CELSS

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Controlled Ecological Life Support System

First Principal Investigators Meeting

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Controlled Ecological Life Support System

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PREFACE

This report consists of papers presented at a Principal Investigators Meeting of the Controlled Ecological Life Support System (CELSS) program. The meeting was held at the New England Center for Continuing Education on the campus of the University of New Hampshire, Durham, New Hampshire, on May 3 through 6, 1981.

The purpose of the meeting, which was the first devoted to the presentation of work done under the sponsorship of the CELSS program, was to provide a forum for the exposition of ideas generated in the many disciplines that comprise the CELSS program. In most cases, attempts were made to present "state of the art" research results, and to explain the rationales and backgrounds of the research at a level appropriate for understanding by a multi-disciplinary audience.

It is anticipated that this meeting will constitute the first of several Principal Investigators Meetings that will be held at intervals during the course of the program's development. Such interactions among the scientists involved in the program are essential to the program's rational development, and to the generation of concepts that will become the subjects of its future research.

The editors of this report would like to thank the participants at the meeting for their contributions, the authors of the papers that appear in this report, and the organizers of the meeting at the New England Center: Clara Clustra, Robert Kaufmann, Claire Tappan Reinhold, and Steve Wolfe.

CURRENT CONCEPTS OF THE CELSS PROGRAM

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The intent of the National Aeronautics and Space Administration in supporting the Controlled Environment Life Support System (CELSS) program is to establish the technological basis for the development of life support systems that are relatively independent of resupply. Such systems, it is anticipated, will be needed in the future to support manned space flight involving long duration missions and large numbers of people.

The establishment of a resupply-independent life support system requires that all or most of the material in such a system be retained and recycled. In fact, leakage of gases into space, or into atmospheres of significantly lower pressure than that found inside of the system, is inevitable. Technical advances in sealing capabilities may reduce losses in the future, but no seals will ever be perfectly impervious to common atmospheric gases. Thus, a CELSS is envisioned to be a recycling system that will need to be resupplied with gases from time to time.

The primary purpose for recycling within the system is to supply human inhabitants with specific quantities and qualities of food, water and air, while eliminating the dangers of biological and chemical toxicity. In practice this will mean recycling waste materials to food, carbon dioxide to oxygen, waste water to potable water, and the removal of non-desirable volatile, soluble and solid inorganic and organic materials.

Autonomous Life Support Systems

A paradigm that is most useful when considering a CELSS is that of an autonomous system, capable both of maintaining any of a series of internal environments, as well as of regenerating wholesome food and air from waste materials. However, it is also very useful to think of a CELSS as the ultimate product of a series of material closures: efficient recycling of CO_2 to O_2; collection and purification of metabolic water to make potable water; and the regeneration of waste solids to food solids. These material closures are often referred to as "loops", and both "partial" and "complete" loop-closure implies some measure of the efficiency with which material can be truly recycled.

Considerable effort has been expended to date in attempting to efficiently recycle water and oxygen. The technologies that have been developed will play important roles in the maintenance of a CELSS. The primary way that the CELSS program differs from these more technologically advanced life support programs is in its consideration of food regeneration. Generation of food requires the use of energy to elaborate simple inorganic molecules, such as CO_2, O_2, N_2, water, phosphate and sulfate, into complex organic molecules, such as sugars, proteins and fats.

There is a common feeling among scientists that at some point in the future the manufacture of non-biological food will become practicable and economically feasible. Indeed, even at the present time, some food materials can be produced abiotically, and these techniques are being studied in the context of the CELSS research program. However, it is also commonly held that within the next generation, the most reliable and efficient methods of food production will be based on biology, although some interesting and efficient methods of using a mix of chemical, physical and biological techniques to make food are now being explored by the CELSS program.

The CELSS research program will, in its formative stages, evaluate the consequences of using biological entities to produce food for humans in closed systems. The program will consider food production from bacteria, algae, higher plants and animals. The exclusive use of non-photosynthetic food organisms (e.g., bacteria and animals) requires other methods of gathering the energy needed for food production. Among the other methods that could be used are those that use light directly to promote chemical reactions (e.g., photoreduction of CO_2), and those that first convert light into electrical power which is then used for effecting chemical changes useful in biological systems. For example, light could be used for the photoreduction of CO_2 to methanol, which could subsequently be used as food for bacteria or yeasts; electrical power could be used to electrolyze water to hydrogen and oxygen, which could subsequently be used as food for hydrogen bacteria.

The nutritional aspects of the food proposed for use in an autonomous life support system must be a major aspect of the CELSS Program. Nutritional factors are intimately involved with other aspects of food, including methods of processing and preparation, and psychological aspects of food acceptability. In addition, nutritional studies must include both short and long term responses to foods, especially those that are not traditional, or those whose composition (content of minerals, vitamins, fibers and ratios of protein, fat and carbohydrate) varies appreciably with growth conditions.

The metabolism of organisms, whether food organisms or the human crew, is accompanied by the exchange of materials with the environment. Of potentially great significance is the production of volatile organic materials by organisms, and the movement of these through the air and liquids in the system. Some of these materials can be toxic, others may elicit metabolic responses that can range from simple avoidance or attraction to the triggering of hormonal or other intrinsic control responses. These materials eventually must be investigated for their biological responses, and may even prove to be helpful in the control of organisms; however, it is likely that preliminary responses will be to consider them potentially toxic.

In addition to the control of organic volatiles, the control of aerosols and particulates, including bacteria and viruses, will have to be investigated.

Other waste materials, such as liquids and solids, have to be recycled to forms appropriate to support the growth of food organisms. The major wastes will be non-usable biological materials resulting from food production, spent food organism growth media, and human liquid and solid wastes. In most cases it will be necessary to change the state of these waste materials, for example, to oxidize all wastes. However, various considerations, including energy costs, equipment weight and volume, and process material hold-up volumes, make the study of other recycling processes worthwhile. Among these are biological waste digestion, and various methods of fractionating and separating the organic wastes for reuse, or for feeding to other potential food sources.

In addition to organic waste materials, recycling processes and schemes must consider inorganic materials. These should be independently investigated because they constitute a class of nutrients that are not easily transferred within a closed system because they exist in a liquid or solid state only. The constraints on soluble minerals include the desirability of removing them from potable water, and maintaining their concentration in growth media at levels that are appropriate for the food organisms. Even gradual changes in the concentrations of these materials can have significant effects on the growth and metabolic characteristics of organisms. The CELSS program will address these issues, as well as the overriding problem of the control, regulation and management of the entire system.

Control of a system containing many separately functioning and essentially independent parts will be a major effort of the CELSS program. The primary functional components of the system will be food production, food processing, atmosphere composition, environmental parameter maintenance, volatile organic, particulate and aerosol control, organic waste processing, inorganic materials separation and concentration control, and organism growth medium maintenance and control. Each of these functions must be monitored in such a way that the state of the system as a whole is known; the activity of each function must be susceptible to control to allow the smooth cycling of materials and to permit intelligent use of energy and other resources; finally, the system must be managed in such a way as to meet both anticipated and unanticipated demands on various parts of the system at a future time.

In general, the short term regulation of individual functions is referred to as "control", and includes the behaviour of each sub-system relative to others. Regulation in time, to allow for the maintenance of the state of the entire system, is referred to as "management". Both system control and system management will receive attention by the CELSS program at practical as well as theoretical levels.

At the fundamental level of process control, the active functions of the CELSS system fall into two categories: physico-chemical functions, such as environmental parameter maintenance, which can be controlled using classical control theory and approaches; and biological functions, such as food production, which does not respond to the imposition of classical techniques. Biological sub-systems contain organisms that have internal or endogenous mechanisms of control; they can be manipulated through changes in external environmental variables, but the linkage between the control signal and the response is very indirect and subject to extensive filtering and occasional "re-interpretation". It is thus important to thoroughly investigate the responses of organisms in some sub-systems to environmental perturbation, both for the purpose of imposing control and to allow adequate control responses for unintentional perturbations of biological systems (e.g., the development of disease or the inadvertent appearance of toxins).

System management will depend on the effectiveness of system control, and upon the validity of predictions of system behavior. For the purposes of management it is essential to accumulate sufficient information to assess the current state of the system, and to predict the consequences of a given control strategy on the future state of the system.

The CELSS research effort will be very complex, will involve many disparate as well as overlapping disciplines of research, and must be integrated to an extent unusual in advanced science. The mechanisms of integration of research work will require special attention; it will be necessary to hold several meetings each year to allow information transfer between program investigators, as well as to permit assessment of the state of research by the program management.

While the task is obviously difficult, and the goal of the research effort is distinctly removed from the preliminary investigative work, it is a very exciting project, one that obviously will push many sciences to their limit and beyond.

THE CELSS PROGRAM: AN OVERVIEW OF ITS STRUCTURE AND USE OF COMPUTER MODELLING

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Introduction

Maintaining people in space in safety and comfort requires control of: 1. Atmosphere composition; 2. Temperature; and 3. Humidity; and means for: 4. supplying food and water; and 5. Disposing of wastes, including volatile organics.

To date, atmospheric composition has been maintained by absorbing CO_2 and replenishing the O_2 consumed. Temperature control of cabin atmospheres has been mastered, and control of humidity has been achieved.

