. They are the Electrochemical $CO_2$ Concentrator, or EDC, and the Steam Desorbed Amine Subsystem (SDAS) /10-12/.

TABLE 4 Possible Degree of Closure Options

| CLOSURE OPTION | $CO_2$ REMOVAL | $O_2$ SUPPLY | $N_2$ SUPPLY | WATER SUPPLY |  |  | FOOD SUPPLY |
|---|---|---|---|---|---|---|---|
|  |  |  |  | DRINKING | HYGIENE | WASH[1] |  |
| OPEN | Expendable (LiOH) Collect, Ship Back, Resupply | Cryogenic, Resupply (Scavenging) | Cryogenic Resupply | Store, Resupply | Store, Resupply | Store, Resupply | Store, Resupply |
| ENHANCED OPEN | *Regenerable* Collect, Dump | *Same* | *Same* | *Same* | *Same* | *Same* | *Same* |
| MINIMUM CLOSED | Regenerable Collect, Reduce To $H_2O$ | Same | Same | Condensed Humidity, $CO_2$ Reduction | Same | Same | Same |
| PARTIALLY CLOSED | Same | $O_2$ From Water Electrolysis | Same | Same | Recycle, Reclaim Urine Water | Recycle | Same |
| ENHANCED CLOSED | Same | Same (Reclaimed $H_2O$ Feed) | $N_2H_4$ Cat. Decomposition | Same | Same | Same | Same |
| CLOSED[2] | Plants | Plants | Plants | Condensed Humidity, Recycled $H_2O$ | Same | Same | Regen-eration |

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1. Shower, dish washing, clothes washing.
2. Technology not available for Initial Space Station.

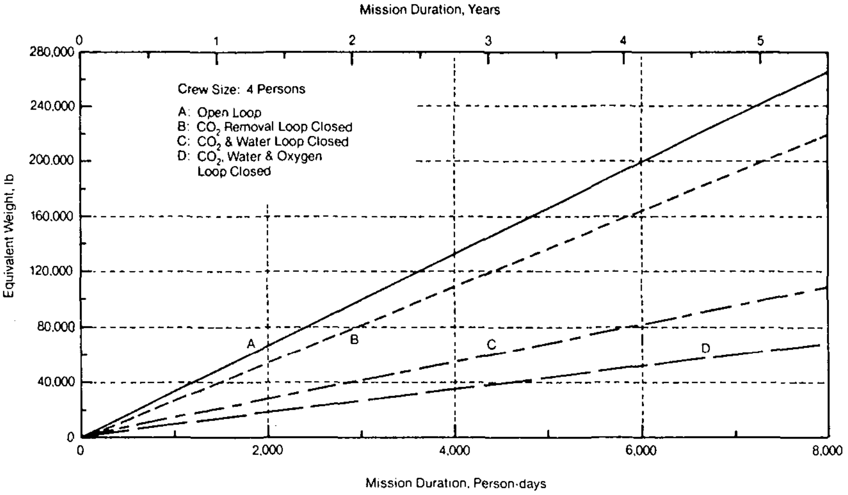


Fig. 1. Regenerative Versus Non-Regenerative ECLSS

## $O_2$ Regeneration

Regeneration of $O_2$ requires the reduction of the concentrated $CO_2$ with hydrogen ($H_2$) to form a carbon product and water. Electrolysis of the latter is then used to regenerate the $O_2$ and simultaneously provide $H_2$ for the reduction of $CO_2$.

Two $CO_2$ reduction techniques are being actively developed. One involves the reduction to form methane ($CH_4$) gas (Sabatier Process). The $CH_4$ would then be vented overboard or be used in a resistojet for attitude control. The other is based on the reduction of $CO_2$ to form carbon (Bosch Process). This would eliminate overboard venting since the carbon would periodically be returned to earth.

Two $O_2$ (water electrolysis) generation techniques are being actively developed. One involves the static feed addition of water to the electrolysis cell (SFE) and uses an alkaline electrolyte. The other is based on a recirculating water feed system and is characterized by an electrolysis cell, which employs an acid electrolyte in a solid polymer form.

## Water Reclamation

Two basic processes are being developed for recovering water. One is based upon phase change techniques, e.g., vapor compression and distillation. The other is based on filtration techniques, e.g., ultrafiltration and then reverse osmosis.

## Open Issues Impacting ECLSS Design

Many issues impacting the ECLSS design remain to be resolved. These include, for example: a) The technology readiness on the specific date the final Space Station design will be initiated; b) The level of extravehicular activity; c) The level of overboard venting to be allowed, and; d) The selected crew size. Many major technology gaps are associated with ECLSS, such as:

1. Regenerative techniques have not flown previously and, therefore, have not reached the highest technology maturity level.
2. Quantitative failure rate data is missing which establishes reliability, defines spares and dictates maintainability approaches.
3. Integration of selected functions or subsystems are only beginning to be implemented.
4. Flight maintainable hardware designs are immature.
5. Fault diagnostic capabilities of instrumentation are limited.

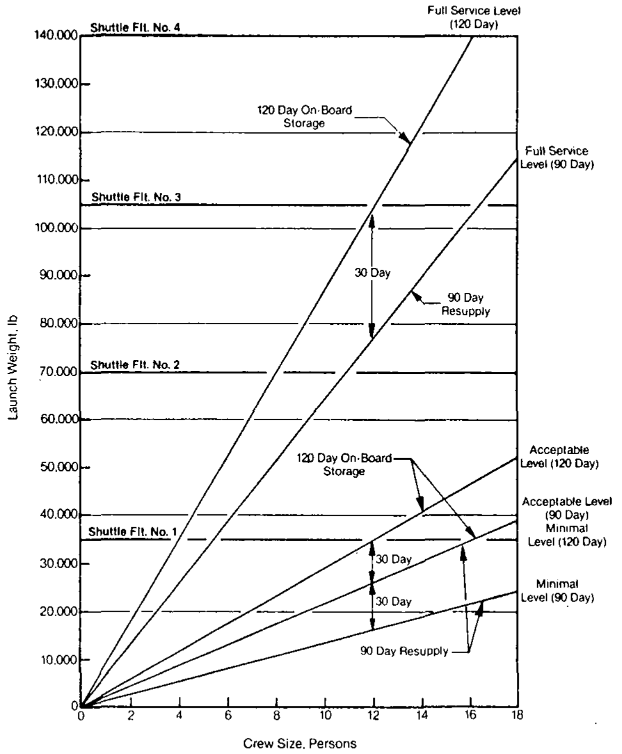
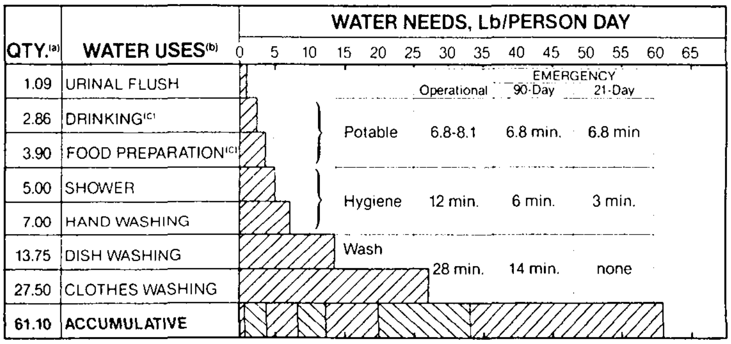


Fig. 2. Space Station ECLSS Block Diagram

TABLE 5 Water Needed: Resupplied or Reclaimed?



| QTY.[a] | WATER USES[b] |
|---|---|
| 1.09 | URINAL FLUSH |
| 2.86 | DRINKING[c] |
| 3.90 | FOOD PREPARATION[c] |
| 5.00 | SHOWER |
| 7.00 | HAND WASHING |
| 13.75 | DISH WASHING |
| 27.50 | CLOTHES WASHING |
| **61.10** | **ACCUMULATIVE** |

| | Operational | EMERGENCY<br>90-Day | <br>21-Day |
|---|---|---|---|
| Potable | 6.8-8.1 | 6.8 min. | 6.8 min |
| Hygiene | 12 min. | 6 min. | 3 min. |
| Wash | 28 min. | 14 min. | none |

---

(a) Lb/Person-Day
(b) EVA cooling water requires additional 3.32 lb/day based on 1,000 EVA hours per 365 days at 9.68 lb water/8 hr. EVA (unless nonventing thermal approach used).
(c) These water users require potable quality water.

TABLE 6 "Hidden" Costs of Expendable (Open Loop) Operation

- More Frequent Resupply Flights
  - Non-mission related work
  - Wear and tear on launch vehicles
  - Chance for major failure
- Lower In-Orbit Crew Productivity
  - Expendable replacement time
  - Resupply unloading time
  - Spent expendable loading time
- Increased Logistics Costs
  - Maintaining "supply lines"
  - Maintaining inventory (and associated documentation)
  - Maintaining waste disposal facilities
- High Retrofit Costs[a]

---

(a) Would probably not be implemented because of high cost, complexity, uncertainty and momentum.

## REGENERATIVE ECLSS TECHNOLOGY

Many regenerative ECLSS developments have been completed over the past 25 years. Major developments relating to air revitalization and water reclamation systems will now be reviewed. The Air Revitalization System alternatives are summarized in Table 7.

### Regenerable $CO_2$ Removal Concentration

The EDC and SDAS processes have been described elsewhere /10-12/. Table 8 presents a comparison of total equivalent weight of the EDC versus the SDAS. The EDC has evolved into a simple, low-cost, reliable and flexible system. It has been designed and tested for Space Station and Shuttle Orbiter missions. Currently more than 20,000 hours have been accumulated on an EDC module under just one endurance/performance test program. Table 9 presents the size of the EDC for Space Stations with crew sizes of 4, 6, 8 and 12. Figure 3 shows the four-person hardware (CS-4). The size is shown in Table 9 under Model CS-4.

TABLE 7 Air Revitalization System Alternatives

| ARS | Alternatives<br>Open | <br>Closed | <br>Technologies |
|---|---|---|---|
| $CO_2$ Removal | LiOH | Regenerative | Electrochemical<br>Solid Amine |
| $CO_2$ Reduction | -- | To Yield $H_2O$ | Sabatier ($CH_4$)<br>Bosch (Carbon) |
| $O_2$ Supply | Cryogenic | Electrolysis | Static Feed (Alkaline)<br>Solid Polymer (Acid) |
| Trace Contam. | Active Carbon & Amb. T Cat. Ox. | High Temp. Cat. Oxidizer | Expend. Absorbers<br>Regen. Absorbers |
| Atm. Qual. Mon. | Yes | Yes | Gas Chrom. & Mass Spec |

TABLE 8 Total Equivalent Weight EDC Versus Steam-Desorbed Amine

| | Requirements<br>EDC | <br>Steam-Desorbed Amine | Total Equivalent Weight, lb<br>EDC | <br>Steam-Desorbed Amine |
|---|---|---|---|---|
| **Fixed Hardware Weight** | | | 86 | 139 |
| **Power** | | | | |
| Requirements, W | | | | |
| AC | 150 | 375 | | |
| DC | 97 | 526 | | |
| Weight Penalty | | | 49 | 577 |
| **Heat Rejection** | | | | |
| Requirements, W | | | | |
| To Air | 277 | 901 | | |
| To Liquid | 128 | — | | |
| Weight Penalty | | | 145 | 394 |
| Subtotal Equivalent Weight | | | 280 | 1,110[b] |
| **Assoc. Subsystem Penalties[a]** | | | | |
| Humidity Control | | | | |
| Water, lb/day | 4 | 32 | | |
| Weight Penalty | | | 102 | 770 |
| Water Processing | | | | |
| Water, lb/day | 4 | 32 | | |
| Weight Penalty | | | 27 | 206 |
| $O_2$ Generation ($H_2O$, lb/day) | | | | |
| Water, lb/day | 4 | | | |
| Weight Penalty | | | 309 | |
| **Total Equivalent Weight** | | | 718 | 2,086[c] |

(a) Including hardware, power and heat load penalties.
(b) Amine is 3.6 times greater equivalent weight than EDC.
(c) Amine is 2.9 times greater equivalent weight than EDC.

The EDC offers many advantages over other regenerable $CO_2$ removal processes:

1. A lower equivalent weight which becomes more significant as the partial pressure of $CO_2$ decreases (see Figure 4) /13/.

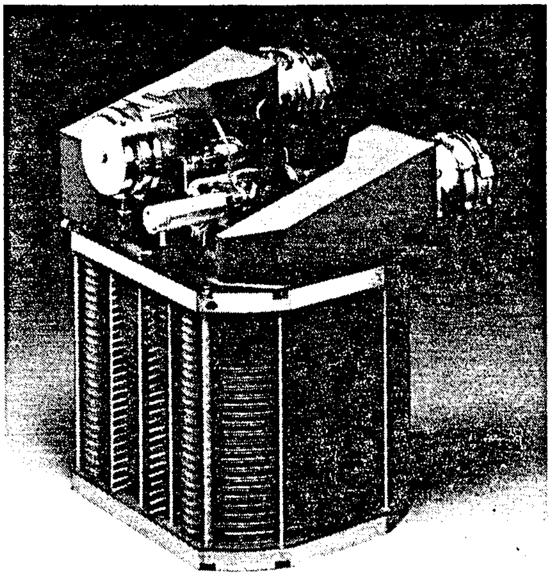


Fig. 3. Electrochemical $CO_2$ Removal Subsystem, Four-Person Capacity

2. Readily adapts to varying crew sizes since only cells are added or deleted rather than developing completely new canisters for each change in crew size.
3. Avoids the large atmosphere humidity load which is a by-product of the SDAS.
4. Operates continuously or cyclically for user flexibility, rather than only cyclically as characteristic of the SDAS.
5. Premixes the $H_2$ and $CO_2$ for transfer to the $CO_2$ reduction process without contamination with cabin $N_2$ as characteristic of the SDAS.
6. The $CO_2$ removal rate can be automatically varied up or down to allow handling variations in loads; not possible with the SDAS.
7. Avoids the compressor, its noise, and $CO_2$ accumulator as needed by the SDAS.
8. The subsystem is maintainable at the individual electrochemical cell level which provides for greater reliability (e.g., a four-person system consists of 24 cells with each one of these maintainable).
9. Adapts to the integrated $O_2$, $H_2$ and water concept for Space Station simplification, cost reduction and flexibility (discussed in more detail below).

