\ \ \ \ 14

METHODS FOR THE DEVELOPMENT OF A BIOREGENERATIVE LIFE SUPPORT SYSTEM

N91-18127

UNIVERSITY OF COLORADO

INTRODUCTION

This paper is the result of a phase zero design project conducted for NASA Ames Research Center. Its goal is to establish the basis for the development of bioregenerative life support systems. This was accomplished through the specification of a comprehensive methodology that follows the process from basic research through implementation. However, before getting into the specifics of the methodology developed, a few points in understanding the driving forces of the space program being considered by NASA are necessary.

As an agency, NASA is designed to promote and embrace the fields of aerospace sciences and technologies. NASA does this by advocating and soliciting public support for its many programs. One aspect of this promotion involves outreach programs to educate students. The space program is full of imaginative possibilities that stimulate many students who may one day become scientists or engineers. Other people become advocates through sharing in NASA's achievements and the resulting national pride. Some of the most effective supporters are of course the myriad researchers, scientists, and astronauts who have performed the experiments that make up a large portion of the space program. These have added greatly to the nation's understanding of space, as well as our home planet, Earth.

Currently, NASA is undertaking the new task of the Space Exploration Initiative. This is a bold program to expand humankind's presence in space as well as to increase understanding of this unique environment. Since astronauts will be subject to this environment, it is hoped that many lessons will be learned about the way humans adapt and behave. Such fields as human physiology and psychology may be greatly enhanced. Away from Earth, the unique environment also enables specialized manufacturing for precision materials and pharmaceuticals. Applications of these technologies may then be used by industry and people on Earth, thus the benefits from the research and development in space are brought back home.

LIFE SUPPORT HISTORY

With the benefits of a manned space program in mind, the requirement to provide adequate life support measures becomes evident. Initially, manned space program efforts were concentrated on putting the first astronauts in space as quickly as possible. Consequently, the life support systems that were developed were little more than storage systems designed to supply astronauts with the minimum of air, food, and water that, once used, would be discarded or stored for return to Earth, but not reused. For the early missions of short duration this approach was successful; yet as mission length increased, sending expendable supplies proved to be expensive. Some efforts were made to remove carbon dioxide from the cabin atmosphere with lithium-hydroxide "scrubbers." While this did not recycle carbon dioxide back into oxygen, it did extend mission duration capabilities.

Surprisingly, the technology now used on the shuttle has changed little from its predecessors on the Apollo missions. A simple projection of future requirements for a mission such as a 1000-day expedition to Mars with a crew of 10, shows that the mass of expendable supplies alone would be more that 100 metric tons. A way to resolve this problem is to utilize systems that recycle or reuse all or part of their mass.

PHYSICOCHEMICAL VS. BIOREGENERATIVE SYSTEMS

There are two basic approaches that can be taken to develop such systems: physicochemical and bioregenerative. The first of these is a system that uses physical or chemical methods to perform a particular life support task. The latter is a system that integrates physical and chemical methods to perform multiple life support tasks. In order to better understand these two approaches, we should examine their basic characteristics (see Fig. 1).

Physicochemical systems are in general more widely understood than their bioregenerative counterparts. The reason for this lies partly in the fact that most physicochemical devices are serial processors. These devices perform simple

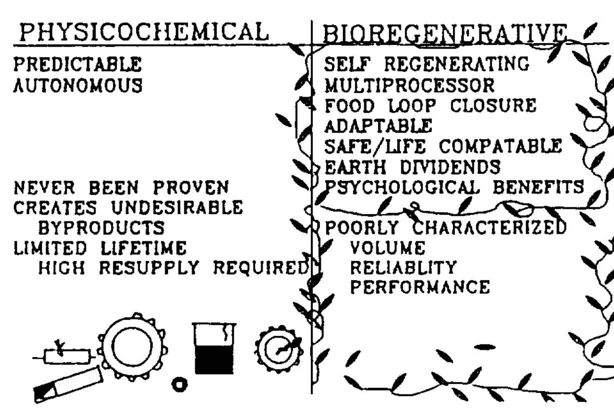

Fig. 1. Basic Characteristics

PRECEDING PAGE BLANK NOT FILMED

PAGE 40 INTENTIONALLY BLANK

operations that are highly predictable and maintain constant performance characteristics. These systems are also relatively autonomous in that they do not necessarily rely on other systems to continue operation. However, this should not be interpreted to mean that physicochemical systems are either completely understood or better suited to space applications.