Food has been carried at launch, either as dehydrated material to conserve weight, or preserved in other ways. Water has also been carried at launch drinking and for personal hygiene.

Long term maintenance of people in orbit, or on another planet, e.g., the moon, focuses attention on recycling of materials. Recycling could reduce the launch weight of materials for human sustenance. For this reason, effort has been expended in regenerating O_2. The methods that can be employed are through the use of the Sabatier reaction:

$$CO_2 + H_2 \text{ -----> } CH_4 + H_2O$$

or the Bosch process:

$$CO_2 + H_2 \text{ -----> } C + H_2O.$$

With either reaction, the water produced can be electrolyzed to O_2 and H_2.

Efforts directed toward recycling water can easily be focused on three sources of contaminated water: 1) Metabolic water, from urine and feces; 2) Expired water which enters the atmosphere from breathing and evaporation; and 3) Waste water from personal hygiene. Each of these sources of used water can be treated separately.

The advantage of recycling O_2 and water can be shown to be economically feasible by comparing launch weight of gases and water for a non-recycling flight, versus the launch weight of the water and gases, plus the weight of equipment for recycling in a flight in which regeneration of these materials is done.

Practical recycling of organic material to regenerate food has not received much attention to date. This is justified when tradeoffs are considered, even with the limited amount of information currently available. Recycling of waste to food is economically practicable only when justified by either the number of people in space or the scheduled duration of the flight. However, the capabilities for launching large numbers of people, or for long distance flight, including the establishment of planetary bases, is increasing. It is time now to face the problems of recycling all materials for use in space, to prepare for a time when the kinds of flights launched will justify recycling.

While the primary focus of the controlled environment life support systems (CELSS) program is the regeneration of food from waste and the recycling of other materials, including water and oxygen, it is likely that the physico-chemical methods for recycling now in research and development phases will become integral parts of any foreseeable CELSS.

The CELSS research program focuses on three distinct but integrated research efforts: waste management, food production and processing, and system management and control. Because the program effort concentrates on fundamental research, integration of research efforts must have special emphasis since all CELSS program research has a common focus: preparation for the development of an autonomous life support system.

Food production in an isolated CELSS will require energy. The energy expended will be used for the reaction:

$$CO_2 + H_2O \longrightarrow [CH_2O] + O_2,$$

where $[CH_2O]$ is the carbohydrate element that can be further elaborated to protein [-NH-CHR-COO-] or lipid $[-CH_2-]$.

The methods available for catalyzing the reduction of CO_2 range from photocatalytic reduction to photosynthesis. The CELSS research program will examine as many of these methods as is economically possible; however, at the present time, efforts will be concentrated on photosynthesis, primarily by higher plants and green algae, and upon photocatalytic CO_2 reduction.

The concepts that have been developed over the years for food regeneration in an autonomous system have concentrated on the use of biological processes to reduce CO_2. The use of organisms as integral parts of the system immediately raises questions about controllability.

While the initial thrust of the CELSS research program has focused on studies of individual biological and physico-chemical processes, the ultimate objective of the program is to learn what is required to create a persistent, autonomous, integrated system. The question arises as to how these individual processes might behave if allowed to interact with each other. As the actual construction of linked, functional systems would be quite costly and as the time constants of such a system would be quite long, it is of interest to use computer modelling as a useful approach to the study of the behavior of conceptualized, closed, regenerative life support systems.

A unique aspect of models of closed, regenerative, human based life support systems is the fact that such systems, with the possible exception of the Earth, do not exist. This approach differs from the usual modelling approach which attempts to construct a model whose behavior imitates the behavior of an extant system. Of necessity, any mathematical model of a CELSS must be more speculative and general than accurate, and validation of the model must await the construction of an experimental CELSS.

Within this constraint, a reasonable modelling approach would be to base the model upon the apparent structure and function of studied ecosystems and to incorporate modifications dictated by the requirements of the CELSS. For example, in enclosing a natural ecosystem or reducing its size or species diversity, natural regulatory mechanisms, such as large buffer sizes, are excluded. Therefore such perturbed systems can only be maintained by replacing excluded natural control mechanisms by exogenous management and manipulation. Since the mechanisms of natural, endogenous ecosystem control and regulation are unknown, the nature of the exogenous management and manipulation required are not clear. Because a focus of the CELSS program is mass closure with the intent of reducing the requirements for mass resupply, it is reasonable to construct models of CELSS behavior which depict the flow of elemental mass in the system. Extensive study of various natural ecosystems suggests that they demonstrate certain common features. The photosynthetic properties of plants allow them to use the energy in sunlight to synthesize complex polymers- carbohydrates, lipids, proteins and nucleic acids-from inorganic minerals and gases. As these nutrients become less available the growth of the plants will be curtailed. If the plants continue to act as sinks for these inorganic nutrients the environment will become depleted. Animals and microorganisms feed upon the plants to obtain energy and materials for growth and in so doing remineralize the organic polymers to provide nutrients for continued plant growth. These processes--photosynthesis, predation and decomposition--determine the flow and storage of elemental mass in a natural ecosystem and analagous processes must form the functional basis of any synthetic, persistent and autonomous human life support system. A reasonable modelling approach would be based upon these processes as described by equations of mass transfer and transformation and guided by the laws of mass conservation.

A mass balance model following these concepts and describing the flow of the elements carbon, oxygen and nitrogen in a rudimentary, conceptual, regenerative life support system is being constructed at Ames Research Center. The life support system of this model will consist of a number of compartments between which elemental mass flows and in which it is stored. The choice of compartments represents a compromise between generality, resulting in unrealistic simplicity, and detailed specificity, resulting in unwieldy complexity. The present model envisions that each day a fraction of the plant biomass is harvested and divided into an edible and inedible stream. The inedible stream is processed by a waste processor into inorganic nutrients while the edible fraction is stored as food. Dietary food, calculated as protein, fats and carbohydrates, is transferred to humans. Provision is made to transfer excess food from storage to waste processing as the system requires. The humans metabolize the food to waste materials: carbon dioxide, urea and undigested material. The solid wastes are transferred to a waste processor for decomposition and the resulting inorganics fed to the plants to provide for growth. The model will be used to provide insight into inherent CELSS features and characteristics, e.g., the relation of buffer capacity and response time to system stability, the identification of system and process control points, the effect of alternate control strategies on system behavior and the effect of environmental perturbation on plant physiology and development.

CELSS SYSTEM CONTROL OVERVIEW

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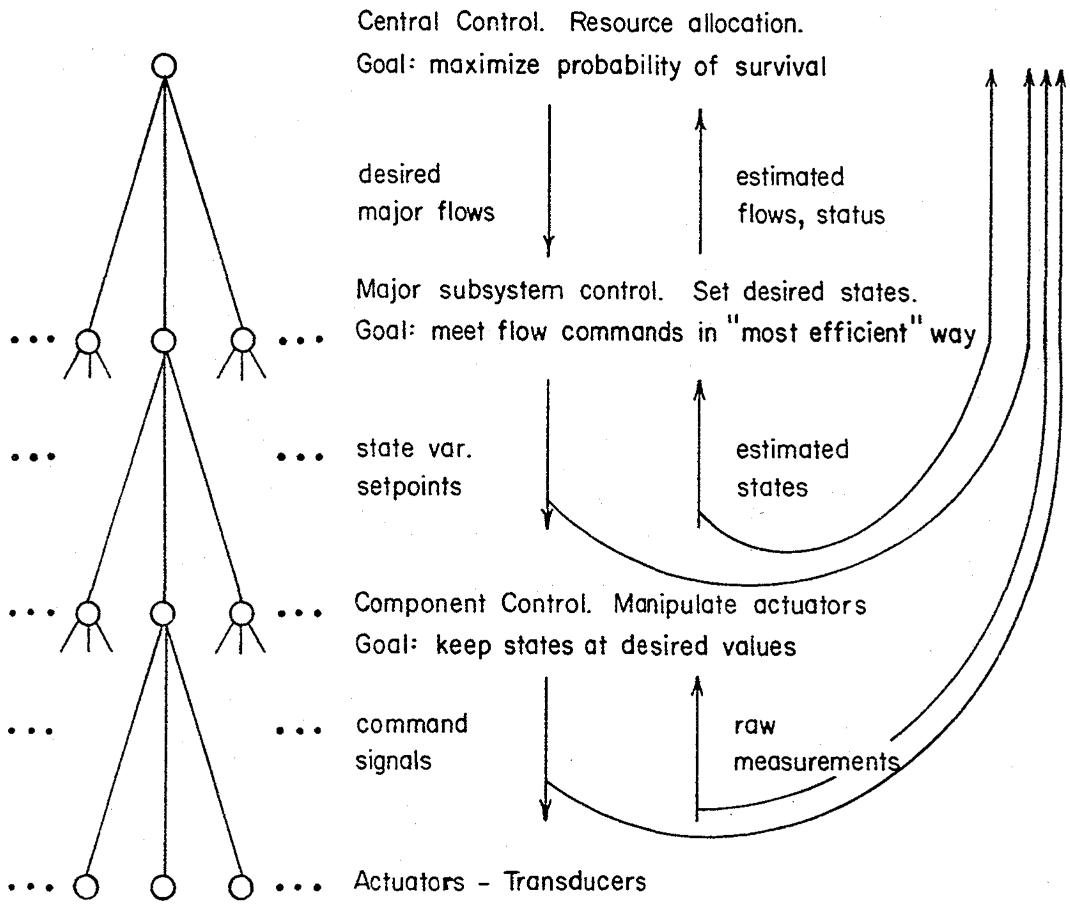
A CELSS presents unique control problems at all levels. Before looking at some of these, however, the bigger question of how much control is <u>necessary</u> (as opposed to just useful) should be addressed. On the largest scale, that of overall system control, this reduces to the question, "Is a CELSS that has been designed for steady-state balance in all its flows, with the addition of reasonable amounts of buffering, stable in the face of perturbations from that operating point?" That is, if some inadvertent perturbation occurs (temporary shutdown of some component, for example), will the system return to its original operating point without the imposition of a global control scheme? If the system is stable in that sense, any kind of large-scale control scheme will be useful for optimizing the system, but will not be necessary. On the other hand, without such stability the system cannot be operated without a management control system. We have started some initial studies in this direction for very simple CELSS models which indicate the possibility of failures occurring at times long after the cause of the perturbation has been removed.