### $CO_2$ Reduction Processes

The Bosch /14, 15/ and Sabatier /16/ processes have been described previously. The Bosch $CO_2$ reduction process reduces $CO_2$ with $H_2$ to form solid carbon and water. Complete conversion is obtained by recycling the process gases with continuous deposition of carbon and removal of water. The carbon is collected in an expendable cartridge (see Figure 5) contained in the Bosch reactor. The Bosch process requires a small quantity of expendables (see Table 10).

The Sabatier process reduces $CO_2$ with $H_2$ to form $CH_4$. Complete conversion (>99%) is obtained in one pass through the Sabatier reactor (see Figure 6). The water is condensed and the exhaust gases, primarily $CH_4$ and unreacted $CO_2$, are vented overboard. The Sabatier process requires no expendables.

### Static Feed Electrolyser (SFE)

The static feed /17, 18/ and solid polymer electrolyte /19/ water electrolysis systems have been described elsewhere. The static

TABLE 9 Electrochemical $CO_2$ Concentrator Charts

| Model No. | Capacity, People (a) | | Weight, Lb | Volume, $Ft^3$ | Dimensions, In | | | Power, W | | Heat Load, W | No. of Cells |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3mm Hg | 12mm Hg | | | Ht | Wd | Ln | DC Out | AC In | | |
| CS-4 | 4 | 8 | 86 | 2.5 | 20.6 | 15.5 | 13.5 | 100 | 50 | 245 | 24 |
| CS-6 | 6 | 12 | 110 | 3.1 | 25.4 | 15.5 | 13.5 | 160 | 80 | 364 | 36 |
| CS-8 | 8 | 16 | 134 | 3.7 | 30.2 | 15.5 | 13.5 | 220 | 80 | 450 | 48 |
| CS-12 | 12 | 24 | 182 | 4.8 | 39.8 | 15.5 | 13.5 | 340 | 80 | 626 | 72 |

a. Based on 2.20 lb $CO_2$/person-day and all sizes for the nominal partial $CO_2$ pressure of 3.0mm Hg.

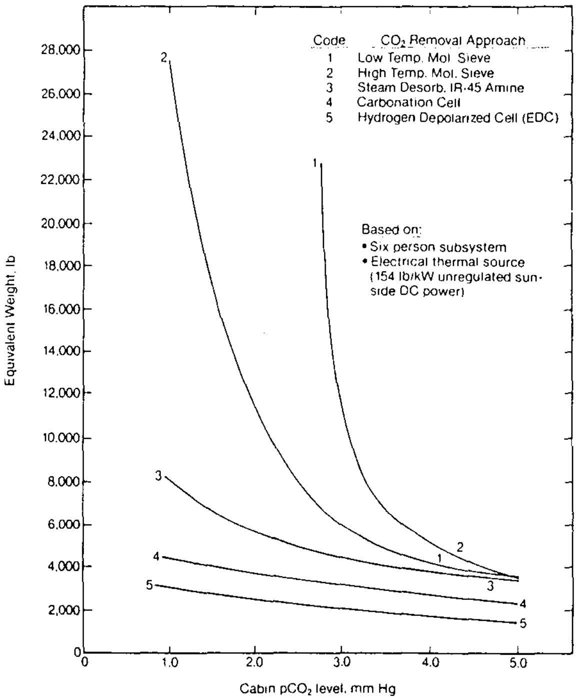


Fig. 4. Space Station Prototype $CO_2$ Concentrator Study Results

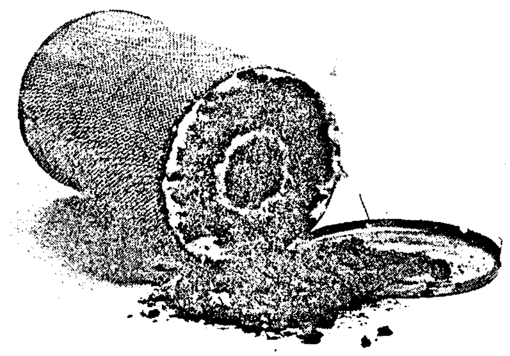


Fig. 5. Bosch $CO_2$ Reduction Cartridge with Carbon Collected

TABLE 10 Bosch $CO_2$ Reduction Expendables (Four People, 90 Days)

| Elements | Wt. | Vol. |
|---|---|---|
| Canister, blanket filter and catalyst | 66.6 | 8.47 |
| Filter blanket and catalyst only | 21.7 | 2.46 |
| Catalyst only | 5.9 | 0.38 |
| Carbon Formed | 216 | 6.96(a) |
| Returned canister | 292.6 | 8.47 |

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(a) Assumes a final packing density of 31 $lb/ft^3$.

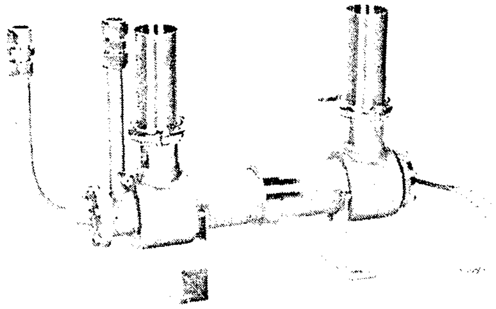


Fig. 6. Sabatier $CO_2$ Reduction Reactor

feed has evolved into a simple, low-cost, reliable system. It has been designed for the Space Station ECLSS and as a major component of a Regenerative Fuel Cell System (RFCS) approach to energy storage. Currently, more than 30,000 hours have been accumulated on several static feed units under endurance/performance test programs. Figure 7 shows a three-person static feed electrolysis subsystem for ECLSS application.

The static feed approach offers many advantages over other water electrolysis approaches for space application, including:

1. Fewer components for less weight, power and volume.
2. Less complex because the gas/liquid separator of the acid electrolyte, solid polymer subsystem is eliminated.
3. Less costly materials of construction, possible because an alkaline versus an acid electrolyte is used.
4. Less sensitive to quality of feed water because the liquid water remains isolated from the electrolysis cell itself, i.e., internally generates "distilled" water rather than circulating the feed water over the electrodes as with the solid polymer approach.
5. A higher electrolysis operating efficiency at a given set of operating conditions (temperature, pressure and current density) because of the electrodes and alkaline electrolyte used.
6. Avoids the need for additional heating and cooling characteristic of the solid polymer's recirculating water feed system.

The static feed electrolyzer is also adaptable to operating pressures from ambient to over 1,000 psig.

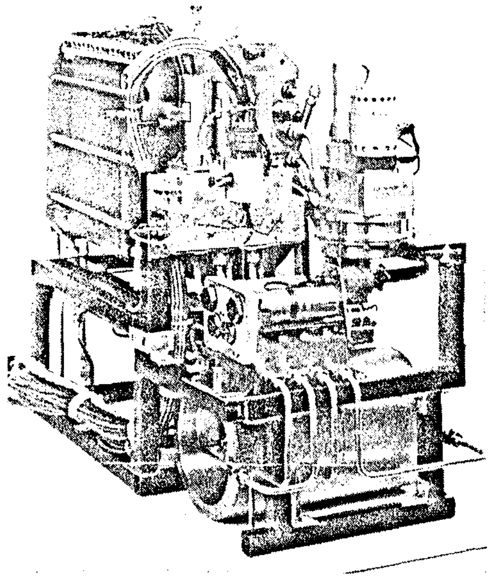


Fig. 7. Static Feed Water Electrolysis Subsystem (SFE)

## Water Reclamation

Water reclamation aboard a Space Station is of equal importance to air revitalization. Water reclamation involves processes to reclaim water from wastewater sources. Various processes, including phase change and filtration, have been investigated for these applications. Filtration processes are less developed than the phase change processes for water reclamation.

Figure 8 presents an overview of the water uses and reclamation processes, which functional groups provide water to be recovered

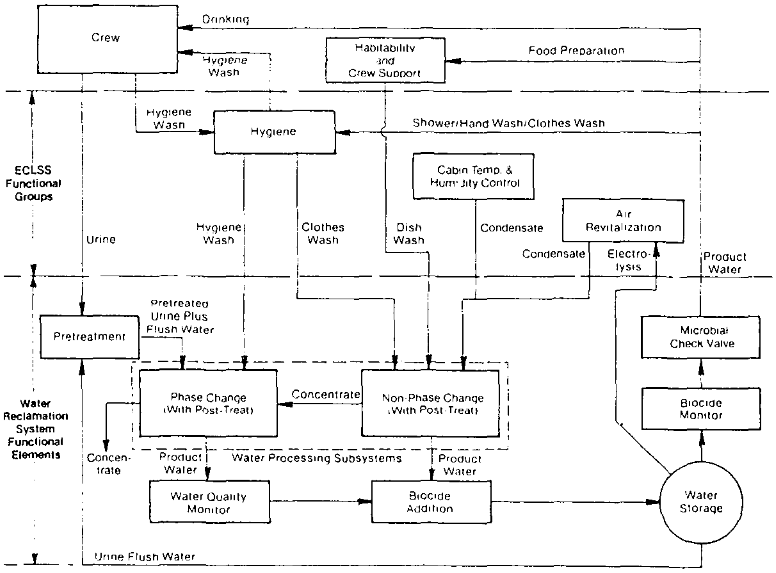


Fig. 8. Water Reclamation/Use Process Overview

and what are the elements of the water reclamation system. Two major water processing techniques have been considered for space use: phase change and filtration. Table 11 summarizes which process is considered most applicable to which waste water source. The goal, however, would be to have one process handle all the water. The preferred process would be the phase change one because of its attractiveness for providing a better quality potable water.

TABLE 11 Space Station Wastewater Sources and Projected Processing Techniques

| | Water Processing Technique | |
|---|---|---|
| Wastewater Source | Filtration | Phase Change |
| Hand Wash Water | | X |
| Shower Water | | X |
| Urinal Flush Water | | X |
| Urine | | X |
| EVA Wastewater | | X |
| Perspiration and Respiration | X | ? |
| Hygiene Latent Water | X | ? |
| Food Preparation Latent Water | X | ? |
| Experiments Latent Water | X | ? |
| Laundry Latent Water | X | ? |
| Clothing Wash Water | X | |
| Dishes Wash Water | X | |

### Phase Change Processes

Many phase change processes have been considered for spacecraft water reclamation. The two currently under active development include the Vapor Compression Distillation (VCD) process which is shown conceptually in Figure 9. Figure 10 is a photograph of a 72 lb/day VCD subsystem. The recovery of latent heat in the VCD process is accomplished by compressing the vapor to raise its saturation temperature and then condensing the vapor on a surface which is in thermal contact with the evaporator /20/.

The alternative is the thermoelectric/membrane process which is shown conceptually in Figure 11. This concept /21/ recovers the latent heat of condensation and transfers this heat to the evaporator via a thermoelectric heat pump. Wastewater is heated to approximately 150°F in the thermal electric heat exchanger and the heated wastewater pumped through a hollow fiber membrane evaporator module. The exterior of the module tubes is exposed to reduced pressure, and water evaporates from the tube surface and is condensed on a chilled porous plate surface in thermal contact with the cold junction surfaces of the thermoelectric heat exchanger.

The above mentioned water reclamation processes typically require pretreatment and post-treatment with expendable chemicals. A vapor-phase catalytic ammonia-removal process is under development which offers the potential advantage of avoiding these expendables /22/.

### Automated Control/Monitor Instrumentation (C/M I)

The ECLSS process hardware requires instrumentation to:

- Control and monitor the process functiuons;
- Provide safety for personnel and equipment including fault diagnostics and backup control functions;
- Operate the equipment in a manner that increases reliability and avoids need for maintenance or simplifies it if it is required; and
- Operate the equipment under optimized conditions which can, therefore, reduce power, weight, volume, etc.

NASA has developed two C/M I series as shown in Figure 12. The first series, known as the 100 Series, used a minicomputer for process control and monitor, and incorporated a simulated Space Station Command Center in the area of operator/system interfaces (visual, audio and touch). The second series, known as the 200 Series, used a microcomputer for process control and monitor, but replaced the simulated Command Center with a data link to a remote terminal. The 100 Series, on the left of Figure 12, is approximately 29x22x21 in, the 200 Series, on the right, is 7.4x15.6x15.4 in.

These computerized C/M I Series demonstrated the feasibility of a generic approach to Space Station System C/M I requirements including the ECLSS. The 100 Series was designed, for example, for operation with nine major subsystems. The 200 Series was designed for operation with 12 subsystems. The next generation, under development by NASA, will employ a generic microcomputer with generic software plus subsystem unique software, generic signal conditioning and dedicated actuator signal conditioning.

### Water Electrolysis — A Space Station Utility

The merits of a Space Station based on water electrolysis as a station utility was identified over ten years ago /4/. The objective is to achieve development commonality to reduce life cycle costs. The $O_2$, $H_2$ and water are common fluids for:

1. Electrochemical $CO_2$ removal (EDC),
2. $O_2$ generation for metabolic use and leakage makeup,
3. Potable water for crew consumption and evaporator cooling,
4. Energy storage through a regenerative fuel cell system, and
5. Clean attitude control propellants.