In fact, no closed physicochemical system has ever been proven on Earth or in space. Nor are all the characteristics of such a system desirable. Several components of proposed systems produce hazardous byproducts. Furthermore, because of the manmade nature of the components, repair and replacement of parts is inevitable.

Unfortunately, bioregenerative systems have been poorly understood by the engineering community. Much of the reason for this lies in the multi- or parallel-processor characteristics of living organisms. Additionally, organisms do not have constant, predictable performance characteristics; rather, they operate within a range of performance characteristics that may differ between individuals, as well as between organisms.

Interestingly enough, it is this very characteristic of wide ranges of performance that makes biological systems ideal for use in life support activities. Furthermore, as the term bioregenerative suggests, the system is always rebuilding itself. In effect, new processors are continuously available, thus minimizing the need for repair and spare parts.

Having selected a mostly bioregenerative system, one of the major characteristics to take advantage of is the similarity of the system to the system that supports life on Earth. Earth has supported life in a robust manner for millennia and the problems that are significant in the environment today might prove to be either disastrous or no more than a "hiccup" in the long term. One way of understanding these problems is the development of an independent and closely monitored model of the Earth's system. This model could be in the form of the bioregenerative system proposed.

CHARACTERIZATION

The main problem in understanding and developing bioregenerative systems is that there exists no standard, systematic way of dealing with them. At first glance, biological systems appear to be too complicated and ambiguous to be of any practical value within a standard engineering system, let alone something as crucial as a life support system. Upon closer inspection, it becomes clear that, with some initial simplifications, it is quite possible to control and manage these systems. As a starting point, it is possible to circumvent the inherent complexities of biological systems by introducing the concept of the "black box."

With this approach, any organism can be treated as a black box. As a black box, the contents and processes that occur within the organism cannot be determined through direct observation. Thus, the only way to characterize the contents of this box is through the description of the box's inputs and outputs. By characterizing only the inputs and outputs of an organism, the extremely difficult process of describing the various biological functions that occur within is avoided. As with any simplification, some degree of detail will be lost depending on the magnitude of the simplification. Besides losing information on the internal processes of the organism, we also lose detail on the temporal aspects of the organism. It will be shown later that the information lost is either integrated at a later time or can be considered to be essentially unimportant when dealt with from a systems standpoint.

To describe the inputs and outputs, an initial breakdown into the three major categories of gases, liquids, and solids is made. This breakdown is used because, with the exception of energy inputs, it is able to handle all the input/output requirements of biological systems. It should be noted that, due to multiple inputs and outputs, this "black box" organism is not simply a serial processor but a highly integrated parallel processor.

To provide further detail the general categories of gases, liquids, and solids are each given more specific subdivisions. Gases may be broken into oxygen, carbon dioxide, and nitrogen, liquids into tissue water (water contained within the organism at time of harvest) and excreted water. Solids may be subdivided into carbohydrates, proteins, fats, nitrogen compounds, and others (vitamins, minerals, etc.). While these subdivisions were sufficient for the characterization of our organisms, other subdivisions may be required for more "exotic" organisms. The characterization of certain types of bacteria, for instance, may require the addition of a hydrocarbon input/output category.