Whether for stabilization or for optimization, the design of a global control system offers interesting challenges. One of these is the basic performance measure for a CELSS--survival. To design a control scheme, a quantitative measure for the probability of survival must be defined. Then a computational procedure must be devised to predict the probability of survival, with specified confidence limits, for a system subject to varieties of statistically possible events. In principle, this is not that much different from a safety analysis and control for a nuclear power plant, for example, but in a CELSS it is complicated by the very long-term dynamics inherent in such systems as growing plants. Furthermore, the control system in a CELSS must be capable of adapting to changes and events that were not anticipated at the time the system was designed. This implies that the control system must be a synthesis of man and machine--computers will be a necessary part, but human interaction in decision-making will be vital.

Control problems at lower levels are a combination of control tasks that are similar to standard process control, and control

Real CELSS - Control Hierarchy



Tasks: model update, long term prediction, functional optimization
Problems: dimensionality, multiple time scales, uncertainty, unobservable states, conjecture evaluation, free will, politics

Tasks: estimate flows, malfunction analysis, steady-state optimization
Problems: changing process structure, uncertainty performance criterion

Tasks: estimate states, estimate "control" model, fix parameters in control algorithm
Problems: dynamics, nonlinearity, dimensionality, unmeasured disturbances, free will, noise, insertion loss

CELSS System Control - The Holistic View tasks that have not been attempted before. The biological components, in particular, will probably require a far greater degree of control than any such systems in use now. Plants, for example, will be grown under highly controlled environments in which the goal is to specify growth rates, metabolic exchanges, etc., not just maximize them. Over its lifetime a growing plant changes drastically in structure (physical and chemical), and control models must reflect that change. Control requires knowledge of a system's state. Our knowledge of how to characterize the state of a plant is very fuzzy, at best, and our knowledge of how to measure it is even less reliable. Thus, even in the best of circumstances, any successful controller will have to be able to cope with considerable uncertainty in its model of the system being controlled.

These and other such problems make CELSS control a challenging and interesting enterprise. The issues raised lead to some problems that are unique to CELSS--such as designing a control system for survival--as well as others, such as uncertainty in control objects, with important implications for conventional systems as well.

CONTROL PROBLEMS IN AUTONOMOUS LIFE SUPPORT SYSTEMS

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Introduction

We are addressing the problem of constructing life support systems which require little or no input of matter (food and gases) for long, or even indefinite, periods of time. Such systems are envisioned for long range space exploration, yet the knowledge acquired for the solution of this problem will certainly be useful in the preservation of a high quality terrestrial environment.

Life support systems presently used in space rely on storage of adequate amounts of food and gases that are gradually depleted during the mission. This method becomes impractical for missions lasting longer than a few weeks. While regeneration of gases and food from human waste requires a larger initial overhead, this approach becomes advantageous, even essential, beyond some specified mission size or duration [1].

We call "autonomous" a life support system that approaches the theoretical limit of complete closure to matter for an indefinite period of time. We assume that energy, at least in the form of light radiation, is available.

The design of an autonomous life support system (ALSS) is potentially guided by two models: natural ecosystems and artificial control systems. In this paper we examine the strengths and weaknesses of both models and suggest an approach to their synthesis.

Natural control in ecosystems

Natural ecosystems can tolerate fluctuations both in numbers of individuals within species, and in climatic conditions. It is clear that internal controls are responsible for this ability, but it is also clear that such controls do not always suffice in maintaining the original system, for example, one or more species can become extinct. Yet, even under such drastic circumstances, a natural ecosystem usually does not collapse; rather it finds a way to persist without the lost species. Analogously, insertion of a new species can often "force" the system to find a way to accomodate it. This property suggests that a system capable of supporting human life can be built empirically. One only needs to select a promising, simple ecosystem, force it to accept different species which are essential to the survival of man, and finally, when conditions appear to be favorable enough, introduce a human population. Indeed, it has been claimed that such a system would be more stable and energetically more efficient than any electromechanical system we might be able to build and control [2]. Could we rely on an ecosystem regulated only by internal controls? To answer this question it is useful to consider the difference between engineering control systems and internal ecosystem controls.

The purpose of engineering control theory is to construct a system which is "stable", where stable means that when the system is perturbed from its equilibrium condition it must return to the same equilibrium as quickly as possible and with as few oscillations as possible. This is the perception of the control engineer, but what is usually not stated is the additional "engineering" assumption that unless the system is stable it will not survive or it will not behave properly. It would certainly be unwise to adopt a different definition of stability when referring to ecosystems, but one must not neglect the fact that, in the case of ecosystems, it is not appropriate to equate instability with non-survival. As said by Kempf [3] "the flow of an ecosystem across its dynamical landscape is more like the flow of water across a hilly region than the movement of a water drop on the side of a coffee cup". Consider for instance the case of an ecosystem in which one or more species have diminished in numbers from their original equilibrium state, due to some external perturbation. To be stable from the point of view of control theory the system would have to return to its equilibrium condition. Indeed the ecosystem might do that, but it might also retain its new population numbers, or reach a new equilibrium state, or continue to fluctuate [4]. It might even settle temporarily to a new equilibrium state, and return to the original one at a later time. In any case a natural ecosystem would probably continue to persist. Holling [5] used the term "resilience" to describe this ability to persist in spite of instability, and even suggested that in some cases ecosystems might adopt a strategy of instability in order to enhance their chances of persisting. Such a concept would appear very strange to a control engineer; which is a good example of how ecology and control theory can stimulate new thinking in their respective camps.

In conclusion, the attractive feature of natural controls is that they seem able to keep the system going under unexpected unfavorable conditions. At the same time, the unsettling aspect of complete reliance on natural controls for food and gas production is that natural controls do not favor any particular species. Even when no species becomes extinct, natural controls can be unacceptable from a human point of view. For instance, the natural controls of a predator-prey system are based on an alternating sequence of two catastrophic events: decimation of the prey population by the predator, and starvation of the predator when little prey is to be found. Natural ecosystems would certainly not hold the human species in special regard.

The purpose of an ALSS is to keep the variable "human population number" constant. The controls needed for this purpose have not evolved in natural ecosystems simply because ecosystem persistence never depended on them.

A control theory for ecosystems

If internal ecosystem controls cannot be relied upon to maintain the environmental requirements of a human crew, can we use control theory to regulate the ecosystem by artificial means? It is relatively straightforward to cast ecosystem dynamics in a very general control theory formalism (e.g., [6]) but the solution of actual ecosystem problems using that formalism has been unapproachable so far. The main reason is that control theory has been developed for man-made systems, whose behavior is well understood in all its parts. Ecosystems are difficult to measure and even to define (e.g., [7]). In addition, the ecosystem properties described above are the result of highly non-linear mechanisms, and control theory is not well developed in this area. Nevertheless there is a wealth of literature concerning the control of particular types of both non-linear and ill-defined systems. Yet, possible connections with ecosystem control are very seldom emphasized (one exception is found in [8]).

Construction of an ALSS provides the opportunity to narrow the gap. By using small laboratory ecosystems we can, in principle, select small portions of "dynamic landscapes" and modify them by imposing suitable constraints. Hopefully the application of control theory to ecosystem regulation will find a good testing ground.

An experimental system now under development at our laboratory will simply try to control the environment of one or more living organisms [9]. Our aim is to account for all gas and mass transfers while the organisms are kept alive, and while their growth is controlled as desired.

Approach to the design of an ALSS

It is likely that in spite of much progress in the extension of control theory to ecosystems, the variability inherent in biological systems, and the complexity of interaction between species and between individuals, will place a practical limit on the degree of external control we will be able to exert. At any rate, even if in theory external controls could reach into the system at any desired level, it is intuitive that a point of diminishing returns will be reached.

As a result of our chamber work, we expect to be able to select a number of reasonably well behaved small ecosystems, to constitute the building blocks for an ALSS. One attractive scenario is that of functional compartments, individually stabilized, joined to form a system which can be handled by control theory. This picture is well in line with schemes for the control of large complex systems by subdivision into smaller subsystems that can be stabilized individually (e.g., [10]). The important difference is that the behavior of the lowest level subsystems will be largely determined by internal natural controls.