The integrated $O_2$, $H_2$ and water concept offers the future growth potential of providing in-flight generation of propellants for use by Orbital Transfer Vehicles as well as process reactants for special uses such as manufacturing process atmospheres. Figure 13

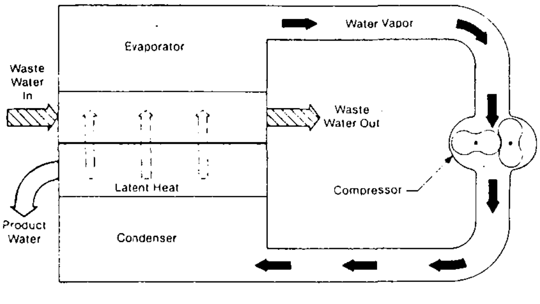


Fig. 9. Vapor Compression Distillation Concept

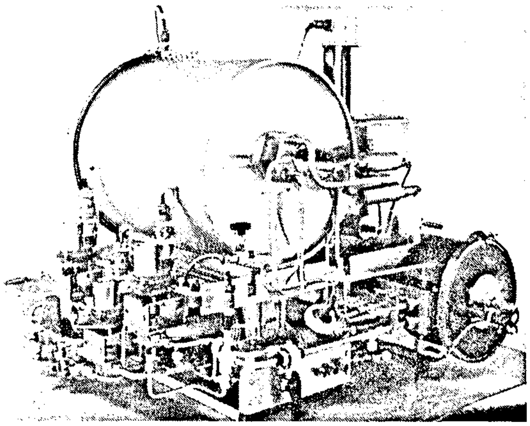


Fig. 10. Preprototype Vapor Compression Distillation Subsystem

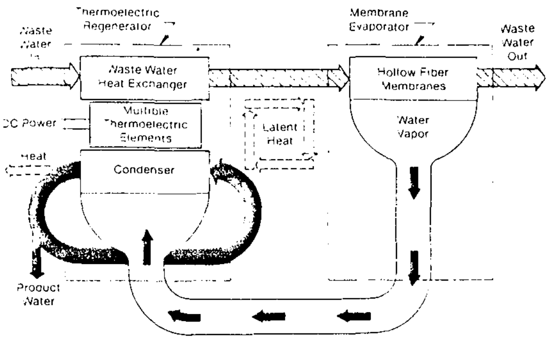


Fig. 11. Thermoelectric / Membrane Evaporator Concept

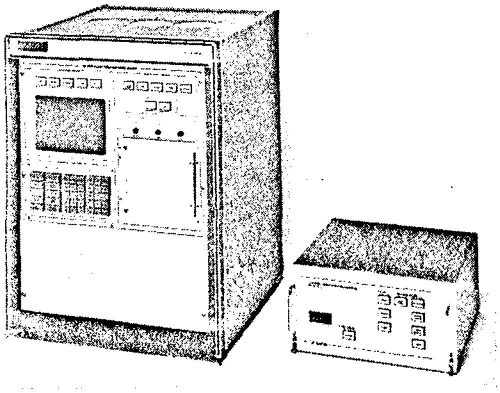


Fig. 12. Series 100 and 200 Computerized Control / Monitor Instrumentation

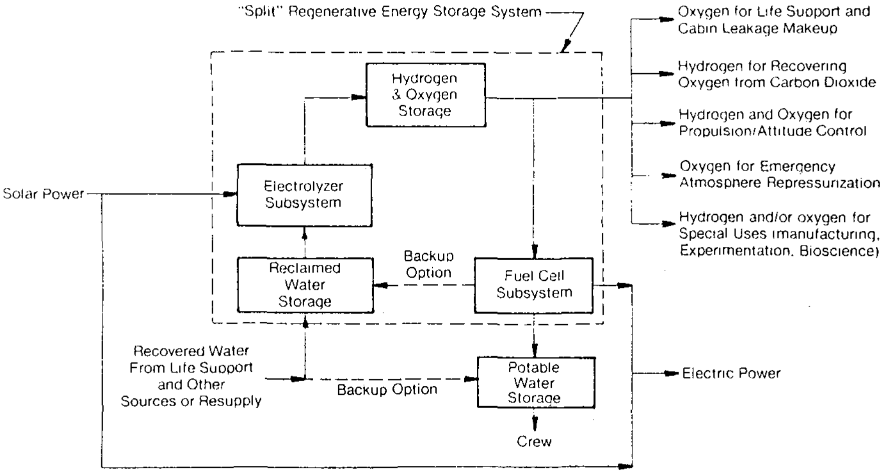
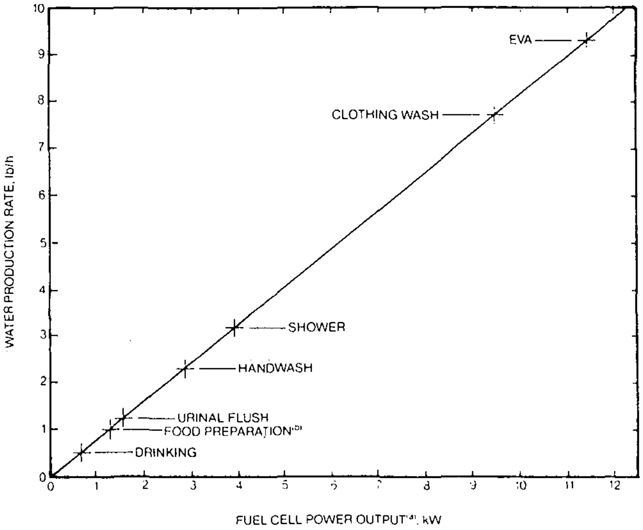


Fig. 13. Water Electrolysis — A Space Station Utility



(a) Based on Shuttle Orbiter Equivalent Fuel Cell Hardware operating at 0.91 V/cell, 200 ASF and 180F
(b) Cited use rates are cumulative and include all lower use rates

Fig. 14. Water Production and Use Rate for Four Persons Versus Fuel Cell Power Output

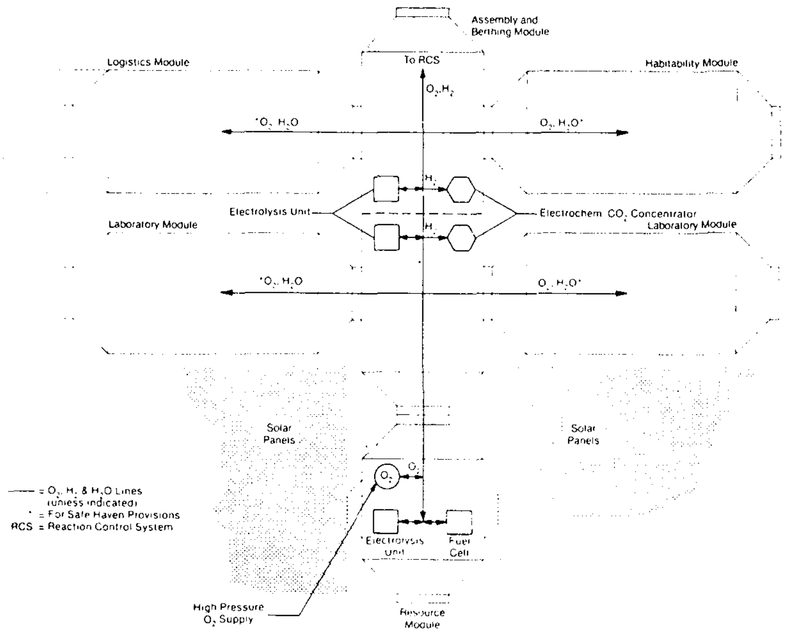


Fig. 15. Integrated $O_2$, $H_2$ and Water Distribution

illustrates the concepts. It shows the use of fuel cells for dark side operation and provides an added benefit in that the product water is a flight proven source of potable water for the crew. Reclaimed water is then used directly to provide makeup water for the electrolyzer, which is a possible when using the static feed (SFE) concept. Figure 14 relates water production and use rates versus fuel cell power output for a four-person ECLSS.

Figure 15 reflects the distribution of such an integrated $O_2$, $H_2$ and water distribution system aboard a pathfinding architecture for the Space Station.

## CONCLUSIONS

The need and requirements of a Space Station have been reviewed. The elements of an ECLSS have been cited including performance requirements, average design loads and fluid interfaces. Open versus closed loop approaches to ECLSS have been quantified. Specific regenerative ECLSS technology has been discussed with some comparisons madse between alternative approaches. The status of control and monitor instrumentation was indicated. The benefits of water electrolysis as a Space Station utility, which results in a Space Station based on an integrated $O_2$, $H_2$ and water for common fluids, was reviewed.

## ACKNOWLEDGEMENT

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# Atmosphere Behavior in Gas-Closed Mouse-Algal Systems: An Experimental and Modelling Study.

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## ABSTRACT

Concepts of biologically-based regenerative life support systems anticipate the use of photosynthetic organisms for air revitalization. However, mismatches in the rates of production and uptake of oxygen or carbon dioxide between the crew and the plants will lead to an accumulation or depletion of these gases beyond tolerable limits. One method for correcting these atmospheric changes is to use physicochemical devices. This would conflict with the constraint of minimal size and weight imposed upon the successful development of a competitive bioregenerative system. An alternate control strategy is based upon reducing the gas exchange mismatch by manipulation of those environmental parameters known to affect plant or algae gas exchange ratios. We have initiated a research program using a dual approach of mathematical modelling and laboratory experimentation aimed at examining the gas exchange characteristics of artificial animal/plant systems closed to the ambient atmosphere. Our goal is to develop control techniques and management strategies for maintaining the atmospheric levels of carbon dioxide and oxygen at physiological levels. A mathematical model simulating the atmospheric behavior in these systems has been developed and an experimental gas-closed system has been constructed. These will be described and preliminary results will be presented.

## INTRODUCTION

A Controlled Ecological Life Support System (CELSS) is one option for maintaining human life during extended space flight. A CELSS uses energy to recycle matter though an integrated variety of biological and physical processes, thereby regenerating consumable supplies. The primary alternative to recycling is storage and/or resupply wherein all consumable materials are brought on board and waste products are discarded. Between these two extremes, various hybrid systems are possible. Although more difficult to design, the CELSS alternative is under consideration because it is more cost effective than storage and resupply for long-term space missions /1,2/.

The NASA-sponsored CELSS program has as objectives investigating the feasibility of producing food and revitalizing atmospheres by growing plants and algae, and processing wastes by microbial or physical-chemical oxidation.

A CELSS can be envisioned as a rigorously controlled, materially closed system (or nearly so), recycling matter to provide a habitable atmosphere, a dependable supply of potable water, and a nutritionally balanced diet. Such a system would still fall short of its goal--to support human life--if it were not capable of being controlled and managed to provide these materials and functions at the proper time and at the proper rates. To meet these two criteria of material closure and controllability, research directed at the development of a CELSS may be divided into two areas: Closure of the Nutrient Loop, which seeks to establish mechanisms by which wastes can be recycled into usable forms, and System Control and Management, which examines the behavior of individual components, their interactions as a system, and how these behaviors can be integrated into a viable control strategy. The focus of this paper will be on the latter, the development of alternative control techniques and management strategies to stabilize the behavior of systems in which biological components are integrated with physical-chemical processes.

An example of a critical systems control problem in a bioregenerative life support system is the development of techniques regulating the rate of production and uptake of carbon dioxide and oxygen so that no changes in their atmospheric concentrations occur beyond allowable limits. This problem is complicated by the fact that the biological cycling of carbon dioxide and oxygen are coupled. Manipulating the rate of photosynthesis and/or respiration will change the rates of oxygen and carbon dioxide exchange simultaneously. Thus, attempting to balance the rate of oxygen exchange can disrupt the balance of carbon dioxide exchange and *vice versa*.

Ideally, in a simple animal-plant system, closed to the exchange of carbon dioxide and oxygen with the ambient external atmosphere, respiration by the animals should be equivalent to plant photosynthesis, thereby maintaining a fixed concentration of atmospheric oxygen and carbon dioxide. An equilibrium based upon the equivalence of photosynthesis and respiration is usually not possible, however, because the RQ (respiratory quotient--moles carbon dioxide produced/moles of oxygen consumed) of animals generally does not match the AQ (assimilatory quotient--moles of carbon dioxide consumed/moles of oxygen produced) of plants. The RQ of mammals is a function of their diet, and for humans has a mean value of about 0.85 /3/, whereas the AQ for plants has a mean value of about 0.95 /4/. Because of this mismatch, the atmospheric concentration of oxygen and carbon dioxide in a gas tight system containing only animals and plants will not be stable.

For example, in the gas-closed system illustrated in Figure 1, the mouse uses 1.0 volume of oxygen for each 0.85 volumes of carbon dioxide produced (RQ=0.85). The algae takes up 0.85 volumes of carbon dioxide and produces 0.89 volumes of oxygen (AQ=0.95). Thus, about 0.11 volumes of oxygen are lost from the atmosphere during each complete cycle. In gas-closed systems where AQ exceeds RQ the stability of the atmosphere will be disrupted by the continual loss of oxygen. In natural ecosystems, the concentration and relative stability of atmospheric oxygen and carbon dioxide is maintained by the buffering capacity of the atmosphere and the oceans. This buffering capacity is provided both by the enormous size of these compartments as well as certain chemical equilibria. For example, there are about 8300 cubic meters of ocean water and 1260 cubic meters of atmosphere for each square meter of land /5/. The atmospheric and water volumes enclosed in a reasonably sized CELSS however, will not be large enough to provide for the dilution or chemical transformation required to maintain a steady-state concentration of oxygen and carbon dioxide.

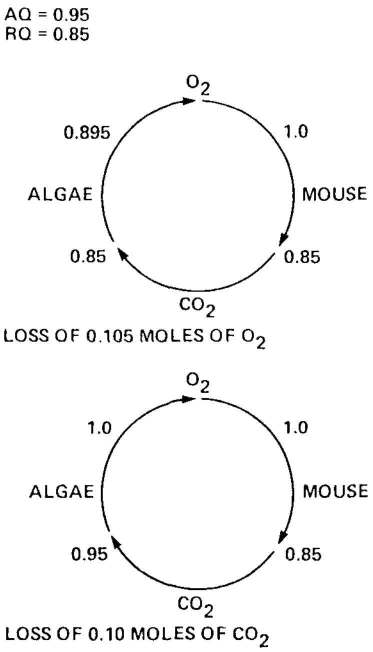

Fig. 1. Stoichiometry of gas exchange in a gas-closed, mouse-algal system in which either carbon dioxide exchange is balanced (top) or oxygen exchange is balanced (bottom).

Within a reasonably sized CELSS, attempting to compensate for this loss of oxygen solely by increasing the rate of respiration or decreasing the rate of photosynthesis may temporarily stabilize the concentration of carbon dioxide or oxygen, but this type of manipulation alone will not produce a stable atmosphere. This is because varying the rates of photosynthesis or respiration will not effect the value of AQ or RQ which are ratios.

Because of this RQ:AQ mismatch, the major premise of this study is that free-running animal/plant systems closed to exchange with external carbon dioxide and oxygen will have an unstable atmosphere /6,7/. This instability stems from two levels: rate instability caused by a mismatch between the rates of photosynthesis and respiration, and ratio instability caused by the mismatch of RQ and AQ. Manipulating the source of rate instability cannot bring about a stable atmospheric concentration of oxygen and carbon dioxide in a gas-closed animal-plant system because of ratio instability, but controlling ratio instability is a prerequisite for any strategy that seeks to limit the effects of rate instability.

## CONTROL STRATEGIES

NASA has, of course, successfully developed the technology required to maintain spacecraft atmospheres within the limits imposed by human well-being. These techniques, however, have been geared to short-term manned missions and, in general, rely upon large reservoirs of liquid oxygen and large stores of chemicals for carbon dioxide removal. These approaches to air revitilization are characterized by an increase in both weight and volume directly proportional to flight duration. For long-duration manned missions such "brute force" techniques must be replaced by more sophisticated methods, which will minimize the requirements for massive amounts of stored life-support supplies by utilizing appropriate regenerative processes, and effective system control and management techniques.