This box can also be examined from the three different levels of a function, a process, and an operation (see Fig. 2). A function deals entirely with the nontemporal aspects of the inputs and outputs. The functional view of an organism is that, given certain inputs, the organism will produce certain outputs, without respect to time. A process, on the other hand, concerns itself with the fact that inputs and outputs occur over a timespan that is dependent upon the organism in question. Finally, the operation component takes into account the power, mass, and volume requirements that are necessary to support each organism.

There are two basic categories of organisms that can be used in the development of a bioregenerative system: plants and animals. Plants can be classified by a few general character-

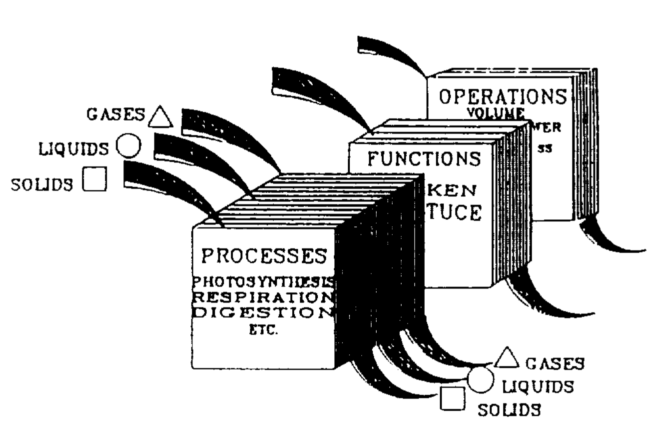

Fig. 2. Biological Characterization of Input/Output

istics: they consume carbon dioxide, water, protein, fat, and nitrogen compounds while producing oxygen and carbohydrates. Animals consume oxygen and carbohydrates while producing carbon dioxide, water, protein, fats, and nitrogen compounds. In addition, while plants store energy in a useful chemical form, animals convert chemical stores back into free energy. As a result, it can be seen that plant and animal systems are complementary when viewed from this production/consumption standpoint. The fact that plants and animals complement each other suggests the possibility of finding a correct balance of organisms whose characteristics allow for system closure.

There are three major steps required to accurately characterize the inputs and outputs of biological systems. The first, of course, is researching the appropriate sources for information concerning the inputs and outputs of these organisms. This is by no means trivial. After having gathered all relevant data, the second step is to consolidate and transfer it into a form that is both easily understood and readily applied. The next step is data comparisons that evaluate data for accuracy and establish relationships between organisms.

It is now possible to choose organisms for integration into the bioregenerative system. How much accurate data are available on each organism is primarily considered. Organisms that tend to have the most accurate and extensive amounts of information are used in agriculture and aquaculture. These organisms seem the most likely to be used in a life support system as they have been tried and tested for thousands of years. For this system, the following organisms were chosen: catfish, chickens, eggs, wheat, lettuce, potatoes, algae, bacteria, and man.

When trying to characterize the inputs and outputs of biological systems, it becomes apparent that many of the data are either inconsistent, incompatible, and/or incomplete for use in engineering. Almost all data available are based on organisms in open, 1-*g* systems. It is difficult to find data on inputs or outputs that are not easy to track. Exact rates of excretion and gas consumption need to be determined. For instance, how much water does a fish drink? Obviously extensive research, cross-referencing and hands-on experimentation is required. With this done, it becomes necessary to put all relevant data into a common metric.

There are a vast number of possible metrics that could be used to compare inputs and outputs (and hence find a system balance) but very few are of a form that can be readily understood and applied. After consideration of several possible metrics, it was decided to put all data into a mass (kg) format. Thus all data (water and feed consumption, carbon dioxide output through respiration, water output through transpiration, etc.) are converted to a mass value. With all inputs and outputs for each organism expressed in this common metric, it is possible to begin direct comparisons between organisms.