What types of external control strategies will be needed at the lowest level? There can be no general answer at this point, but the analogy mentioned above, between dynamic landscapes and regions of flowing water, illustrates the problem very well. The ideal situation is for each subsystem to behave dynamically like a lake surrounded by steep walls, i.e., like a very stable linear system. All the external control system would have to do in this case is to maintain a constant environment. This linear behavior may not always be attainable in practice. We might only be able to confine a region containing a number of valleys, and thus deal with a system which can switch between states. In this multi-state case, the control system would have to recognize which state has been chosen by the ecosystem, and would have to be able to modify the dynamic landscape temporarily in order to send the system back to the desired state. Worst of all, but also conceivable, is the case of a landscape with no minima. Then the control system would have to constantly monitor the trajectory of the ecosystem and constantly change the landscape as appropriate, much like a juggler keeping three objects in the air with only two hands. Clearly this situation should be avoided if possible.

In outline, the approach to the design of an ALSS consists of the following steps: 1) choose a set of ecosystems which, together, could generate food and oxygen for a human crew, and could regenerate all waste; 2) determine the dynamic landscapes of these ecosystems and identify the regions where they are most easily controllable; 3) devise the control system and the constraints that keep the ecosystems within these regions; 4) link these subsystems to form a larger system, which would include a human crew.

Conclusions

While ecosystems certainly incorporate the basic mechanisms for the survival of any species, they have no controls that guarantee that any specific population will remain constant in numbers, an absolute requirement for a human crew in an ALSS. On the other hand, artificial control of natural ecosystems will require considerable progress in the theory of control of ill-defined and non-linear systems. We propose to study the behavior of small experimental ecosystems in closed chambers and to develop appropriate control strategies. Among these systems we will select the functional building blocks for an ALSS. If these systems can be stabilized individually by suitable combinations of internal (natural) and external (artificial) controls, the problem of stabilizing the overall ALSS will be greatly simplified.

Acknowledgments

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DEVELOPMENT OF SELECTION CRITERIA AND THEIR APPLICATION IN EVALUATION OF CELSS CANDIDATE SPECIES

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Plant species grown in a CELSS must provide a nutritionally and psychologically adequate diet for personnel as well as for controlled air revitalizaton. The ultimate selection of suitable crops will depend on species performance within the unique restrictions imposed by recycling ecosystems and on the ability of harvested plant parts to meet human needs. Two general categories of selection criteria have been identified which will be used to identify promising species upon which future research efforts should be focused: use and cultural criteria. Certain aspects included under each category are incompletely known for many species and therefore introduce elements of uncertainty into the selection process. A total of 21 criteria were considered; nine of them fall into the realm of human nutrition and convenience (the "use" criteria), and the remaining 12 are predominantly cultural considerations. Five criteria were considered to be of great importance in the selection of plant species and were given double weight relative to the remaining criteria. "Use" criteria include the following: energy concentration, nutritional composition, palatability, serving size and frequency, processing requirements, use flexibility, toxicity, and human experience. "Cultural" criteria include the following: proportion of edible biomass, yield of edible plant biomass, continuous vs. determinate harvestability, growth habit and morphology, environmental tolerance, photoperiodic and temperature requirements, symbiotic requirements and restrictions, carbon dioxide-light intensity response, suitability for soilless culture, disease resistance, familiarity with species, and pollination and propagation. A total of 115 species were evaluated and scored according to suitability for a CELSS. In terms of their anticipated function, we categorized crop species as follows: pulse crops; root and tuber crops; leaf, flower, and vegetable crops; salad crops; grain crops; fruit crops; nut crops; sugar crops; stimulant crops; and herbs and spices.

Re-Evaluation of CELSS Basic Assumptions

A basic stipulation guiding the development of CELSS has been that "Long duration (multiyear) manned space missions would incur almost prohibitively large storage or resupply costs" (NASA/Ames Workshop, January, 1979). This concept apparently grew out of various NASA summer study programs (Space Settlements: A Design Study, NASA SP-413, 1977; Space Resources and Space Settlements, NASA SP-428; Foundations of Space Biology and Medicine, Vol. III, NASA, 1975), and has been theoretically expressed by Spurlock and Modell (NASA SP-428). We have re-examined the basic assumptions underlying the current CELSS research emphasis. In doing so we compared two scenarios, one characterized by a supply of stored food prepared, packed, and preserved on Earth, and by a capability to recycle water and oxygen by physico-chemical means, and the other as a CELSS based on plant culture. The comparison was made in terms of payload at launch and requirements of yearly resupply of consumables of all kinds. Clearly, the two scenarios have a common payload consisting of items such as personnel quarters, navigational quarters and instrumentation, and equipment and facilities serving the specific function of the mission. The comparison was made on the basis of excess payload beyond this common basis. This payload excess was thus specific for each scenario. The analysis leads to the conclusion that the Spurlock-Modell model assumes the existence of a relatively self-sustaining space colony, large enough to be essentially regenerative in terms of structure and materials as well as life support , therefore comprising populations on the order of 100,000 people (NASA SP-413). For space missions that are appreciably smaller in scope, it appears that the break-even points in terms of mission duration easily exceed 50 years and may be several times this figure depending on the need for resupply.

Bioavailability of Minerals and Trace Elements in Total Plant Diets

The bioavailability of minerals from vegetarian diets produced in a manned CELSS is likely to be quite different from that of an average American diet. The presence of large amounts of fiber and metal-sequestering compounds such as phytic acid and oxalic acid is bound to affect the absorption of minerals. Other factors such as relative concentration of minerals (imbalance), mineral nutrient interactions, and competition for absorption sites will also affect bioavailability. In order to obtain a clearer impression of potential problems and indications of the nature of corrective measures such as selection of suitable plant species, supplementation of minerals to the diet, etc., we have initiated rat feeding studies using candidate plant species. A second objective was to study the effect of controlled environment agriculture (CEA) on plant mineral compositon and bioavailability. These experiments are conducted in cooperation with C. A. Mitchell, who will be providing plant materials as facilities for highly controlled environments become fully operational. As a first step we are using materials purchased commercially to give us baseline open field agriculture values with which we will compare the material produced experimentally by CEA. Fifteen candidate species were selected to compose five different diets, each diet containing a "protein supplier" species (either potatoes, rice, corn, wheat or oats) and a "mineral and vitamin supplier" (either mustard greens, pea pods, kale, turnip greens, or broccoli). The diets were proportioned according to USDA guidelines for dietary food composition (the 4-4-2-2 serving concept) and adjusted for the particular nutritional needs of rats. Radioactive isotopes were added extrinsically to the diets and feeding experiments conducted according to the methodology of Hertoghe (J. Nutr., vol. 93, 1967, pp. 454-460), whereby the isotope-containing food is introduced in one meal after several days of acclimation to the diet. Following the intake of the label, retention of the isotope is determined by whole-body counting for a period of 12 days while the animals are maintained on the diet, isotope-free. Calcium absorption was generally very good for these diets. This is probably a reflection of the fact that these diets were all marginally deficient in Ca in terms of rat nutrition. The highest value was obtained with the peanut-rice-peapods diet while the lowest values were given by the split pea-corn-kale and navy bean-wheat-turnip green diets. A negative correlation was observed between Ca absorption and Ca in the diet. Fe absorption was more dependent on plant species. Highest values were again obtained with the peanut-rice-peapod diet and the lowest values with the split pea-corn-kale and the navy bean-wheat-turnip green diets.

CANDIDATE SPECIES SELECTION--CULTURAL AND PHOTOSYNTHETIC ASPECTS

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The objective of our research program is to provide cultural information for a data base that will be used to select candidate crop species for a controlled ecological life support system (CELSS). Working in cooperation with food scientists and nutritionists at our institution, lists are being generated of food crops which will satisfy most nutritional requirements of humans and also fit within the scope of cultural restrictions that logically would apply to a closed, regenerating system.

We seek to identify cultural and environmental conditions that will allow the most rapid production of edible biomass from candidate species in the shortest possible time. The potential for controlled environment (CE) agriculture to decrease the duration of a crop production cycle while increasing yield per cycle relative to open field agricuture (OFA) has already been amply demonstrated, but optimizing conditions for production of any single crop has never been achieved, and perhaps never can be. However, we seek to remove limitations of as many environmental parameters as is practical.

Using leaf lettuce as a model crop system that can provide fiber, minerals, and some vitamins to the human diet, we have been selecting cultivars which are most productive in terms of edible biomass production by (CE) conditions, and which respond to the ever-closer approach to optimization realized by each shortened production cycle. Our experimental approach with lettuce has been to grow the crop hydroponically in a growth chanber and to manipulate such variables as light level and duration, day/night temperature, and nutrient form and level in the solution culture. So far, we have been able to reduce the length of a production cycle from 32 to 18 days, the result being an acceptable, palatable product.