An alternate approach to atmosphere control is to minimize the RQ:AQ mismatch by manipulating those environmental parameters known to effect animal RQ e.g., diet, or, more realistically, known to effect photosynthetic AQ, e.g., the type and concentration of inorganic nitrogen species added to the algal medium. The research described herein is part of a program aimed at investigating the feasibility of stabilizing the atmosphere in a gas-closed, mouse-algal system by varying the algal AQ through environmental manipulation.

Control strategies fall into many categories. Chamber volume, algal biomass, light flux density, temperature of the algal culture, the concentration and species of nitrogen in the algal medium, are all variables that can prompt stabilizing system responses. Increasing chamber volume will modulate the effects of biological processes on the atmosphere. The amount of algal biomass determines the maximum chamber rate of carbon dioxide removal from the atmosphere. The photosynthetic rate shows a saturating response to light flux density and by manipulating this factor one can limit the rate of photosynthesis. The algae shows an optimum temperature for both photosynthesis and respiration, and by shifting the chamber temperature both above and below the intersection of these two curves one can limit these rates. Low nitrogen concentrations in the algal medium limit N uptake and subsequent protein synthesis. This shifts biosynthesis to either increased lipid production, which lowers the AQ, or increased carbohydrate synthesis, which can raise the AQ. At the extreme, nitrogen starvation can prevent carbon dioxide fixation and growth. Additionally, the use of nitrate as the nitrogen source lowers the AQ. By shifting from urea to nitrate one can bracket the RQ of the mouse with the AQ of the algae.

The strategy and techniques required to manage the system and the need to project the effects of present decisions on future operation of the system, has led to an approach emphasizing the parallel and complementary use of mathematical models and experimental systems. Computer simulations have been developed for each of the system components. The development and feasibility of possible experimental systems and control strategies will be evaluated based upon the linked operation of these models. As experimental systems are run, information will be extracted from the experimental systems and added to the models for future generations of systems and strategies.

## MODEL STRUCTURE

The major components of the model are the autotroph (alga) and heterotroph (mouse), their respective chambers, and their input and output storage pools (Fig. 2). Biomass is broken into three classes of molecules: carbohydrates, lipids, and proteins. The atmospheres of the chambers are described in terms of their $CO_2$, $O_2$, and water vapor content. Heterotroph inputs include drinking water and food storage. Output includes solid and liquid waste, followed as carbohydrate, lipid, protein, stool water, urea and waste water. The autotroph input and output storage include new and old medium and harvested algae.

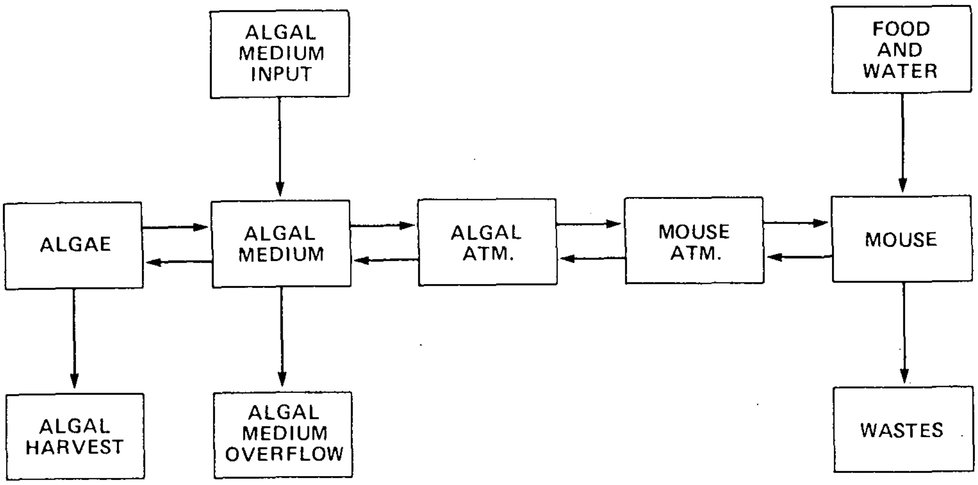

Fig. 2. Model structure of a gas-closed, mouse-algal system.

### The Autotroph

Presently, carbon dioxide fixation is described as function of carbon dioxide and oxygen concentration, temperature, light flux density, and chlorophyll concentration. In biosynthesis, the apportioning of fixed carbon to carbohydrates, lipids, and proteins determines the AQ. Algal respiration includes both maintenance respiration in darkness and light respiration. Growth is described in terms of packed cell volume, cell number, and chlorophyll content.

### The Heterotroph

The respiratory demand of the mouse is derived from a daily caloric input and output. The waste stream is a function of chamber environmental conditions and the daily caloric output. Daily caloric output is distributed to represent a range of metabolic rates. Respiration of reserves of carbohydrate, lipid, and protein provides the caloric requirements and creates oxygen demand. Differential oxidation of carbohydrates, lipids and proteins determines the rate at which carbon dioxide is evolved in respiration.

### The Physical System

Carbon dioxide, oxygen, and water vapor are exchanged between the two chambers at a rate determined by the air flow rate and their respective concentrations. Solid waste from the mouse is generated as a percentage of the food intake rate. The production of metabolic water in respiration modulates the output of waste water from food water and drinking water. Urea production is determined by rate at which proteins are respired. The algal chamber is maintained by a continuous culture system that can run in either a chemostat or turbidostat mode.

### Model Results

The model has been run to simulate the behavior of a gas-closed system containing a mouse alone or in the presence of algal cultures continuously grown under varying environmental conditions. Figure 3 depicts the behavior of the system when it contains only a mouse. As expected, the atmospheric level of carbon dioxide increase while the oxygen level decreases. The volume of the closed system is such that at approximately ten hours, the concentrations of these gases had exceeded acceptable levels and the system "died". If under the same conditions an algal culture, manifesting an AQ of 0.95 is added to the closed system, the mouse will survive for a longer period of time; approximately fifty hours. However, due to the mismatch of gas exchange quotients, there is a continual loss of oxygen from the atmosphere (Fig. 4). If the AQ is lowered to 0.80 the system will survive for more than 150 hours. However, the mismatch in quotients will cause a continual increase in oxygen concentration until it will eventually be above some allowable limit (Fig. 5 ). If the AQ is equivalent to the RQ the system will be stable.

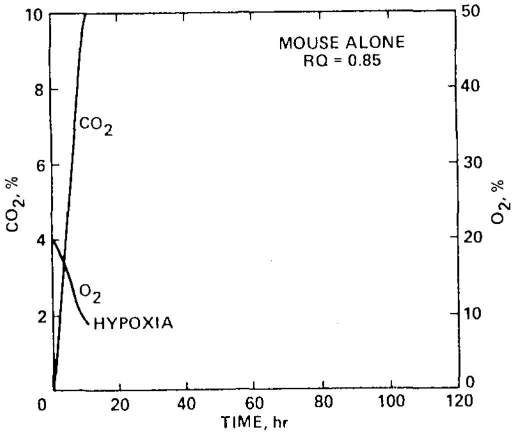

Fig. 3. Atmospheric behavior in a simulated gas-closed, mouse-algal system containing only a mouse, RQ=0.85.

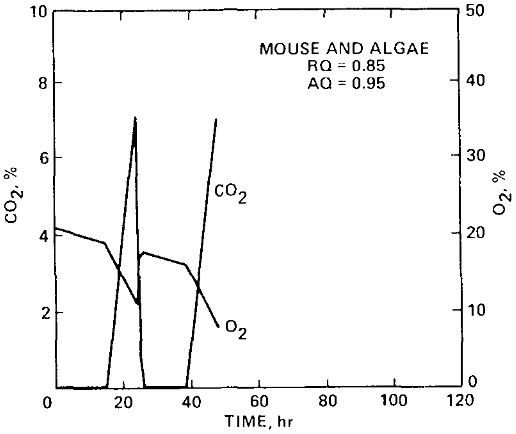

Fig. 4. Atmospheric behavior in a simulated gas-closed mouse-algal system containing a mouse, RQ=0.85, and an algal culture, AQ-0.95.

To attempt to maintain stability by the continuous matching of the gas exchange quotients would be extremely difficult. An alternate strategy. would be to bracket the mouse RQ by using several algal cultures, either simultaneously or in sequence, each culture manifesting an AQ either higher or lower than the mouse RQ. Increases or decreases in the oxygen concentration could be countered by increasing the growth of the appropriate culture. Growth on nitrate will lower the AQ and increase the atmospheric oxygen concentration, while growth on urea will raise the AQ and reduce the oxygen concentration.

continuous growth either as a chemostat or as a turbidostat. The chambers, either singly or together can be attached to a gas delivery and measurement system so constructed as to allow for operation either in a gas flow-through or gas-closed mode. The atmospheric concentrations of oxygen and carbon dioxide are determined by paramagnetic and infra-red analysis respectively. Tests of the algal reactor run as a chemostat indicate that, after initial transients, steady-state algal growth is achieved as measured by dry weight, turbidity and cell counts. Measurements of gas exchange by mice or algae are carried out by closing the system and determining the change of gas concentration in the closed chamber atmosphere. During the measurement period the kinetics of gas production or uptake are linear. Using this system we have obtained initial data on algal (Chlorella pyrenoidosa) assimilatory quotients as a function of nitrogen source and concentration. As well, mouse respiratory quotients under short-term resting conditions have been determined.

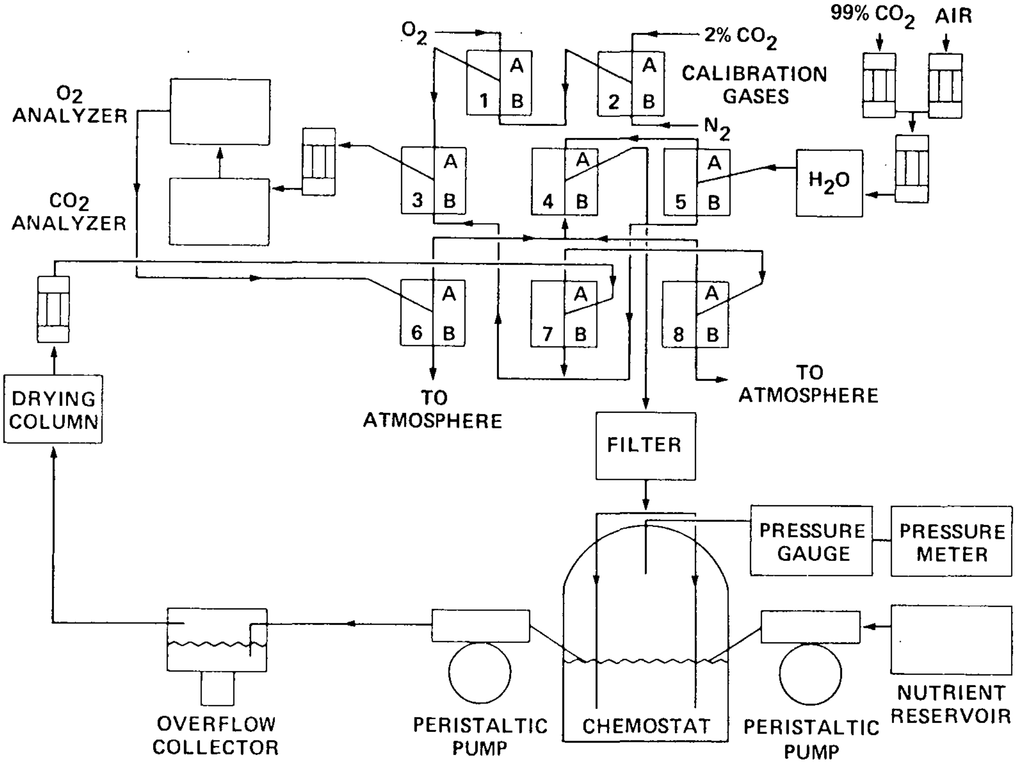

Fig. 7. Experimental apparatus for determining the atmospheric concentrations of carbon dioxide and oxygen in flow through and gas-closed systems.

The respiratory quotient of non-eating mice as measured in our system is 1.04 (SD=0.07) which agrees well with the expected value of 1.0. Assimilatory quotients measured during algal growth on nitrate and urea were qualitatively correct but were quantitatively lower than predicted.

Analysis of these data indicated that the AQ of the algal cultures might vary as a function of the cell concentration. Measurements of the AQ of steady-state algal cultures grown to different cell densities on urea and turbidometrically controlled were carried out. The expected AQ for Chlorella grown on urea is 0.82 /8/. The AQ's observed in our growth conditions were consistently lower than 0.82 and were a function of the optical density of the culture (Fig. 8). As algal cultures increase in optical density without any compensatory increase in illumination, the rate of photosynthesis will decrease due to shadowing effects. This decrease in photosynthetic rate is depicted in Figure 9. This figure depicts the carbon dioxide uptake rate and the oxygen production rate normalized by the optical density of the culture and plotted as a function of the optical density of the culture at which the measurement was made. As expected the normalized rates decrease as a function of the optical density of the cultures. The slopes of the curves, however, are different. This difference in slope will result in varying AQ's. Only at the intercept of the curves at the ordinate does the ratio of the curves appraoch that expected for urea (0.82). The basis for this effect of cell concentration on AQ is presently under investigation.

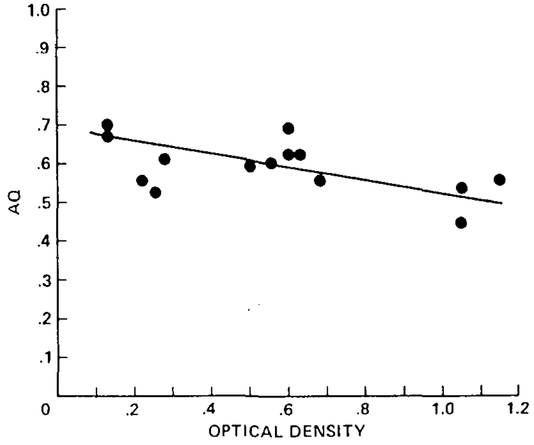

Fig. 8. AQ's of urea grown, steady-state cultures of Chlorella pyrenoidosa as a function of culture optical density.