EVALUATION

Even though all the different inputs and outputs for each organism are defined with the same metric, it is still difficult to perform a direct comparison and evaluation between organisms. Data on organism A may state that 124 kg of mass

ELEMENTS	INPUT%	OUTPUT%	DIFFERENCE%
GASES:			
O_2:			
CO_2:			
N_2:			
CO:			
hydrocarbons:			
LIQUIDS:			
H_2O (tissue):			
H_2O (external):			
SOLIDS:			
carbohydrates			
protein:			
fat:			
fixed N compounds:			
other:			
TOTAL	100%	100%	0

(100% is equal to 1 kg)

Fig. 3. Data Sheet

is input and output over the lifetime of that organism. At the same time, data for organism B may state that the input/output mass is 30 kg over the course of its lifetime. Thus, it is necessary to normalize all data to its simplest form: 1 kg into the system and 1 kg out of the system.

In conjunction with the normalization of data into standard input/output units, a standardized data sheet was developed (see Fig. 3). This sheet defines the relative amount of inputs and outputs of an organism and defines them as a percentage of total output. By comparing inputs and outputs in this form it is possible to track elements the organism has a tendency to produce in surplus and those that it tends to consume or create a deficit. This data sheet allows consistent, comprehensive characterization of the inputs and outputs for any organism.

Checks on the validity and accuracy of the data must be performed. A fundamental concept in the validation of these functions is the conservation of mass. All mass going in must be accounted for in the mass output.

After having defined each organism's inputs and outputs, the organism can be treated simply as a set of transfer functions (see Fig. 4). A certain mass is input and the resulting output

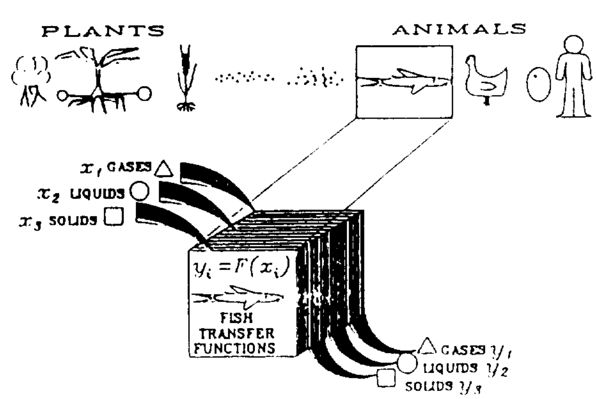

Fig. 4. Transfer Functions

of the substance is determined by the organism transfer function. Thus every biological system within the CELSS can be interpreted as a prepackaged set of transfer functions. Now these organisms can be handled using well understood control systems methods rather than from less understood (for the average engineer) biological approaches.

INTEGRATION

Now that any organism can be treated as a transfer function, it is possible to integrate multiple organisms into a closed system. Integration refers to the use of an organism's outputs as the inputs for any number of other organisms and thus input requirements can be balanced with output production.

As an example we will consider two ideal organisms in a closed system, the first of which (organism A) has a characteristic pattern of inputs and outputs given by its transfer functions. If we take a second organism (organism B) that is entirely complementary in terms of its inputs and outputs to organism A, it becomes possible to match inputs to outputs between the organisms and achieve a mass balance. If organism B has three times the amount of inputs and outputs (in kg) as compared to organism A, a mass balance can be achieved by creating a system composed of three organism As and a single organism B.

Since the organisms being dealt with are not ideal, it is nearly a given that after matching inputs and outputs, there will be some amount of mass left over (surplus) or still required (deficit), without which a perfect balance will not be attainable.

For our system, the nine previously mentioned organisms were integrated with a spreadsheet program (see Fig. 5). By summing the amounts of production (+) and consumption (-) of any single element across all nine organisms, it is possible to determine whether there is an overall surplus or deficit of this element. After determining the total surplus or deficit of each element, the absolute values of each of these quantities are summed to find a total system error or mass mismatch.

Although it appears that the mass mismatch within each element would cause a complete system failure, in actuality, this is not the case. Manmade physical systems are designed with singular, discrete performance characteristics. A car has a specific minimum turning radius, a plane has a maximum rate of climb, and a microwave oven requires a specific energy input. Both the inputs and outputs of these physical systems are specific, essentially nonvarying values, and a mismatch of inputs or outputs to these physical systems is unacceptable.