A second phase of our crop production research involves the on-going installation of a walk-in growth room equipped with high-intensity discharge (HID) lighting fixtures which is sufficiently "tight" that we will be able to establish a carbon dioxide control system within the room. This facility will be used in coming months to produce crops in soilless culture and under highly controlled environments. The harvested edible biomass will be provided to the cooperating food science group for analysis of food quality and bioavailability relative to that of crops produced by OFA. Additional environmental "optimization" also will be done on a larger scale than previously with newly gained capabilities for HID lighting, tighter humidity and temperature control and, ultimately, carbon dioxide enhancement. Production of candidate species to be emphasized during the coming year in this CE facility will include protein crops, carbohydrate/calorie crops, and fiber/mineral/vitamin crops.

A third phase of our reserach program is also currently in a "building" stage. We have been developing a series of miniature plant growth chambers (called "minitrons") which will presently allow us to manipulate atmospheric composition as well as the other environmental factors associated with plant growth regulation (e.g., light, temperature, mineral nutrition, and water relations). The minitron system employs a flowing atmosphere with control of gas flow rate as well as composition, and also can be operated in the reduced atmospheric pressure, or hypobaric, mode. We recently have installed a hydroponic system in the minitrons and have interfaced atmospheric outflow with an infrared carbon dioxide gas analyzer. A second generation version of the minitrons presently is under development and will be dedicated to the CELSS program. This system not only will be a larger version of the present system (maxitrons?), but will incorporate a number of features that will improve our environmental control and monitoring capabilities. Once integrated into its environmental support system (HID lighting, atmosphere purification, etc.), this system will be used to determine growth dynamics and photosynthetic rates of small leaf canopies of candidate species growing hydroponically with greatly expanded capabilities for environmental manipulation at almost every level. Development of the second generation minitron system has been in progress for the past year, and two such systems are nearing operational status.

CANDIDATE SPECIES SELECTION AND CONTROLLED ENVIRONMENT INJURIES

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Two workshops were organized between November 1979 and March 1980 to develop research recommendations for use of higher plants in life support systems. A group of 27 plant physiologists met first in Chicago, Illinois and then at Moffett Field, California, to recommend plant species that should be utilized and to outline research that was required. These recommendations are compiled in a report that has been published (NASA CP-2231).

Research has been undertaken to attempt to identify the causal agents for intumescences that develop on many different species of plants in controlled environments. Concentration and filtration procedures have not been successful in identifying any particular compounds. The injury has been found to develop, even though the atmosphere for the plants is filtered through activated charcoal, potassium permanganate, or is subjected to catalytic combustion at 450 degrees C. Thus, the causal agent is apparently either an oxidized compound or specific element, or the result of some unrecognized variation in physical conditions around the plants. The research has demonstrated that the injury is controlled to a significant extent by temperature. Growing temperatures of 20 degrees and 25 degrees C resulted in serious injury on plants, but temperatures of 30 degrees C resulted in very little injury. The research also confirmed previous reports that the presence of ultra-violet light of 300 to 350 mm in the irradiation spectrum prevents injury and provides healthy plants.

Research has also been directed toward trying to prevent calcium-related injury to young leaves of lettuce plants. This work has demonstrated that low daytime humidities (40-50% relative humidity at 23 degrees C) and saturated moisture conditions at night increase calcium concentrations in the young leaves and delay tipburn development. Control of root temperatures at levels between 12 degrees C and 25 degrees C has provided no significant differences in tipburn injury. Studies are under way using tritiated water and labeled calcium to establish the significance of water movement to young tissues for the movement of necessary amounts of calcium.

STUDIES ON MAXIMUM YIELD OF WHEAT AND OTHER SMALL GRAINS IN CONTROLLED ENVIRONMENTS

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We are anxious to gain experience with special growth chambers, control of CO_2, etc. In the absence of that experience the following goals seem reasonable.

I. To achieve the maximum yield of wheat and perhaps other small grains under controlled environmental conditions. Maximum yield implies at least the following two groups of factors:
   A. Achieving maximum yield of energy and nutrients (calories, protein, etc.) per unit of growing time. Can such energy and nutrients be obtained from plant parts other than grain?
   B. Achieving maximum yield with the least expenditure of energy and materials.

   In our study, we emphasize space and time and consider energy expenditure. Requirements for these three factors are all influenced by the plant's genetics and physiology, whereas the efficient use of materials is an engineering problem.

II. Specifically, to manipulate most of the following factors, striving to control or at least to recognize individual factors and to be aware of those that are limiting:
   A. Cultivars. There are two aspects to this problem:
      1. To choose from the thousands of available cultivars those with features that might be best adapted for CELSS.
      2. To test uniculm (nontillering) lines that will allow dense planting with rapid development of high leaf-area-index values (efficient light use) and a controlled population of highly productive, primary heads. At present an agronomically acceptable uniculm wheat is about 5 or 6 generations away. We hope to breed these generations rapidly (3 months each) in one of the growth chambers we will purchase (simple back-cross to standard cultivar).
   B. Photosynthesis: Light, carbon-dioxide, and temperature levels. After good baseline conditions have been established, we hope to determine saturating irradiances at "ideal" CO_2 levels and temperatures.

Cuvette studies of CO_2 exhange will be a principal focus, with actual yield measurements to confirm trends. We expect to experiment with several light sources, since solar irradiances or above are crucial for this research.

C. Nutrient levels. Various levels and interactions of mineral nutrients (some emphasis on nitrogen) must be studied, and time of application during the life cycle must also be examined. We find ourselves deeply involved in such studies.

D. Light Quality and Duration. Spectral quality (especially red/far-red balance) and photoperiod could influence photosynthesis directly and might well influence such photomorphogenetic responses as stem height, flowering time, seed development, and rate of maturity--all factors that could influence yield. Initially, investigation of these effects will be a greenhouse study separate from our growth-chamber investigations of photosynthesis. We are examining the effects of light quality on secondary plant products.

E. Humidity and Plant Water Potential. These factors need to be considered, especially as they might influence the maturation of grains. (We expect to postpone this approach, although the parameters will be continually monitored.)

III. To study ways of promoting grain maturation with minimum energy expenditure (light), in minimum space, and in minimum time. (To be postponed.)

IV. To consider the design of a workable cross-gradient chamber, which could be an efficient way of achieving optimum combinations of light, temperature, and even carbon dioxide. We are aware of the experiences of others with cross-gradient facilities and hope to build upon those experiences.

V. We are considering single-celled clonal multiplication of wheat plants, which could be highly appropriate for CELSS. Highly productive hybrids could thus be propagated without the necessity of making the hybrid for each generation, and all of the seeds could be used for food.

SELECTION OF CROP VARIETIES FOR EFFICIENT PRODUCTION USING UREA, AMMONIA, NITRITE, AND NITRATE IN CELSS

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Oxidation of human waste and inedible plant parts can furnish a substantial portion of the N to support continued growth of crops. The expected products of N regeneration are NO_3^-, NO_2^-, NH_4^+, and urea, depending upon the oxidation process. A primary question that must be answered is how optimally to use those mixed N sources, some of which can be toxic, for successful food production. Little information is available in the literature concerning how each source of N affects the uptake, assimilation and toxicity of the others.

Nitrogen, like CO_2, is required by plants in mass quantities. Plant species and varieties within species differ greatly in their ability to use the above forms of N. The species of N absorbed by a plant greatly influences its growth rate, its ability to absorb other nutrient ions, and the forms of N that it stores. Even plant morphology differs between plants grown on NH_4^+ and plants grown on NO_3^-.

Assimilation

The assimilation of NO_3^-, NO_2^-, NH_4^+, and urea to amino N can occur in both plant roots and leaves. In darkness, the reduction of each is driven by respiration in both roots and leaves. The ratio of NO_3^- reduced between roots and leaves depends on the plant species and the NO_3^- concentration in the medium. Barley plants reduce about 20% of NO_3^- in their roots and 80% in their leaves.

Recent information shows that the assimilation of NO_3^- and NO_2^- in light can be coupled to photosynthetic light reactions in barley leaves. Hence, plants that assimilate NO_3^- and NO_2^- primarily in leaves instead of roots have a great advantage since that could produce net energy rather than deplete it. Nitrate reduction in barley leaves is twice as great in light as in darkness and is apparently driven by both glycolytic reactions and chloroplast-cytoplasm shuttling systems involving recently fixed products of photosynthetic CO_2 fixation. Hence, photosynthesis, as affected by light, temperature, and CO_2 and O_2 concentrations, can greatly affect the utilization of NO_3^-, NO_2^-, and NH_4^+. Direct links to photosynthesis make more energy available for growth.

NH_4^+ and urea can be assimilated in both roots and leaves. In darkness the assimilation of NH_4^+ is driven by respiration, whereas in leaves in light photophoshorylation can furnish the ATP requirement, and photosynthetic electron flow can furnish the necessary ferredoxin. NH_4^+ can be assimilated both in the chloroplast and cytoplasm.

Plants contain large amounts of urease, which converts urea to NH_4^+ and CO_2. The resulting NH_4^+ is then assimilated as above. It appears that plants can tolerate higher levels of urea than of NH_4^+. That may be due to a slower formation of NH_4^+ from urea once inside the plant, such that the steady-state concentration of NH_4^+ remains lower than with NH_4^+ applications.