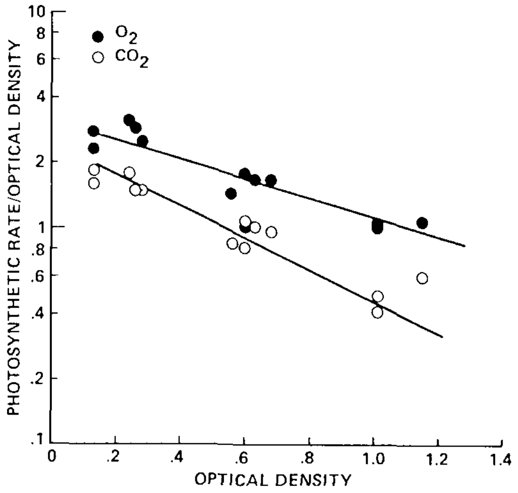

Fig. 9. AQ's of steady-state cultures of Chlorella pyrenoidosa, normalized by the optical density, as a function of optical density.

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# DYNAMIC CONSIDERATIONS FOR CONTROL
# OF CLOSED LIFE SUPPORT SYSTEMS

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## ABSTRACT

Reliability of closed life support systems will depend on their ability to continue supplying the crew's needs in the face of perturbations and equipment failures. These dynamic considerations interact with the basic static (equilibrium) design through the sizing of storages, the specification of excess capacities in processors, and the choice of system initial state (total mass in the system). This paper uses a very simple system flow model to examine the possibilities for system failures even when there is sufficient storage to buffer the immediate effects of the perturbation. Two control schemes are shown which have different dynamic consequences in response to component failures.

## INTRODUCTION

The usefulness of a Closed Environmental Life Support System (CELSS) depends critically on its mass and volume. The larger and heavier the system, the more costly it will be to move to its operating orbit. At a certain point it becomes more feasible to resupply or stock enough resources for the entire mission (Gustan and Vinopal, 1982). Therefore, the sizes of the CELSS' internal mass and storage tanks are critical to determining the role regenerative schemes will play in such missions.

Initial design studies for closed life-support systems concentrate on the equilibrium requirements for supporting the crew (Modell and Spurlock, 1979). These studies give some indication of mass and volume requirements by specifying the flows that will be necessary through various processors, and thus give some indication of the minimum unit size. However, the life support system must be capable of maintaining vital functions during temporary failures of some of its components. Extra storage must be provided, processors must have the capability of operating above (or below) their equilibrium flows, and total amounts of flowing masses in the system must be specified. This part of the design can only be done by considering the system's dynamic behavior as none of these parameters enter into the static equilibrium calculation.

An important consequence of finite size storage in a closed system is that if the storage is full, the flow that would be going into it will have to go somewhere else. It is our assumption in this work that such overflows will always have deleterious effects. The only way to guarantee that there will be no overflows is to make all storages large enough to contain all of the system's mass.

Through the use of a simplified, abstract model of a CELSS, we will show that the system's dynamics depend on the storage tank sizes and the internal mass of the system. There are many nonintuitive consequences that result from changing the size of various internal components. Further, the choice of control scheme is shown to have a dramatic effect on the dynamic behavior of the system after a component failure. Though there are no firm conclusions to be drawn from these experiments, the peculiar interaction of delays, mass location within the system, and the relative storage tank sizes should be noted. A true CELSS will have many more flow paths and internal loops and will probably have much more complex dynamic behavior than is shown in this simplified model.

## THE CELSS MODEL

A CELSS is usually viewed as having mass closure but an external supply of energy. It is possible to model such a system using conservation of mass equations that describe the storage tank behavior. Flows between tanks can be treated as controllable variables. Averner (1981) used this approach where the mass balance was performed on the elemental masses (H, O, N, etc.) in the system. Stahr, et al. (1982) developed a model where bulk masses (water, CO2, edible food, etc.) are followed through the system. We will use the latter approach in this paper, because it lends itself to examinations of storage tank size and system mass interaction.

To examine the dynamic interaction of internal system mass and storage tank sizes, the model of a CELSS shown in Figure 1 is used. This abstract model is a simplification of the true complexity of the system. It does, however, contain some essential components of a CELSS: i.e. constant mass, finite storage tank sizes, and limited processor capacities. We will be showing some of the dynamic interplay between these components.

To understand the model better, we examine its behavior at steady state. The crew consumes food at a rate of one unit/day (steady state) from food storage. With the food plants growing to maturity in 60 days, the 6 plant chambers produce a harvest every 10 days. This harvest must have an edible mass of 10 units for the system to stay at steady state. The harvest has both an edible and inedible component, which each comprise 50% of the harvest under normal conditions.

The inedible part of the harvest is placed in waste storage. As food is consumed, the crew's waste also goes into this tank. The waste is reoxidized in the waste processor and the resulting nutrients, water, etc., are placed in the plant chambers. To insure adequate growth for the steady state, this processor flow must be 2 units/day.

The food storage and waste storage have capacities. If a capacity is exceeded, the tank's output flow is increased. The waste processor also has a capacity. If the waste flow to the processor exceeds its capacity, some of the flow is bypassed. Clearly overflow conditions can occur given finite storage tanks and a component failure.

The flows in this model are mixtures of solids, gases and liquids. Thus, the "nutrient" flow refers to nutrients, water, CO2, and other material needed for plant growth. The "harvest" contains excess water, O2, edible and inedible plant matter, and other byproducts of plant growth. The proper mixing of the elements in the nutrient and harvest flows is assumed. Therefore, the plant growth depends only on the rate of the input stream.

Plants are grown in 6 chambers. Each chamber's plants are at a different stage of growth so there can be harvests at 10-day intervals. As a simplification, an independent supply of seeds is assumed for this model. The steady state plant growth is shown in Figure 2 (top). This curve follows the general behavior of plant growth (Salisbury and Ross, 1979). The plant mass reaches 10% of the harvest mass in the first 20 days from a nutrient flow of 0.1 units/day. The plant grows faster in the second 20 days reaching 45% of its total mass. During these 40 days no edible mass has grown. In the last 20 days, 90.9% of the growth is in edible mass. This results in a harvest that is 50% edible.

If the nutrient flow into the plant chamber is not at the steady state value two effects are seen (Incropera, 1975). First, the slopes, representing the total plant mass in Figure 2 (top), change as this is a representation of conservation of mass. Second, if this occurs during the last 20 days of the growth cycle (when the edible mass is grown), the percent of the nutrient flow that becomes edible mass is affected as shown in Figure 2 (center). The nutrient flow into the 6 chambers is always divided so as to do the least damage to the growing plants.

If the waste processor's capacity is exceeded, the bypass flow goes into the plant chambers (see Figure 1), according to this model. This waste overflow accumulates as "inert matter" in the plant chambers and does not contribute to the plants' growth. If there is inert matter in the plant chamber during the last 20 days (when the edible part of the plant is growing), its growth is inhibited (see Figure 2 bottom). The inert matter is removed from the plant chamber during harvest, and is sent to the waste storage with the inedible part of the harvest.

Figure 3 shows the system operating at steady state. Both the food and waste storage tanks have an extra supply that can maintain their respective outputs for 10 days. The harvest occurs at 10-day intervals. Each harvest (both edible and inedible) causes a vertical jump in the storage curves, and continuous output flows cause the smooth downward slopes.

## A 10-DAY PROCESSOR FAILURE

Dynamic interaction of system mass and storage sizes can be seen when we consider the case where the waste processor fails for 10 days, stopping the supply of water and nutrients to the plants. During this failure, from the fifth to the fifteenth day, the output of the waste storage is set to zero to avoid a bypass of the processor. From a static design viewpoint the steady state contains enough food and waste in their respective storages to ride out the 10-day processor failure. In this section we will examine the system's dynamic behavior during transients using a few combinations of system mass, storage size, and processor control.

The simplest action to take after the failure is to maintain the storage output flows at their steady state values. Figure 4 shows that the system returns to an equilibrium in 60 days. This is not the original steady state, however. The original food buffer of 10 units is gone and the waste buffer has increased from 20 units to 30. This transfer of mass leaves the system in a configuration that would be disastrous if another processor failure occurred.

In addition to moving away from the original steady state, two other dynamic effects occur that could not be predicted from a static design. First, although the waste storage had an adequate supply for the failure, for a period of 10 days the plants did not receive any nutrients or water. Considering that the plants did not die over this 10-day period, the reduced yield of the plants causes a 2-day period with no food in the food storage (i.e., no food to eat) on the 38th day, 13 days after the failure. Second, the waste storage needs a capacity of 50 units to absorb the transient without causing an overflow (see Figure 4, bottom).

## CONTROL OF PLANTING

To enable the system to return to its original steady state (10-day food and waste storage buffer), a means is needed to increase the edible yield. There are many ways to accomplish this. We consider first the case where each plant chamber is only 50% occupied by seeds, and therefore plants, when the system is operating at steady state. If the food storage is not at its desired level when a crop is harvested, the number of seeds planted at this time is adjusted to compensate. The system keeps track of the number of seeds in each chamber. Also, the flow of nutrients, water, etc., to each tank is scaled to the number of seeds so that the edible yield of each individual plant is 90.9% of its maximum. We assume that there is perfect knowledge of the plant behavior so this yield can be achieved reliably. If the waste storage is empty or overflowing this goal will not necessarily be achieved.

The seed planting control is shown in Figure 5 where the planting correction is proportional to the error between the actual and desired food storage levels. Hence, this control is called a proportional or P control.

Using the P control with a gain of 0.2 generates the results seen in Figure 6. The initial transient is the same as when no control action was taken (see Figure 4). However, at the 70th day extra seeds are planted because of the low food storage level. Subsequent adjustments in the number of seeds planted return the system to the original steady state by approximately day 250. The 2 days without food about the 38th day are not avoided.

The system behavior can be drastically altered by changing the control gain. Figure 7 shows the consequences of raising the gain to 1. The initial transient is unchanged. At the 70th day extra seeds are planted and this correction continues for a few planting periods. As these plants grow they require a high flow of nutrients, reducing the level of the waste storage. When this crop is harvested, the food storage level climbs, resulting in fewer seeds planted. When, in turn, they are harvested, there is not enough food for a few harvests in a row. This pattern repeats about every 200 days without ever diminishing. This is all due to a processor failure for 10 days and a control gain set at 1.

## THE EFFECT OF STORAGE SIZE

We repeat the last example, but now introduce a waste storage tank size of 50 units (Figure 8). This is large enough to absorb the initial transient. However, at day 190, the waste storage is full and the output flow must be increased to avoid an overflow. During this time the plants are exposed to nutrient flows above their steady state. The waste processor has a capacity of 5 units/day and this value is exceeded for a short time causing a bypass of the processor. These two effects, excess flow of nutrients, water, etc., and the bypass of unprocessed waste, reduce the edible yield of the growing plants. Harvests then contain little or no edible food for a period of 65 days. This oscillation continues without dissipating. In this example the food storage level never exceeds 38 units (see Figure 8, center), and hence, we can consider that the food storage has any capacity above this level. For convenience we will use 40 for this capacity.

In the next example (Figure 9) the food storage capacity is reduced to 20 and the waste storage capacity is increased to 70. Hence, the total capacity of the system storage is unchanged from the previous example. Now the system returns to its original steady state by the 160th day. This result is due to the smaller food storage capacity stabilizing the system. It redistributes the system mass back to its steady state value. While the systems in Figures 8 and 9 have the same total capacity, their different dynamic behavior results from the placement of the excess capacity. Hence, small storages are not always detrimental to the system behavior. The location of the small storage can be more critical than its size.

## CONTROL OF GROWTH

We now consider an alternative scheme for controlling the edible harvest, and hence, the food storage level. In each chamber are planted a constant number of seeds producing the maximum number of plants the chamber will hold. At steady state (Figure 3) the flow from the waste storage is only enough to achieve half the total edible yield. In other words, the plant chambers are full but the plants are only growing at 50% of their maximum rate. The control structure remains the same as shown in Figure 5, but now the "nutrient" flow to plants is adjusted instead of seed numbers. We call this a "growth control" scheme to distinguish it from the "seed planting control" described previously. The equilibrium level of the waste storage is increased because this new control policy requires 3 units/day of waste output. This new level is in accordance with the static design for a 10-day processor failure.

Figure 10 shows the system behavior caused by a waste processor failure from the fifth day to the fifteenth day. The proportional gain of the growth control is set to 1 and the system recovers to the original steady state in 200 days. There are a few short periods with no food during the transient. Once again, recovery depends on the storage tanks having enough excess capacity to absorb the transients.

In comparing Figure 10 with Figure 7 it can be seen that the growth control with a gain of 1 is more useful than the seed planting control with a gain of 1. First, notice that the two proportional gains are not equivalent. The growth control always gives larger harvests under the same constant disturbance. Although larger gains were shown to give erratic behavior using the seed planting control, the growth control, with its higher effective gain, gives improved system stability.

This apparent contradiction is resolved when the dynamics of the control and system interaction are examined. The seed planting control can only affect a part of the system that will not show up in the food storage for 60 days. On the other hand, the growth control affects all 6 plant chambers, so its results are seen in 10 days. The controller can then make further adjustments to the plants as they are growing. Delays, such as those between the control measurement and action, have a critical effect on the system behavior.

In Figure 11 the effect of waste storage capacity is shown. The waste storage capacity is set to 50 units and the growth control still has a gain of 1. Although the capacity is only exceeded for 6 days at day 20, the system has no food for more than 100 days. And although the system recovers to the steady state by day 380 (one year after the disturbance), such transient behavior is not likely to be survivable.

As a final example of dynamic interaction within the system, the waste storage capacity is raised to 70 units and the food storage buffer is reduced by 10 units. Now the system has less mass in it than in the previous 2 examples. Here the system is not able to return to a steady state but there are no long periods without food (see Figure 12). The reduction of mass in the system did not result in obvious disaster.

## DISCUSSION

Simplified, abstract models of CELSS show complex dynamic behavior. The system must have excess capacity to absorb transients caused by component failure. Also, the amount and location of this excess capacity can critically affect the system performance. Excess internal mass is used during transients and the level and location of these buffers has been found to have a nonintuitive relation to the survivability of the system.

Following a component failure the system needs to return mass back to its original configuration. This can only be accomplished by altering the flows from the steady state values through a control policy. The dynamic interaction of the control with the system can introduce unusual results.

In this paper we have assumed that the effects of input flows on the plants are understood. In this way the controller can reliably improve the edible yield when this is required by the control algorithm. In practice this may not be achievable without sophisticated monitoring of each plant as it is growing (i.e., state estimation). Also, the consequences of each plant behaving individually within the chamber has not been examined.