Biological systems, on the other hand, have a range of performance characteristics. Through training, an individual can improve his or her performance in a specific activity (time to run the 40-yard dash, for instance) by a significant percentage. As another example, nutritional inputs to a person can be varied through a remarkable range with little or no serious effects. Thus, for biological systems, mass mismatch does not render the system unfeasible because of its adaptability or range of performance characteristics. Biological organisms have an innate flexibility and robust quality that is normally not found in physical systems; hence, biological systems have their own inherent "safety net" that is different

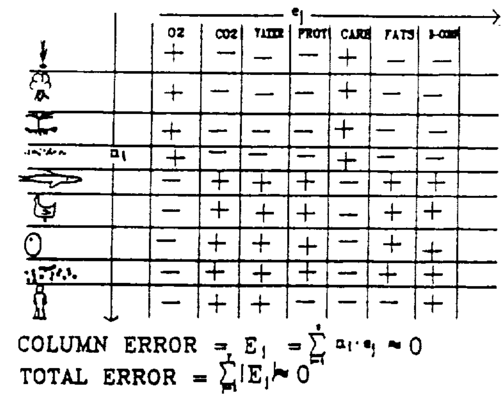

Fig. 5. System Mass Balance

from physicochemical systems (see Fig. 6). Through inherent control mechanisms and ranges of performance organisms are effectively self-regulating. If the carbon dioxide input into a plant is slightly reduced, for instance, the plant does not die but merely adapts to the new condition. It may not grow as quickly or as large, but it will live. Thus the attributes that make organisms difficult to work with (range of performance characteristics, etc.) are the same attributes that make biological systems worthwhile.

PROCESS DESCRIPTION

Any process takes place over time. This is certainly true for organic "devices" such as a plant or animal. For example, the time to maturity for lettuce is 30 days. Wheat and potatoes take 80 days. Single-celled organisms such as algae and bacteria have very short doubling times of 4 hours and 2 days, respectively. Animals, however, have longer times; chickens take 120 days and catfish, 180. Eggs, a special case in that they are produced by another organism, are laid daily (see Fig. 7).