Assimilation of Mixed Sources of Nitrogen

Presentation of a mixture of the above N compounds to the plant introduces problems that the plant generally does not face. Under ordinary conditions, with NO_3^- as substrate, the steady-state concentration of NO_2^- is very low and that of NH_4^+ somewhat higher, both the latter being reduced almost as rapidly as they are formed. When NO_2^- and NH_4^+ are present in the substrate solution, large amounts can be taken up, flooding the cytoplasm with concentrations of each usually not present. That can inhibit NO_3^- reduction under these unusual conditions since NO_3^- reduction occurs in the cytoplasm. Since in leaves the mixed N sources can either directly or indirectly utilize photosynthetically derived electrons for reduction, photosynthesis can affect the overall efficiency of utilization. Conversely, the mixed N sources might inhibit photosynthetic CO_2 fixation due to competition for the available electrons required for reduction.

Brief Summary of Results

The presence of NO_2^- in the external solution increased the overall efficiency of the mixed N sources by cereal leaves. The NH_4^+ in the substrate solution decreased the efficiency of NO_3^- reduction, while NO_3^- in the substrate solution increased the efficiency of NH_4^+ assimilation. That observation correlates well with a previously reported enhancement of growth by a combination of NO_3^- and NH_4^+. It appears that the leaves preferentially utilize NO_2^-, possibly to detoxify it. The leaves assimilated urea very efficiently. Overall, the leaves metabolized the mixed N sources very well with a minimum of inhibitory effects. That is not the case with cereal roots. Nitrite greatly inhibited the uptake and assimilation of NO_3^- and NH_4^+. Neither NO_3^- nor NH_4^+ had any effect on NO_2^- uptake or reduction. The roots reduced almost 100% of the NO_3^- absorbed. The effect of NO_2^- on urea uptake and assimilation has not yet been examined. In summary, the presence of NO_2^- greatly decreased the overall efficiency of utilization of mixed N sources in roots while increasing the efficiency of use of mixed N sources in leaves.

PLANT GROWTH IN CONTROLLED ENVIRONMENTS IN RESPONSE TO CHARACTERISTICS OF NUTRIENT SOLUTIONS

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Introduction

This report summarizes the results of the research done during the first year of funding. During the initial series of experiments, emphasis has been given to environmental factors that alter the flux of carbohydrate from the shoot to the root system to support the absorption of nitrogen and the subsequent interaction between nitrogen uptake and whole plant growth. These initial studies have utilized only the nitrate form of nitrogen in order to establish base line reponses for evaluation of future studies utilizing both ammonium and nitrate.

Conclusions have several implications to design and performance criteria for the plant growth facilities of CELSS. (1) In CELSS, where temperature and other environmental conditions can be expected to be relatively stable, utilization of light energy by plants may be more efficient than is indicated from other reports from field environments or short-term experiments where environmental conditions are not stable and steady-state conditions are not possible at a whole plant level. (2) Limited nitrogen supply can affect both the morphological component of photosynthetic efficiency by altering the rate of initiation and expansion of leaf area and the physiological component of net carbon dioxide exchange rates (NCER) per unit leaf area; however, the physiological component of NCER is a reversible change of short duration while leaf area may be more sensitive to a decrease in nitrogen supply and have a longer term impact on efficiency of the lighted area. (3) In a CELSS system utilizing a flowing hydroponics nutrient supply, soybeans can tolerate a wide range in solution acidity when nitrate is the source of nitrogen. Although changes in uptake efficiency of nitrate are characteristic of solution pH, the plants acclimate to a change in solution pH by changes in the morphological component of root mass.

Site of Nitrate Reduction

Reduced nitrogen is a fundamental determinant of plant growth.

At low solution concentrations, since ammonium is already in reduced form, it is rapidly assimilated within the root system to provide a large pool of amino acids for ready transport to growth areas of the plant. In contast, when plants are exposed solely to nitrate, the nitrate must be reduced to ammonium so that availability of reduced nitrogen is controlled by nitrate uptake into the root, transport within the plant to the site of reduction, and the process of nitrate reduction. Since nitrate can be stored in relatively unavailable pools in the root, translocated in the xylem as nitrate to reduction or storage sites in the shoot, or reduced in the root, it is necessary to understand whole plant processes that affect the proportion of nitrate reduced in the root in order to evaluate the contribution of nitrate reduction to the amino acid pool of the root in later studies involving both ammonium and nitrate.

The relative content of nitrate and reduced nitrogen are often used to approximate the percentage reduction within the root of the concurrently absorbed nitrate. Use of xylem exudate for determination of the proportion of concurrently absorbed nitrate that is reduced within the root is valid only if the nitrate and reduced nitrogen originate from exogenous, recently absorbed NO_3^- and not from endogenous pools. In order to distinguish whether the nitrogen in the xylem originated from exogenous or endogenous sources, soybean plants that previously have been exposed only to N14-nitrate were transferred to N15-nitrate; thus, endogenous pools contained only N14 and concurrently absorbed nitrate was labelled with N15. Plants either were decapitated and exposed to N15-nitrate solutions for two hours or were decapitated for the final 20 minutes of a 50-minute exposure to N15-nitrate in the dark and in the light. Considerable amounts of N14-nitrate and reduced-N14 and N15-nitrate were transported into the xylem, but almost all the N15 was present as N15-nitrate. Dissimilar changes in transport of N14-nitrate, reduced-N14 and N15-nitrate during the two hours of sap collection resulted in large variability over time in the percentage of total nitrogen in the exudate which had been reduced. Over a 20-minute period the rate of N15 transport into the xylem of decapitated plants was only 21% to 36% of the N15 delivered to the shoot of intact plants. Based on the proportion of the total amount of N15 that was present in the exudate and in intact plants in the dark as reduced-N15, only between 5% and 17% of concurrently absorbed N15-nitrate was reduced in the root. This was much less than the 38% to 59% that would have been predicted from the relative content of total nitrate and total reduced nitrogen in the xylem exudate.

CARBOHYDRATE FLUX TO ROOTS AND NITRATE UPTAKE

The continued uptake of nitrate by intact plants is dependent on the flux of carbohydrate from photosynthate production in shoots and the metabolism of the root carbohydrate. The flux of carbohydrate from the shoot to the root carbohydate. The flux of carbohydrate from the shoot to the root is altered by changes in carbon dioxide concentration and light levels in the aerial environment and carbohydrate utilization in the root is altered by changes in the temperature of the root-zone. Under high light (700 $10E^{-06}$ E m^{-2} sec^{-1}) at ambient carbon dioxide (400 $10E^{-06}$ l l^{-1}), nitrate absorption and root growth were less at 18°C and 30°C than 24°C. Both nitrate absorption and root growth were more sensitive to increasing root temperature under low light (325 $10E^{-06}$ E m^{-2} sec^{-1}) and less sensitive under enriched carbon dioxide (1000 $10E^{-06}$ l l^{-1}). As indicated by dry matter accumulation, net flux of photosynthate to the roots was correlated with the changes in aerial environment. From these relationships it appears that the variation in root growth and nitrate uptake can be attributed to altered utilization of carbohydrates in the roots, and that altered utilization of carbohydrates with increasing root temperature resulted from disproportionate partitioning of carbohydrates among root functions. Although differences occurred in the amount of nitrogen translocated out of the root, nitrogen accumulation in the shoot was primarily a function of nitrate absorbed. Restrictions in dry matter accumulation in the shoot were similar to the restrictions observed in the root. A decrease in the emergence of new leaves was often the first response observed, with decreases in leaf area and dry weight occurring later. The integrated plant response to moderate root temperature stress is interpreted as evidence for an interdependent plant system, predominately regulated by carbohydrate flux to the root and nitrogen flux to the shoot.

Although changes in carbon dioxide and light in the aerial environment altered photosynthate production on a plant basis, most of the increased photosynthesis resulted from an interaction with nitrogen assimilation in production of new leaves and expanded leaf area. The steady-state rate of photosynthesis per unit leaf area was not different over the range of light carbon dioxide levels even though light levels were below the saturation levels reported from field and detached leaf studies. These results indicate that in CELSS, where temperature and other environmental conditions are stable, utilization of light energy by plants may be much more efficient than in field environments or short-term experiments where other environmental conditions are not stable and steady-state conditions are not possible at a whole plant level.

EFFECT OF SOLUTION pH ON NITRATE UPTAKE

Absorption of nitrate by plants is a function of changes in root mass and the specific uptake rate (nitrogen uptake rates per unit root mass). The effects of acidity on these separate components of total nitrate absorption by non-nodulated, vegetative soybean plants were examined during a 30-day growth period in flowing solution culture. The acidities of nutrient solutions were maintained at pH 6.1, 5.1 and 4.1. Root growth rates were reduced by increasing acidity for about 20 days, but then recovered to rates which exceeded those at low acidity so that root mass in all treatments were similar after 30 days. In contrast, the specific uptake rate of nitrate was enhanced by increased acidity within the first day of exposure to rates that remained constant throughout the treatment period. Plant uptake of nitrate and shoot growth declined until about day 20 as root growth was continually restricted, and thereafter recovered to rates which exceeded those at low acidity in parallel with the recovery in root growth rates. The coordinated acclimation of root and shoot growth rates to acidity is interpreted as consistent with the concept of interdependency of root and shoot functions. These results indicate that in soution culture in a CELSS, soybeans can tolerate a wide range in solution pH when nitrate is the sole source of nitrogen.