Finally, with this model we have only considered a single "loop". A more realistic CELSS contains one loop with the atmospheric gases, another with the food and solids, and another with the water and liquids. The dynamic interaction of these loops may introduce system behavior that is more peculiar than the examples shown in this paper.

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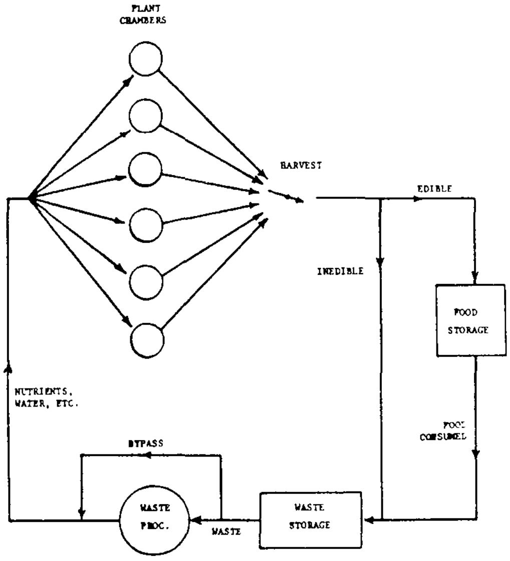

Figure 1: A CELSS Model

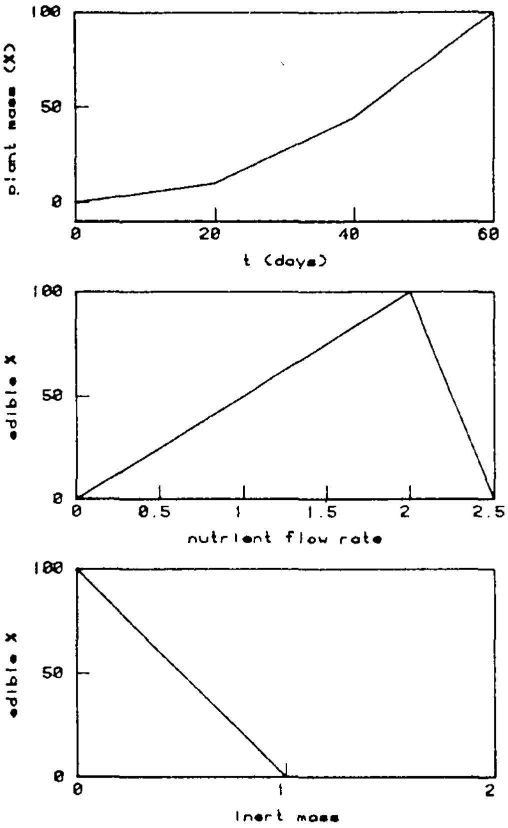

Figure 2: Plant Growth

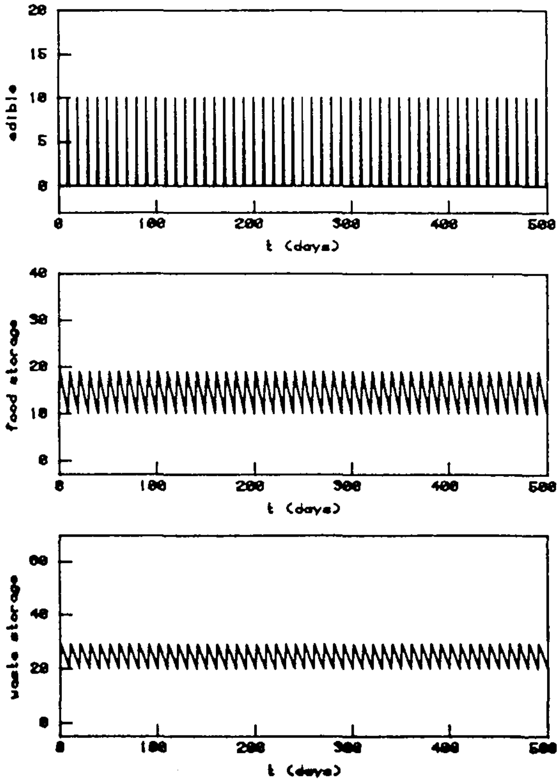

Figure 3: Steady State

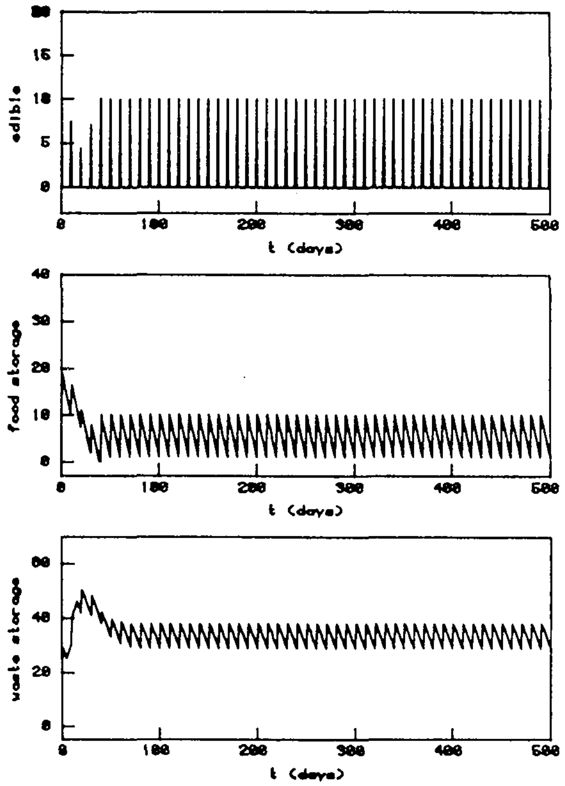

Figure 4: Failure Response - Steady State Flows

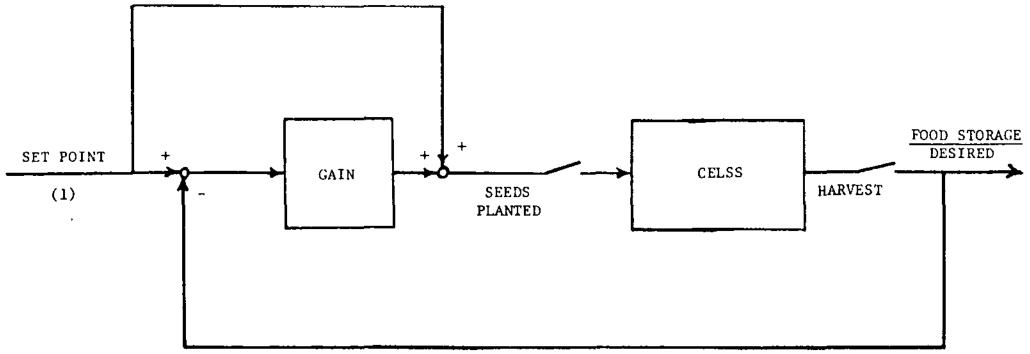

Figure 5: CELSS With Seed Planting Control

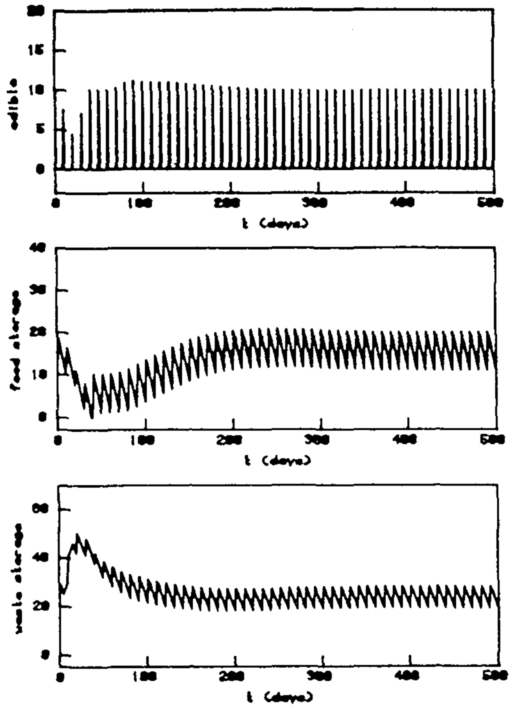

Figure 6: Planting Control - Gain = 0.2

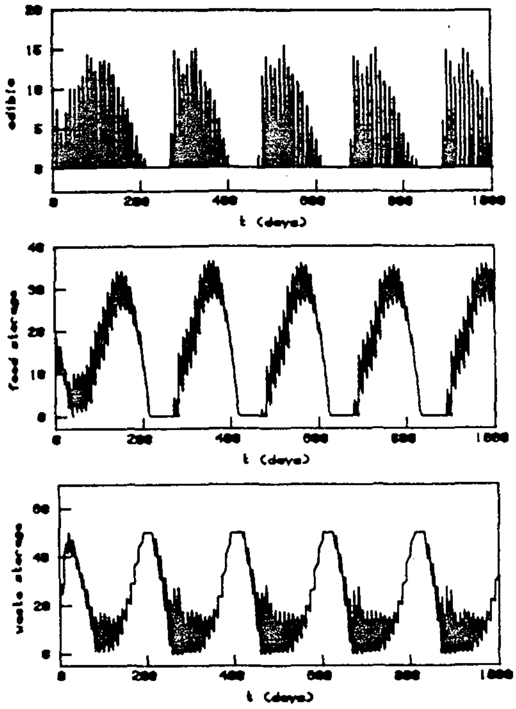

Figure 8: Waste Storage Capacity = 50
*Planting Control - Gain = 1*

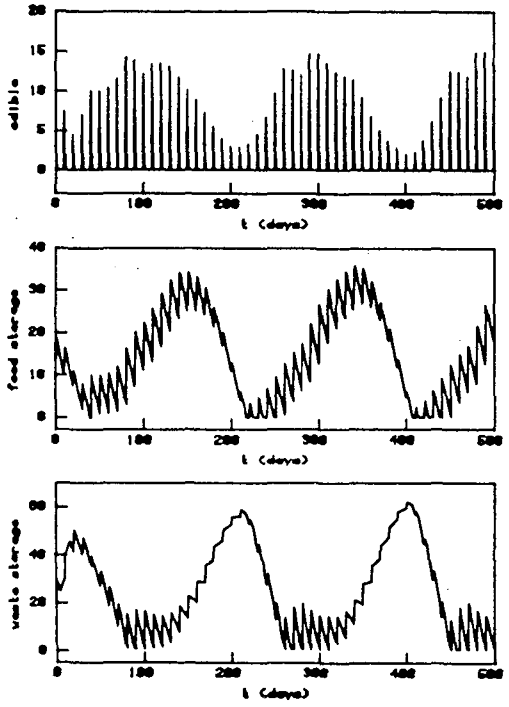

Figure 7: Planting Control - Gain = 1

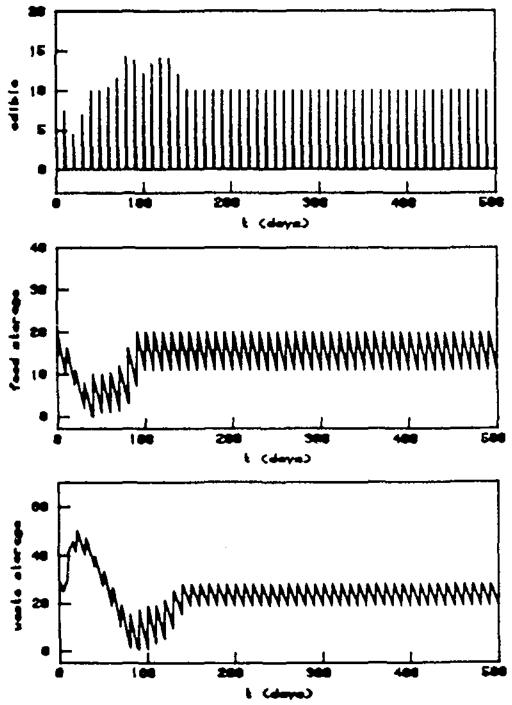

Figure 9: Food Storage Capacity = 20
Planting Control - Gain = 1

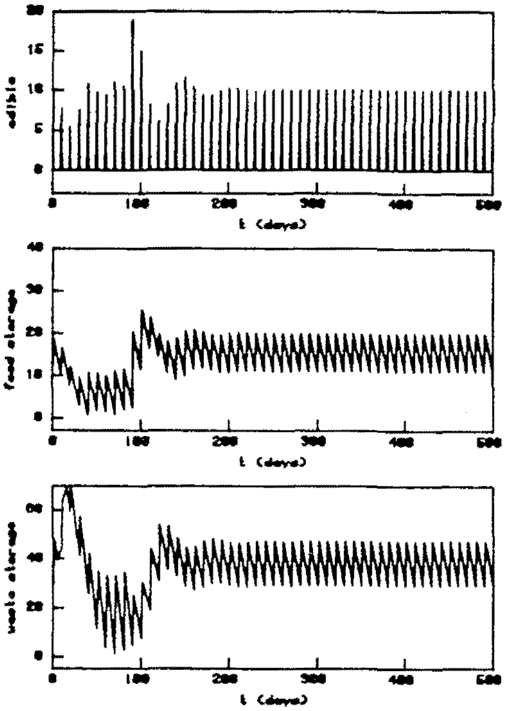

Figure 10: Growth Control - Gain = 1

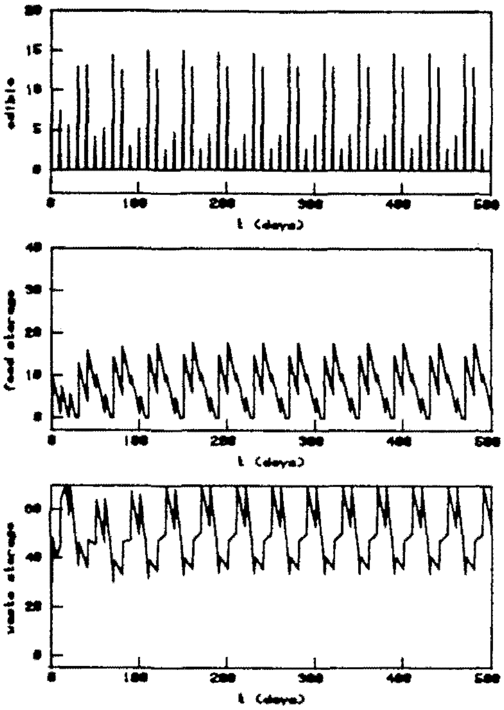

Figure 12: Food Buffer = 0
Growth Control - Gain = 1

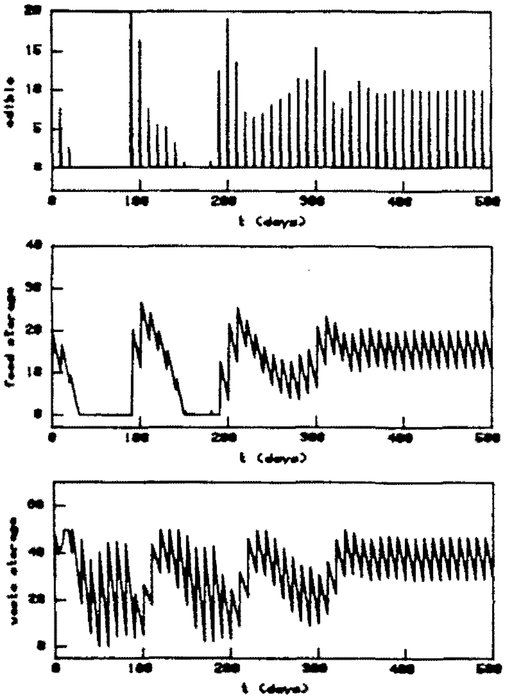

Figure 11: Waste Storage Capacity = 50
Growth Control - Gain = 1

# CELSS TRANSPORTATION ANALYSIS

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## ABSTRACT

Regenerative life support systems based on the use of biological material have been considered for inclusion in manned spacecraft since the early days of the United States space program. These biological life support systems are currently being developed by NASA in the Controlled Ecological Life Support System (CELSS) program. Because of the progress being achieved in the CELSS program, it is time to determine which space missions may profit from use of the developing technology. This paper presents the results of a study that was conducted to estimate where potential transportation cost savings could be anticipated by using CELSS technology for selected future manned space missions.