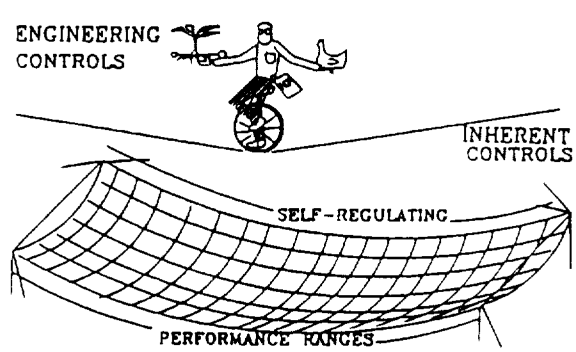

Fig. 6. Safety Net

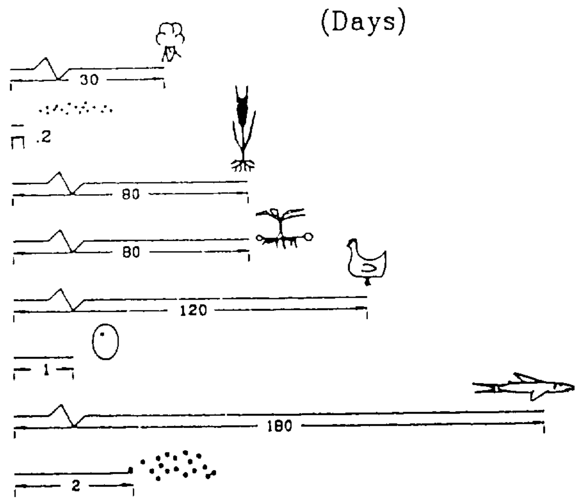

Fig. 7. Time to Maturity, Days

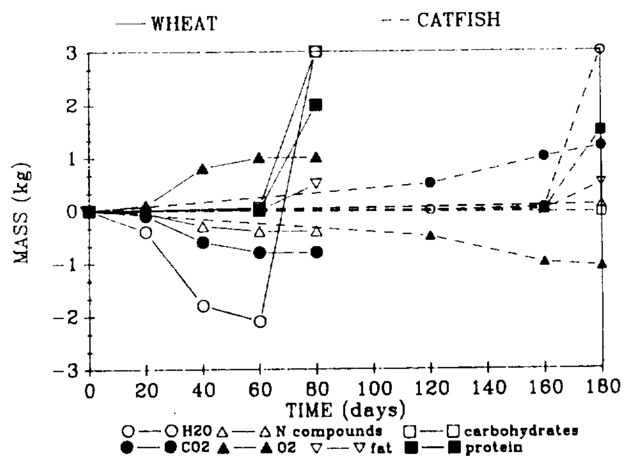

Fig. 8. Performance Curves for Wheat and Catfish: Surplus and Deficit of Throughput Elements

Each of the organisms selected, all of which are multiprocessors, also has an associated growth curve that dictates its performance characteristics over time. This curve can be used to determine the flow rates of inputs and outputs over time. All input flow rates are thus directly proportional to the organism's mass. So too, all outputs, with the exception of the tissue of the organism itself, will be directly proportional. The remainder of outputs, in the form of the tissue mass, will manifest itself as a spike in the output portion of the performance curve (see Fig. 8).

It is possible to integrate the mass balance over time. To do this in terms of supporting one human per day, the scalar for human input/output data must be multiplied to account for the average inputs and outputs of one human on a daily basis. This factor must then be used to multiply the scale factors of the other organisms. These modified scale factors are the number of organisms produced daily to achieve the desired balance. Based on these calculations, an example of a system balance to support one human per day was achieved (see Fig. 9).

Within this process description it is of great importance to have a sound understanding that the resultant configuration is dependant upon the time characteristics of each organism. In other words, further multiplication of the system balance figures by each organism's respective time to maturity will determine the number of organisms on average that must be growing at any one time. With this understanding one can then begin the operation and implementation phase.

OPERATION AND IMPLEMENTATION

After achieving a mass balance, based on transfer functions and the integration, the next step is to determine the possible configurations that could support such a balance. In so doing, one should examine the implications of performance characteristics; mass, volume, and power requirements; and the sensitivity of the overall system.

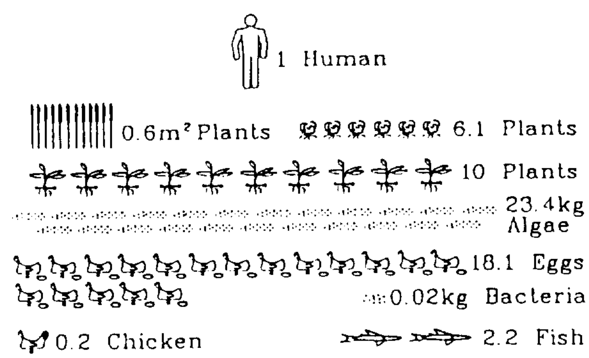

Fig. 9. System Balance to Support One Human per Day

To understand the overall performance characteristics of the system the performance curves may be integrated with the system balance to understand the fluctuations in surpluses and deficits that occur for the whole system over time. This is accomplished by the superposition of the curves based on the organisms' performance scaled to the number achieved in the system balance and their subsequent summation to create a system performance curve. It is important to note that this curve will be a reflection of whether a continuous production system or a batched system is chosen, and that it is based on single design points, while the system operates in a range of characteristics (or points). Thus, a large portion of these surpluses and deficits will be absorbed by the organisms due to adaptive responses in their performance. This feature of performance flexibility can be thought of as an inherent buffer on the system. As long as the surplus or deficit for each element remains within the buffer zone for the continued function of the organisms, the system will support itself. It is also possible to accommodate a larger surplus or deficit through the use of additional buffers in the form of storage systems. A thorough understanding of both inherent and additional buffers will increase the range of possible configurations.