TO PRODUCE NUTRIENTS FOR PLANT GROWTH

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On July 1, 1979 a new research program entitled "Development of a Prototype Experiment for Treating CELSS and PCELSS Wastes to Produce Nutrients for Plant Growth" was undertaken by the Massachusetts Institute of Technology and the Georgia Institute of Technology under grant from the National Aeronautics and Space Administration's Ames Research Center. The program was designed to be completed over a five-year period, with the work divided into two phases. Phase I covers approximately two years and involves the development of necessary facilities, chemical methodologies and models to allow meaningful experiments during Phase II, which will involve interfacing waste oxidation with plant growth.

Homogeneous samples of freeze-dried human feces and urine have been prepared to assure comparability of results among various CELSS waste treatment research groups. A model of food processing wastes within a PCELSS was developed, and an initial batch of waste was prepared. An automated gas chromatographic system to analyze oxidizer effluents was designed and is operational. A state-of-the-art quantitative elemental analysis capability, built around inductively coupled plasma emission spectroscopy and atomic absorption spectroscopy using electrothermal atomization, has been demonstrated. A continuous flow wet oxidation system was constructed and is now operational. Potentially useful salt separation phenomena have been observed.

FOOD SYSTEMS FOR PCELSS

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Future manned missions, beyond those of the Space Shuttle and Soyuz programs are likely to involve missions of substantial duration and will involve large groups of people, since their objectives may include the development of permanent stations, and/or missions to the planets. In considering extended manned space missions it is necessary to evaluate the potential for regenerative life support systems, including those with limited as well as complete closure. Analysis of problems related to nutrition, diet, and food will be required if a fully regenerative food ecology is to be developed. The questions to be answered in such a long-range program include the following broad categories (each being a parent to a host of subsidiary questions).

A. Nutritional requirements of humans on a limited variety diet, especially while operating under conditions of space environment.

B. Capability of agriculture, waste disposal technology, and subsidiary technological operations to attain a closed-cycle operation adequately supplying the life support needs for the expected population.

C. Need for buffering capacity (storage or resupply capability) to accomodate expected or unexpected breakdowns in regenerative capabilities.

D. Development of an "industrial" base for the conversion of animals and synthetic materials into "food." This will involve the development of food processing, food preparation, food storage, and waste disposal systems adapted to the unique requirements of space colonies.

E. Development of industrial support for the food processing operations. This includes the capability for producing necessary chemicals, energy, and machinery for the space habitat "agribusiness."

In view of the complexity associated with these problems, another option which should be considered is the total or partial resupply or stocking of food for the space colonies. This might range from resupply of a portion of the diet (for instance, of animal-derived foods and of all vitamins and some other essential nutrients with the calorie requirement met primarily by local production) to the resupply of all of the food, with the local regenerative system limited to water and oxygen.

The aim of closed or partially resupplied food production and food processing systems is areliable supply of food that will be be much more complex than simply replicating, on a smaller scale, the food pattern of the United States.

The abundance of food in the United States has given rise to a myth that in order to satisfy the needs of any special feeding situation, the only procedure necessary is to select the appropriate items from among those available in the commercial marketplace. This is untrue. The facts are that foods in the commercial marketplace have been developed to meet specific criteria which are quite different from the criteria for any food systems other than those designed for mass supply of huge populations.

Failure in attempts to adapt commercial foods to specialized feeding situations has been repeatedly demonstrated in the development of camping systems and outdoor recreational supply equipment. Successful life support systems for explorers have only resulted from the development of highly specialized foods. The NASA achievement in food systems for projects Mercury, Gemini, Apollo, and Skylab are major milestones in the development of highly specialized, cost-effective foods to match the specific demands of the special life support system criteria.

Providing a sophisticated and varied food supply for the limited facilities available in space habitats, in conjunction with dietary requirements, is a difficult task. Moreover, the need to optimize nutrient balance and minimize food system mass--while providing an appetizing diet of variety and quality even remotely similar to that enjoyed on earth--presents immense difficulties.

We are currently conducting research on the following aspects of partially closed ecological life support system (PCELSS).

A. Utilization of "Engineered Foods" in PCELSS

Engineered foods are produced by incorporation of natural and/or synthetic components into systems having desired nutritional, organoleptic, and stability characteristics. The development of knowledge about functionality of ingredients provides the basis for development of engineered foods. Since organoleptic properties are by far the most important stimuli for making nutrients into food, development of organoleptic equivalents of engineered foods allows utilization of a variety of nutrient sources no matter what their origin. Furthermore, organoleptic equivalence also permits, for the first time, the construction of nutrient sources to the specification of human need rather than dependence on the vagaries of natural products.

Flexibility is an obvious advantage for many reasons. It will allow a gradually increasing level of incorporation of space-grown food ingredients into the engineered food system (if at least part of the food preparation in done in the habitat); it will allow choice of components, particularly to resupply (because of stability, palatability or other considerations); and it will allow modularization of the diet, which could be invaluable in case of changes in requirements or in supply.

Our research has the following objectives:

1) Evaluation of the feasibility of developing acceptable and reliable engineered foods from a limited selection of plants grown in the ground based CELSS demonstrater (GBCD), supplemented by microbially produced nutrients and a minimum of dehydrated nutrient sources (especially those of animal origin). This evaluation will include analysis of physico-chemical compatibility of ingredients and of presently available engineering capabilities for production of such foods under GBCD and eventually CELSS conditions, as well as for integration of regenerative and resupplied components.

2) Evaluation of research tasks and specification of research projects to adapt present technology and food science to expected space conditions. In particular, problems arising from unusual gravity conditions, problems of limited size and the isolation of the food conditions for improved processing storage operations (for instance, opportunites of oxygen-free storage systems) will be considered.

3) Evaluation of food conversion operations appropriate to specific scenarios of food production within PCELSS. The specific PCELSS-related requirements of these food conversion operations include: a) flexibility (one process to serve as many of the needed products as possible); b) miniaturization of equipment (expected small scale of operation); c) minimal maintenance needs of equipment; and d) adaptability to special space requirements.

B. Development of Waste Treatment in PCELSS

We are collaborating with Dr. M. Modell at MIT and Dr. J.

Spurlock at the Georgia Institute of Technology in the development of a prototype experiment for treating CELSS and PCELSS wastes to produce nutrients for plant growth. Our task in this project is the development of a model of waste materials generated by food processing operation, and to prepare freeze-dried samples of such a composite model for use by our collaborators in testing analytical and waste conversion procedures.

GENERIC WASTE MANAGEMENT REQUIREMENTS FOR A CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEM (CELSS)

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Introduction

Controlled ecological life support systems (CELSS) are projected to be used in space stations or spacecrafts containing human occupants on long missions. The basic concept of a CELSS is 1) to process and recycle wastes generated by the human occupants and their activities; 2) to regenerate food and revitalize air from these recycled waste materials; and 3) to maintain a material balance within the system. The system elements include the human occupants, a waste management subsystem, and a sustenance (food, water and air) regeneration subsystem. The concept of regeneration or recycling requires that each subsystem be integrated with another subsystem. One subsystem's outputs must match the other subsystem's needs and must be within the tolerance ranges in terms of quantity and quality of required materials.

Waste management in a CELSS is defined as the pretreatment and the digestion/conversion of the various waste materials. In the management of human urine, the removal of salt (sodium chloride) before processing can be considered a pretreatment step. The reduction in particle size and adjustment of moisture content of the feedstock are other possible pretreatment steps. For biological waste management the pretreatment of the waste input would involve such factors as the removal of non-digestibles such as plastic wrappers and space industry wastes. Also, substances that are toxic to waste digestion organisms must be removed or reduced to a benign level. We have only touched on a few of the possible pretreatment topics, and because this paper will focus on waste processing, pretreatment will not be discussed further.

In this discussion, we are primarily concerned with the waste processing subsystem and its generic requirements. It is assumed that 1) the waste processing output will be given to photosynthetic plants that will serve as food and oxygen sources, and 2) the waste input will be from humans living on a vegetarian diet. The mineral output of the waste processing subsystem by and large is assumed to be in the conventional salt form, although complexed states are also considered. Furthermore, various forms of plant culturing media will be considered from the viewpoint of the possible output from the waste processing subsystem.

Not discussed are the energy requirements, the mineral balance and exchange rates, the regimes of light and temperature, and precisely detailed accounting of such wastes as perspiration and hair clippings from humans and the loss of nitrogen in the cabin atmosphere.

We will focus on the various constituents of the wastes that will be used as feedstock for the waste processing subsystem and on the resultant products that will be generated. The quality of the waste input is of prime consideration. The ratio of the chemical elements in the waste such as nitrogen, phosphorus and carbon must be known, and hopefully they would be in the proper ratio for plant production.

If the crew size and daily activity are constant, the input into the waste processing subsystem would probably be uniform and highly predictable. Also, waste processing and food production would not change to any extent each time the materials were cycled through.

Sources of Waste

Most early studies on controlled environmental systems have been devoted to the incineration and storage of wastes. These systems were of the open type where stored food, water and oxygen were used to maintain the human occupants. Only recently have research and development efforts focused on systems where food, water and oxygen are to be regenerated within a spacecraft. Thus, in a life support context, few of the data available on wastes generated from food production and processing or from scientific and industrial activities are as complete as those on human waste data [1]. This represents an area where research needs to be done and data gathered.