Six representative missions were selected for study from those included in NASA planning studies. The selected missions ranged from a low Earth orbit mission to those associated with asteroids and a Mars sortie. The crew sizes considered varied from four persons to five thousand. Other study parameters included mission duration and life support closure percentages, with the latter ranging from complete resupply of consumable life support materials to 97% closure of the life support system. The paper presents the analytical study approach and describes the missions and systems considered, together with the benefits derived from CELSS when applicable.

## INTRODUCTION

Man's basic requirements for oxygen, water, food, and waste removal must be met by the spacecraft life support system to sustain life and provide an acceptable environment for productive crew activity. To date, these basic requirements have been met on space missions by simply storing the necessary consumable materials on board for use during the mission and returning the waste products to Earth. This "open" life support technique has served well for the relatively short missions that have been flown. As manned missions become longer and crew size increases, the weight, volume, and transportation penalties associated with storing or routinely resupplying consumables will eventually become prohibitively expensive /1/2/3/. This paper reports the results of a study to determine for specific missions when consideration should be given to replacing open life support systems with "closed" systems that recycle metabolic materials.

For over two decades, NASA and its contractors have studied techniques for closing spacecraft environments by using regenerative life support technology. This effort has resulted in an extensive data base for both physical-chemical and biological regenerative systems. The physical-chemical technology has reached a point where a number of prototype subsystems are being tested. The biologically based systems have not reached the same level of advancement; however, the Controlled Ecological Life Support System (CELSS) program is making significant progress toward producing a closed life support system based on biological technology. The CELSS program is primarily directed toward biological systems for food production and environmental control mechanisms /4/5/6/.

The objectives of this study were to identify future NASA missions that will require CELSS technology and to develop cost estimates and comparisons for using controlled ecological life support systems based on selected mission model analyses. The study focused on six manned missions selected from NASA planning forecasts, compared various life support scenarios and transportation systems, and made cost evaluations.

## APPROACH AND ASSUMPTIONS

The study was conducted in two separate phases: (1) a space transportation system analysis and (2) a characterization of the environmental control and life support system (EC/LSS). The results of these two phases were combined in the final step of the study to provide the mission cost estimates.

Six missions were selected for study during the transportation analysis. Several EC/LSS's were investigated for estimates of weight, volume, and power requirements. These systems were used in developing life support closure scenarios that, when combined with the transportation analysis, provide mission life support cost estimates.

Certain assumptions and ground rules were required to accomplish the study because in some cases, extensive extrapolations from the current data base were necessary. The assumptions and ground rules follow:

a. Advanced transportation technology projections were used, in conjunction with the specific mission location and mission era, to determine the corresponding costs.

b. Development costs for transportation systems or EC/LSS's were not considered.

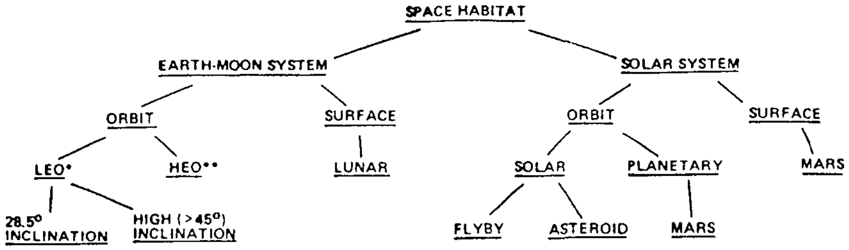
c. Full payload manifesting on transportation vehicles was used to determine cost as opposed to providing fractional credits for partial loads. This is similar to airline industry practices whereby individual tickets cost the same regardless of the number of passengers or amount of cargo on each flight.

d. The current data base was used when available to determine EC/LSS and CELSS mass, volume, and power requirements; otherwise, engineering estimates were made.

e. EC/LSS consumables attributed to vehicle leakage and extravehicular activity were not considered.

## MISSION DEFINITION

The missions selected for study were taken from information provided in NASA long-range planning documentation and from discussions with Air Force Space Division personnel. Potential locations for CELSS-equipped habitats were identified based on the projected missions. Figure 1 shows the locations that were considered.



* LEO = LOW EARTH ORBIT <1000 KM

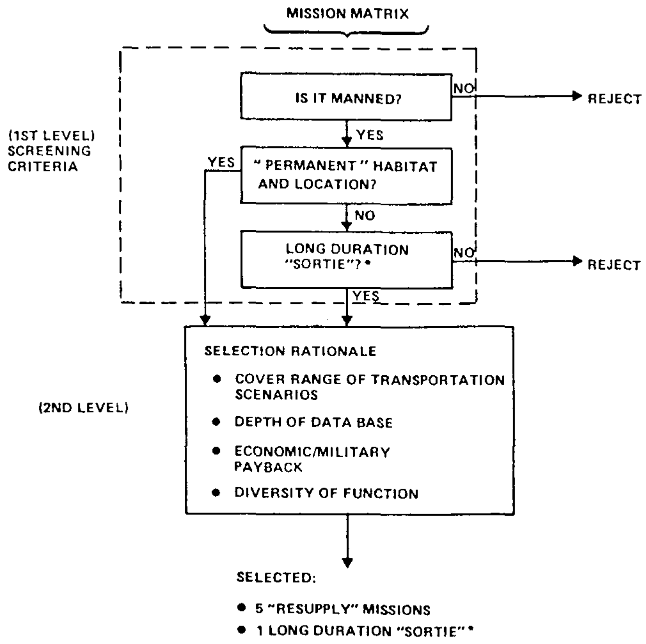
** HEO = HIGH EARTH ORBIT >6000 KM

Fig. 1. Potential habitat locations

The two-step screening process used to select the missions for study is shown in Figure 2. This screening method was used to reduce approximately 34 candidate missions to the final 6 that were analyzed. The selected missions included the five resupply missions and the one sortie mission listed in Figure 3, along with the crew size range, crew rotation period, and resupply periods used in the analysis of each mission.

## PHASE I TRANSPORTATION ANALYSIS

The transportation analysis was conducted in two parts: a trajectory analysis to determine the route of travel and a vehicle analysis to determine the rocket or combination of rockets



* A "SORTIE" IS DEFINED HERE AS AN IMPERMANENT MISSION FOR WHICH IT IS IMPRACTICAL TO RESUPPLY, SUCH AS A PLANETARY FLYBY

Fig. 2. Mission selection schematic

| MISSION | CREW SIZE RANGE | CREW ROTATION PERIOD | RESUPPLY PERIOD |
|---|---|---|---|
| | | DAYS | DAYS |
| OPERATIONS CENTER | 4 - 12 | 90 | 90 |
| MONITORING BASE | 4 | 90 | 90 |
| COMMAND POST | 4 - 24 | 180 | 180 |
| LUNAR BASE | 12 - 48 | 180 | 90 |
| ASTEROID MISSION | 5000 | 1856 | 928 |
| MARS SORTIE | 8 | 944 | NONE |

Fig. 3. Crew size and rotation

needed to efficiently accomplish the mission. The trajectory analysis was accomplished using the standard orbital mechanics relationships, which determine time line and velocity change data. The vehicle analysis was performed using the vehicle data base compiled by Boeing, which includes inputs on mission trajectory data, mission-technology era, and approximate payload mass estimates. The results of these studies determined the optimum vehicle types required, their size, and estimated cost per kg to transport payloads from Earth to the respective space base.

## LEO-Low Inclination

The low Earth orbit (LEO) operations center is located at a circular Earth orbit altitude of 370 km with an inclination of 28.5 deg. The center is serviced directly by the shuttle orbiter from an eastern test range (Kennedy Space Center) launch. In 1990, an unmodified shuttle launched to the operations center can carry approximately 65,000 lb (29,480 kg).

The operations center orbits the Earth beneath the Van Allen belts to minimize solar array degradation and radiation shielding requirements. However, the power system is quite massive due to the fact that one-third of the 90-min orbit period is in darkness requiring storage batteries for power.

### LEO-High Inclination

The monitoring station mission is very much like the LEO operations base, in that it can be directly serviced by the shuttle orbiter. The station is located in low Earth orbit at an altitude of 450 km and a sun-synchronous inclination of 97.5 deg. Because of the high orbit inclination, this mission requires a launch from the western test range at Vandenburg AFB, California. The higher altitude requires that some of the orbiter payload bay area is used for fuel tanks, which are needed to extend the shuttle range. The high inclination and altitude of the station lowers the payload capacity of the shuttle to 40,000 lb (18,144 kg). The high inclination of the orbit might expose the station to a greater amount of solar proton flux, although it was determined that no additional shielding was required to protect station personnel. The sun-synchronous orbit of this station ensures that the solar arrays will be in continuous sunlight; therefore, batteries for energy storage are not required.

### 6 X GEO

The 6 X GEO command post is not directly accessible by the shuttle orbiter; therefore, payloads must first be brought to a LEO operations base by a shuttle orbiter. Once at the base, the payload is mated to an orbital transfer vehicle (OTV) that flies to and from the command post. The mission sequence is straightforward: a single revolution in phasing orbit establishes the correct longitude for moving into the command post orbit, followed by propulsion into transfer orbit and coast to altitude. Circularization and plane change is followed by rendezvous with the command post. After the transfer operations are completed at the command post, the manned OTV executes a plane change burn and moves into the transfer ellipse. The braking ballute (a special inflatable balloon stored on the front of the vehicle) is inflated several minutes before perigee passage through the Earth's upper atmosphere. The ballute provides controlled aerodynamic drag to decelerate the vehicle for moving into phasing orbit. The ballute is jettisoned at the apogee of the phasing orbit, followed by propulsion of the OTV into a 160-nmi orbit for rendezvous and recovery by the orbiter. The high-Earth-orbit location causes the solar array to be exposed to sunlight at all times; no energy storage system is necessary. However, the increased orbit altitude places the station above the Van Allen belts and exposes it to direct proton flux radiation. This severe radiation environment causes greater array degradation and increased module shielding weights.

### Lunar Base

The lunar base mission requires three types of transportation vehicles: (1) a shuttle orbiter to raise payload from the Earth to an LEO operations center, (2) an OTV that takes payloads from LEO to lunar orbit and back, and (3) a lunar transfer vehicle (LTV) that ferries payloads from lunar orbit to the lunar surface.

The shuttle orbiter must bring the payload to an operations center where it is mated to an OTV. The OTV then propels the payload, the resupply module, into lunar orbit. After circularizing in low lunar orbit, the manned OTV module rendezvous with an LTV that was launched from the lunar surface into orbit. Crew, supplies, and propellant for the LTV are exchanged in orbit, after which the LTV descends to the lunar surface base. The manned OTV executes a plane change burn and moves into the transfer orbit where it will coast until ballute deployment and LEO aerobrake maneuver. The long lunar night precludes the use of a solar array for energy production. A SPAR-type nuclear reactor was determined to be the most mass efficient energy producing system for this mission. Both the nuclear reactor and the manned habitats use lunar soil for shielding.

### Asteroid Base

The asteroid mission assumes an asteroid mining operation with a 5000 person habitat. The complex transportation scenario for this advanced mission involves four different vehicles and three separate space bases. Payload and propellant are launched from the Earth's surface by a heavy lift launch vehicle to a LEO staging base (operations center). The LEO base serves as a staging area for all personnel, cargo, and propellant enroute to the final fusion rocket assembly area in geosynchronous orbit. At the LEO base, the cargo and propellant are loaded onto a solar electric powered transfer vehicle. The personnel and any priority cargo are transported on an enlarged version of an aerobraked OTV for a faster trip to the GEO assembly base.

The GEO base serves as the final assembly area for the large fusion rocket system used to propel payloads out to the asteroids. The complex fusion propulsion system is assembled at the GEO base with the fusion power core, propellant tanks, large thermal radiators, and the personnel and priority cargo modules. The resulting vehicle, can transport 1250 passengers and 150 metric tons of priority cargo to the asteroids. The habitat power is derived from solar arrays that assume 1990 technology. In this case, the power mass factor is necessarily conservative, as projecting solar cell performance 70 years into the future is speculative at best.

### Mars Surface Exploration

The Mars sortie spacecraft is first assembled at a LEO base from individual modules brought up by the shuttle orbiter. The Mars mission vehicle consists of one stage for Mars transfer orbit injection, one stage for Earth transfer orbit injection, an enroute habitation module, and a Mars landing and ascent vehicle. Additionally, when the vehicle intercepts Mars it must be configured for aerobraking maneuvers (such as disposable nosecone and correct lift-drag) in order to dump excess velocity. The returning Earth-intercept module must also carry an aerobraking ballute. The Mars mission was included as the most realistic long-duration sortie. The technology for this mission is available today. Mission design involves two power systems: a solar array for the transit and orbiting period of the mission, and a small nuclear reactor for Mars surface exploration using Martian soil for the reactor radiation shielding.