Once the system performance curves have been determined, the next step is to consider operational parameters. As with physicochemical systems, bioregenerative systems have certain characteristics in terms of system mass, power, and volume. With the system balance, it is possible to determine the overall system values for these parameters by multiplying the number of each type of organism in existence at one time by that type of organism's respective mass, power, and volume requirements on a per organism basis. The values for all organisms are then summed to reach the system mass, power, and volume requirements. These values should be inclusive of all support requirements such as lighting, circulation, pumping, ventilation, growing space, and structural materials. However, in the category of power requirements, creative phasing between batches and between organism type may reduce the load on the power system at any given time and should be carefully examined.

Definition of operational parameters will then lead to the tradeoff analysis. This phase weighs the degree of closure achieved in the mass balance against the requirements for system mass, power, and volume. At this point it may become obvious that certain aspects of the system are unacceptable for mission requirements (see Fig. 10).

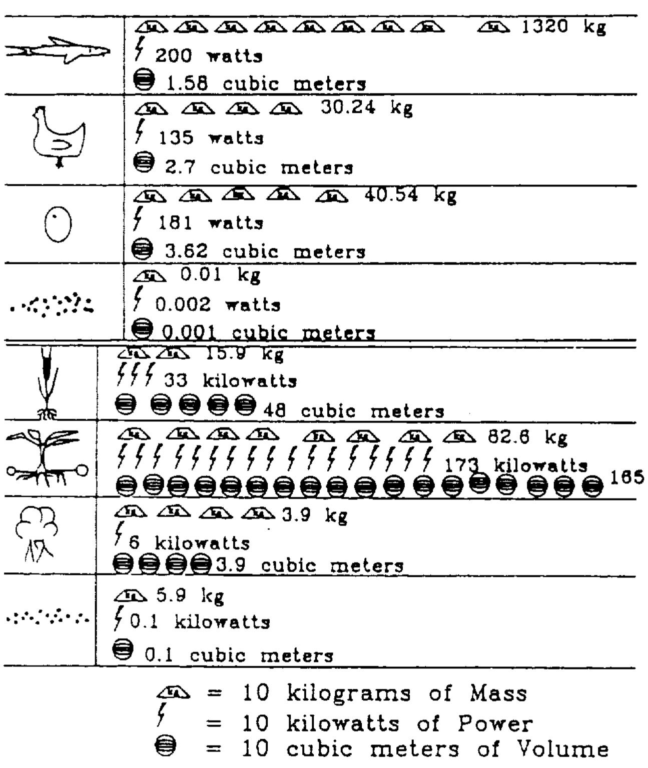

Fig. 10. Operational Parameters

An example might be that the mass to support one organism might be heavier than the mission's launch capabilities. If this is the case, several options are available. One is to rescale the mass and system balance to achieve a smaller system mass while accepting the subsequent decline in system closure. Should this be the outcome, provisions for extra supplies or physicochemical supplementation of the biological components could be made. The decline in closure may not occur, however, if the resulting performance remains within the inherent buffer zone and no additional adjustments are necessary. Another option to reduce system mass is to replace the organism in question with one that has more favorable characteristics. This will likely require extensive research to attain sufficient data on the organism, which must be considered before choosing this option. A point of interest here, is that when attempting these adjustments, the results are often counterintuitive. Thus the aid of computer modeling is essential for ease of performing tradeoff studies.

The final aspect of the tradeoff study is to perform a sensitivity analysis. This should be done for both minor perturbations, such as a decreased power supply, introduction of pathogens, or the removal of humans, to catastrophic failures of subsystems such as the elimination of one or several species of organism. The results should be weighed and further iterations may be required. On the other hand, it is likely that the system will prove sufficiently robust, requiring no adjustments.