## PHASE II LIFE SUPPORT SYSTEMS CHARACTERIZATION

The life support systems characterization was based on estimating the total mass of equipment and system elements required to supply man's needs by using either an open or closed system or some combination of the two. When a system is open, the basic elements are storage containers and resupply. When a system is closed, recycling equipment must be provided in lieu of the resupply process. Trade studies were conducted based on the total weight of each type of system to determine the optimum combinations of supplying materials. Total weight was determined by the sum of the weight of the following elements: (1) required materials such as water, oxygen, food; (2) appropriate storage containers; (3) recycling equipment; (4) pressure vessel to house the elements, based on a weight penalty of the volume occupied by the system elements; and (5) the resupply module, based on the volume of material to be resupplied. Power requirements were also determined for each system type. Figure 4 shows the logic flow used to derive the weight, volume, and power estimates.

The following paragraphs summarize the data that were derived for the water, air, waste, and food systems considered in the study. Weight, volume, and power were estimated for open and recycle conditions for each system. For the food system, three food growing scenarios (i.e. food growth comprising 3%, 50%, and 97% of the total diets) in addition to the 100% food resupply scenario, were considered and are shown in Figure 5.

A four-man crew segment was used as a basic module size for developing the weight, volume, and power estimates. The rationale for the four-man module baseline selection follows:

a. It fits the range identified in the mission crew size analysis with the exception of the asteroid mission, which was handled separately.
b. It provides a generic baseline for mass, volume, and power estimates.
c. It eliminates the necessity for a detailed EC/LSS design for each mission and closure scenario, which was outside the scope of this study.
d. It is the module size on which the most current data base for the physical-chemical systems is based (Space Operations Center).

### Closure Scenarios

Seven closure scenarios were selected to enable the comparison of an entirely open system with various physical-chemical system closures and the comparison of a closed physical-chemical system with three food-growing scenarios. Figure 6 defines these seven closure scenarios using codes A through G assigned to each case respectively. The initial total mass, resupply mass, and power requirements are also summarized for each closure scenario.

Plant growth systems provide advantages in addition to supplying fresh food. The water that passes through plants in the transpiration process is purified. This phenomenon can be used

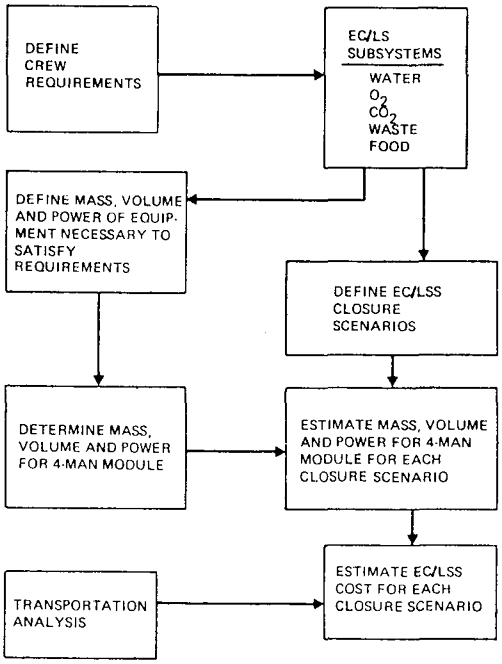


Fig. 4. Approach to life support systems characterization

| PLANT SPECIES (% OF DIET) | | |
|---|---|---|
| 3% | 50% | 97% |
| LETTUCE | DRY BEANS | SOYBEAN |
| TOMATO | PEANUTS | POTATO |
| CARROT | CABBAGE | MUSTARD GREENS |
| | CARROT | PEANUTS |
| | TOMATO | RICE |
| | POTATO | PEA POD |
| | GREEN BEANS | SPLIT PEA |
| | LETTUCE | CORN |
| | MELONS | KALE |
| | PEAS | DRY BEANS |
| | WHEAT | WHEAT |
| | | TURNIP GREENS |
| | | CHICKPEA |
| | | OATS |
| | | BROCCOLI |

Fig. 5. Plant species for projected diets

to advantage if water purification equipment can be reduced in the total system. This study assumed that no water purification equipment would be necessary if the daily water requirement for the crew could be met by the growing plants. It was further assumed that waste products removed from the water by the plants during transpiration are later removed from the inedible plant material during waste processing. The other important advantage offered by plant systems is the removal of carbon dioxide and the generation of oxygen by the plants. Again, this is an advantage to the total system based on estimated quantities of $CO_2$ removed and $O_2$ generated.

When credits for water and oxygen generation and carbon dioxide removal are applied to the total system characterizations, the weight, volume, and power system requirements are affected. For the 3% plant growth scenario, the percentage credits are 19% for water, 6% for oxygen, and 5% for $CO_2$. Because percentages in this case are relatively low, no credit was given the 3% scenarios. In the case of growing 50% of the required food, the water requirement is clearly met with 180% and the oxygen and carbon dioxide credits are approximately 50%. Credits given for the 97% food growth scenario were assumed to be 100% for all three materials, even though the $CO_2$ removal was shown to be only 85% of the requirement. It was assumed that 100% $CO_2$ removal could be easily achieved by adjusting the plant species in the diet. The number derived for $CO_2$ removal in this study was averaged from several plant species; numbers for individual species vary widely.

Other factors to be considered in estimating the total closure scenario weights are (1) a pressure vessel module to house the equipment in the space environment and (2) a resupply module to provide protection for transporting supplies. To determine a first-order estimate of the weight of these modules, a density factor of module weight-to-volume was applied. The density factors for both modules were derived from Space Operations Center (SOC) data /7/. The habitat module from the SOC study was used as a baseline to estimate the housing module for CELSS equipment. The SOC resupply module was used as the baseline for transporting CELSS resupply materials. The derived weight-to-volume factor of 44.0 kg/$m^3$ was used for the CELSS module and 27.8 kg/$m^3$ was used for the resupply module.

Mission and Scenario Comparisons

The total mass and power estimates developed for each of the closure scenarios, shown in Figure 6, were used to generate two sets of comparisons. The first set compares the mass data for the open system, closure scenario A, with each of the physical-chemical system closures, scenarios B, C, and D. The second set compares the closed physical-chemical system, D, with each of the food closure scenarios, E, F, and G. These two sets of comparisons are based strictly on the mass and power estimates that were developed for each of the closure scenarios and do not include any transportation considerations. The transportation analysis is used in combination with the closure mass estimates to derive potential cost savings that can be available by closing the food system. The mass comparisons for each closure scenario must be worked separately for each mission because the factors for converting power to mass and the radiation shielding factors are different for each mission.

| Closure Scenario | Initial Total Mass, kg | 90-Day Resupply Mass, kg | Nominal Power, Watts |
|---|---|---|---|
| A - Open | 17,895 | 13,552 | 1,140 |
| B - $H_2O$ Closed | 5,814 | 2,102 | 1,907 |
| C - Air Closed | 16,216 | 12,523 | 5,399 |
| D - $H_2O$ and Air Closed | 4,135 | 1,069 | 6,166 |
| E - 3% Diet | 5,785 | 1,064 | 7,762 |
| F - 50% Diet | 15,389 | 549 | 17,445 |
| G - 97% Diet | 27,002 | 237 | 26,740 |

**Fig. 6. Summary of mass and power estimates for closure scenarios (4-man module, 90-day resupply)**

In the comparisons that follow, closure scenario E (3% food closure, salad plants) is not considered. Due to the small amount of oxygen generated and carbon dioxide removed by these plants, the physical-chemical systems must be used to the full extent to satisfy the requirements; therefore, no savings would be realized. Scenario E could provide psychological advantages but it is not considered significant from a life support system viewpoint.

LEO-low inclination mission. For this mission the power penalty factor is 113 kg/kW and includes the weight of the solar array and batteries necessary for power in the near Earth orbit. Radiation shielding is not required for this mission because the orbit is below the Van Allen radiation belt and the pressure vessel wall of the module provides adequate protection.

The curves drawn in Figure 7 show the weight and cost advantages of closing the physical-chemical systems. All closures show an immediate advantage over the open system, although the combined water and air systems closure provide the greatest savings. The physical-chemical system closure comparisons follow this pattern for other missions as well. Because of the tremendous weight saving from closing the water and air systems, it does not appear reasonable to consider open water and air systems for long-term missions, especially those beyond the Earth-Moon system. For these reasons, the other five mission comparisons for physical-chemical systems are not reported.

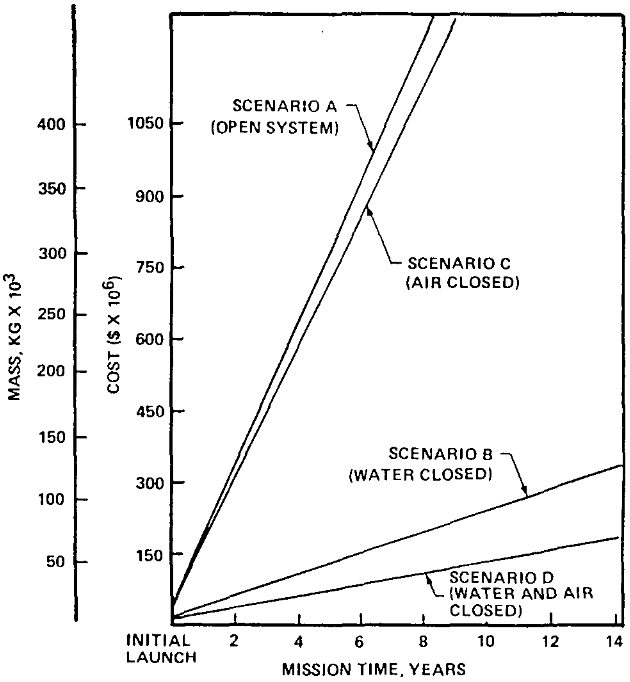


Fig. 7. Mass and cost comparison of physical-chemical systems mission: LEO—low inclination

Mass estimate data used for comparing food system closures, scenarios F and G, with the closed physical-chemical system, scenario D, were used to draw the curves in Figure 8. The mass penalties for power and radiation shielding are the same as discussed previously for this mission. Breakeven times for the LEO-low inclination mission are shown at the intersecting points of the curves for scenarios F and G with the curve of scenario D. Breakeven times for the mission are approximately 5.9 and 7.5 years for closure scenarios F and G respectively. These numbers indicate that at least some growing plants could be beneficial, especially if mission life is 10 or more years.

Comparing the cumulative cost data for the first 6 years of operation, the physical-chemical scenario D is the least expensive system. If station life is expected to be between 6 and 10 years, scenario F, which is the 50% food closure, is the minimum cost system. For an expected station life greater than 10 years, 97% CELSS closure is the most cost-effective system. After 15 years of operation, a 97% CELSS closure would save approximately 68 million dollars when compared with a physical-chemical system—or almost one-half of the cumulative transportation cost of the system.

Comparisons similar to these just described for the LEO-low inclination orbit were made for each of the remaining five missions selected for study. The results of these cost comparisons are shown in Figure 9. These data show that significant potential cost savings may be achieved in five of the missions by using a CELSS. The Mars sortie mission was the only mission that did not show a benefit by using a CELSS over a 15 year period. A complete derivation of results is presented in the study final report /8/.

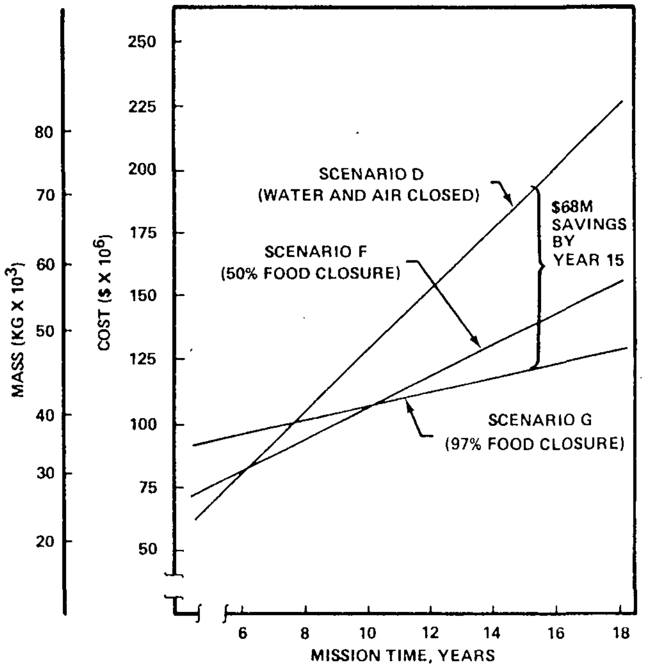


Fig. 8. Cumulative mass and cost savings with CELSS mission: LEO—low inclination

| MISSIONS | BREAKEVEN TIME YEARS * | | DOLLAR SAVINGS AT 15 YEARS |
|---|---|---|---|
| | 50% CELSS DIET (F) | 97% CELSS DIET (G) | |
| LEO - LOW INCLINATION | 5.9 | 7.5 | 68M |
| LEO - HIGH INCLINATION | 5.6 | 7.1 | 260M |
| 6 X GEO | 10.5 | 12.9 | 30M |
| LUNAR BASE | 5.7 | 7.2 | 455M |
| ASTEROID | 1 | 1.8 | 25.5B |
| MARS SURFACE | N/A | N/A | -0- |

* NOTE: COMPARED TO CLOSURE SCENARIO D (WATER AND AIR CLOSED)

Fig. 9. Mission breakeven time and cost savings summary

While a great deal of development work will be required to develop operational, reliable CELSS hardware, large benefits can be achieved. The analysis shows that small manned space stations in the Earth-Moon system can derive significant benefits from CELSS while large manned bases beyond the Earth-Moon system will require CELSS technology if these bases are to be established.

## ACKNOWLEDGEMENT

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16. Abstract

This report consists of seven papers presented at the XXVth COSPAR Conference in Graz, Austria, during July 1984. The papers (1) discuss fundamental concepts of bioregenerative life support, (2) review Japanese concepts of BLS and associated biological experiments to be conducted in the Space Station, (3) review a German industry's concepts of BLS, (4) discuss technology related to physical-chemical regenerative life support, (5) present data on the operation of an experimental algal-mouse life-support system, (6) discuss the problems of controlling a BLS system, and (7) project the breakdown points for various life-support techniques for several conceived space missions.

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