CONCLUSION

What is presented here is a rudimentary approach to designing a life support system based on the utilization of plants and animals. The biggest stumbling block in the initial phases of developing a bioregenerative life support system is encountered in collecting and consolidating the data. If a database existed for the systems engineer so that he or she may have accurate data and a better understanding of biological systems in engineering terms, then the design process would be simplified. Also addressed is a means of evaluating the subsystems chosen. These subsystems are unified into a common metric, kilograms of mass, and normalized in relation to the throughput of a few basic elements.

The initial integration of these subsystems is based on input/output masses and eventually balanced to a point of operation within the inherent performance ranges of the organisms chosen. At this point, it becomes necessary to go beyond the simplifying assumptions of simple mass relationships and further define for each organism the processes used to manipulate the throughput matter. Mainly considered here is the fact that these organisms perform input/output functions on differing timescales, thus establishing the need for buffer volumes or appropriate subsystem phasing. At each point in a systematic design it is necessary to disturb the system and discern its sensitivity to the disturbance. This can be done either through the introduction of a catastrophic failure or by applying a small perturbation to a the system. One example is increasing the crew size. Here the wide range of performance characteristics once again shows that biological systems have an inherent advantage in responding to systemic perturbations.

Since the design of any space-based system depends on mass, power, and volume requirements, each subsystem must be evaluated in these terms. While one system, such as the catfish, proved itself to be mass (including support hardware) intensive, another system, the potatoes, proved itself to be power intensive. The ultimate design of a closed life support system will balance these criteria (mass, power, volume, closure, etc.) through the use of appropriate weighting factors based on mission constraints. This is an iterative process that also weighs these system design criteria against the system mass balance until all requirements are satisfied. These requirements are satisfied because bioregenerative systems operate within characteristic ranges. The mass blance is considered throughout the design process because this balance insures the closure of the system.

Phasing is another issue that must be addressed. Some systems are more suited for continuous harvest (daily egg collection), while for others, batch harvesting will be preferred (catfish or wheat). Storage facilities may be required to store system outputs to ensure the availability of needed inputs.

Since this is only a rudimentary analysis of a complex system, many other critical issues were not analyzed. Examples of these are labor requirements and the integration of bioregenerative with physicochemical systems. What has been shown, though, is that developing a bioregenerative system is possible from the design engineer's perspective once the approach has been adequately defined. Indeed, implementation can begin presently, and must do so in order to be utilized for the Space Station, the Moon, or eventually, Mars.

RECOMMENDATIONS

As was mentioned earlier, the compilation and consolidation of information on biological systems was a major obstacle to overcome. This obstacle could be minimized if a centralized database with information on biological organisms were in place. This information might exist, but often in places or forms which are unusable to the systems engineer.

Another related problem is that a significant amount of data on closed and well-monitored systems does not exist. Research and development of these systems is within our reach today and is not only of significance to NASA and the space program but to other entities, such as the planet Earth.

While bioregenerative-based systems are complex, their development is not unattainable or unreasonable. The basic methodology that has been provided has several steps, and in order to make a bioregenerative system a reality, one of the safest and most comprehensive ways would be to utilize each of these steps, coupled with support activities such as experimentation, modeling, and testing. With such a program, closed bioregenerative life support systems will soon be a reality, and manned missions to Mars will become feasible through self-reliance and less dependence on Earth resources.

ACKNOWLEDGMENTS

Special thanks to the students of the Space Habitation classes, Steve Johnson and Alex Hoehn, TAs, Dr. Marvin Luttges, and NASA/USRA. This paper was prepared by Michelle Goldman, Shawn Gomez, and Mike Voorhees. We thank Dr. Robert MacElroy and Dr. Mark Kliss of NASA ARC for support.