The various sources of wastes that will be processed by the waste system are identified as those from human occupants, food production, food preparations, housekeeping, scientific activities, and industrial processes.

Wastes from the human occupants in terms of types and quantity have been documented by Spurlock et al. [1] in their study which evaluated and compared three different water/solid waste processing systems for a simulated spacecraft. Their tables defined in some detail the wastes in terms of the major chemical elements. Earlier, Putnam [2] analyzed human urine not only for the various elements but also for the various ionic states and for chemical compounds. (NaCl, urea, creatinine and ammonium hippurate were the four major compounds among many described).

These studies and that by Ingram [3] provide good qualitative and quantitative data on the waste products from the humans. The data provided can form a reliable reference for human waste input to a waste processing subsystem.

A study on housekeeping waste indicates that more than half of the waste was in the cellulosic form with nearly equal parts of paper and cotton materials [1]. In food production and preparation processes, the non-edible portion of the plants, parts removed during preparation for cooking and long-term storage, and the leftover wastes from cooking and eating will represent the types of wastes that will need to be defined and quantified.

Wastes from scientific and industrial activities will naturally depend on the work being performed and will probably vary greatly. However, one might expect outputs like washwater, various dissolved chemicals in the form of acids, bases and salts. Waste gases from instruments, paper trash, filter materials and containers may also be present as waste products. Industrial wastes might include debris from various cutting and shaping tools. Chemical byproducts which may result in air pollutants are another factor.

General Requirements For Plant Growth

For higher plants to grow, sunlight, proper temperatures, pH, water, carbon dioxide and various minerals are required. Oxygen is also required for the respiring cells and is generally supplied as a by-product from photosythesis.

One of the main tasks of waste management is to provide the materials necessary for plant growth. Physical conditions such as light in one form or another and proper temperature range will be provided by the environmental system and are not a direct concern of the waste management subsystem. Oxygen will only be mentioned here briefly to indicate that it is a necessary element but can be supplied by the photsynthetic process and is not considered a product from the waste processing subsystems. Likewise for pH, the level can be monitored and controlled. The only thing to be said here is that for optimal mineral availability, the pH of the root medium should be maintained between 6.2 and 6.8.

Water provided to plants will come from the waste stream. It will ideally be purified only to a level where the plants can readily grow in it [11]. If hydroponic or aeroponic culture is used, the removal of organisms such as protozoans, algae, bacteria and fungi from biological systems will more than likely be required to minimize buildup of organisms in the root chamber. If soil or modified soil is used, the change of environment from a liquid to an open aerated soil matrix may minimize the growth of the waterborne organisms and removal may not be necessary. Also, competition from native soil organisms (if these are permitted to exist) may minimize this problem. Studies will probably have to be done to determine this.

The gas, carbon dioxide (CO_2), will be generated mostly by the humans and the waste processing subsystems. Any living cell, whether animal or plant, will respire and produce CO_2. Thus, even plants will produce it and especially so when photosynthesis is not occurring. If methane gas or other hydrocarbons produced for an energy source are burned, one of the end products will be CO_2.

The types of minerals required by higher plants have been well defined [4]. Table 1 lists the various elements that have been found to be essential for plant growth and their nominal ionic state and concentration in a hydroponic nutrient solution (Cf. essential elements for animals/humans, Table 4). The nutrient solution is an unnatural environment for the roots and is not representative of conditions found for plants growing in soil. The striking difference of the lower concentration of certain minerals in a natural soil solution is evident [5]. Most striking is the phosphate ion, which is several orders of magnitude lower in concentration in the soil solution. The difference lies in the fact that most of the phosphorous is in the soil matrix and is released slowly as it is needed. Thus the rate and amount of each mineral given to and taken up by the plants is not a simple straightforward procedure. It may depend on the type of medium the plant is grown in. Table 2 lists some considerations for nutrient solutions used in different root media and is discussed in the next section.

Even though the rate at which the various minerals are needed is not precisely known for various species, the form in which they can be absorbed is known. The mineral nutrients are listed in those forms in Table 1 and are the desired form as output from the waste processing subsystem. Not listed is the NH_4^+ (ammonium) form of nitrogen that is frequently used in nutrient solutions to minimize pH shifts as the nitrogen is taken up. This form of nitrogen can be derived from urea, contained in urine, via the urease reaction and is also the form derived from an anaerobic digester.

The output from the waste processing system must not only have the plant nutrients in the proper form but also in the proper proportions. The proportions needed for each selected species would be different and will also be different as the plant grows from seedling to a mature plant producing a crop. The elemental proportion in the tissue of the mature corn plant is given in Table 3. It is interesting to note that the elemental chemical percentages of corn are surprisingly close to those from mixed municipal waste [7] and also to a hypothetical 6-man crew waste output [1]. It appears that with the values so close there may be few major adjustments required in the element ratios before the processed waste materials are applied to plants. Human urine, however, may require removal or dilution of NaCl. Along this line of thought, the greenhouse hydroponics trials by Wallace et al. [11] has shown that processed sewage water from Calabasas, California can more than adequately support the growth of horticulture species (see Table 4). The difference in mineral concentration of the processed sewage water from the usual hydroponic concentration is quite large for several minerals, yet plants like tomatoes, lettuce and cucumbers grew very well.

Further information on the materials taken up and used by plants can be obtained from various tissue culture media. In addition to the inorganic elements listed previously for nutrient solutions, various organic compounds such as sugars, vitamins and growth substances have been used to promote growth in tissue culture. These substances, which are listed in Table 5, will more than likely appear in the output from waste processing, and some of these could be recovered and used either by plants or by the crew. Whether such supplements as these can be effectively used by higher plants grown in CELSS needs to be studied.

Plant Culturing Systems

A discussion of various plant culturing systems is presented to delineate the output requirements of the CELSS waste processing subsystems and to elucidate some of the factors that need to be considered in integrating the CELSS subsystems. The media for growing plants can be generalized into three broad categories. These are soil, modified soil and hydroponics, including aeroponics (see Table 2).

Soils of different types are the traditional media that have been used from time immemorial. Soil is generally stable and can be used for many years with fertilization to replace consumed minerals. Soil has a good buffering capacity and can retain nutrients in various forms. It is a very complex medium and is therefore very difficult to define and duplicate. Thus, being an undefined medium, soil appears not to be a good candidate for a highly defined, controlled regenerative life support system. The outstanding quality of soil is, however, its stability and high buffering capacity.

Modified soils are used extensively in horticulture and are quite varied in composition. Because these soils are made up artificially, their composition can be fairly well defined. These modified soils have many of the attributes of natural soil except for stability. Generally one or more of the components breaks down after a period of time and needs replacement. Occasionally, detrimental products are formed. Expanded mica is one example, where the spent, flattened remains are not conducive to good plant growth.

Hydroponic culture is a method where plants are grown with their roots immersed in a water solution containing nutrient chemicals. These chemicals must be replaced as they are taken up by the plant. If nitrate is not replaced, the pH of the solution will drift to the alkaline side as the nitrate nitrogen is removed by the plant. The task of replacing nutrients, maintaining pH and osmotic pressure, and replacing the water absorbed and transpired becomes rather arduous, especially as the plant size increases relative to the volume of hydroponic solution. Aeroponic culture is basically the same as hydroponic culture. The solution is sprayed on the roots in a fine mist instead of continually bathing the roots. This system has the advantage of low solution volume and weight per plant as compared to the other culture systems.

Nutrient solutions are also applicable for the straight soil and modified soil cultures. The nutrient solution can be used to irrigate the crops with the nutrient concentration in the solution adjusted to the water consumption rate of the crop irrigated.

An alternative method would be to process the waste partially and supply the materials to the plants in the form of complex molecules which can enter and be used by the plants [8]. Partially digested waste materials could be given to plants in a form similar to a mulch which would be degraded further. A strategy much like that found in tropical rain forests is envisioned here. The litter or mulch placed on the soil surface would then be decomposed by the soil organisms, and the products would be taken up by the mycorrhiza and plants with little loss of the nutrients.

The liquid portion of the waste would also contain dissolved complex compounds along with the simple mineral salts and would be given to the plants as part of the watering process. Examples of the complex compounds might be various sugars, auxins, cytokinins and vitamins. These are compounds that are readily found in plant tissues and have been used in tissue culture media (see Table 5). The effect of such a method on the total size of the regenerative system will have to be considered. The root medium volume will probably increase from the application of the partially digested waste, but concurrently, the waste processing subsystem may be decreased more than proportionately, and possibly the chemical processing unit necessary to formulate the nutrient solution may be eliminated or greatly reduced.

Output Requirements to Match Candidate Plants

The amount of various elements in an optimal growing medium for individual crops can vary greatly. The optimal concentration and ratio of elements will have to be determined for each crop species [10]. Determining the mineral content of a plant tissue can give an indication of the amount of the various elements that are needed for particular crops [5]. However, such data may be misleading because some elements can be absorbed in excess of the plants' metabolic needs, especially if the element happens to be readily available [5].

A more important factor to determine is the tolerance range of the plants to different mineral concentrations in the nutrient solution. Tolerance end points are poorly defined for man elements. Along this line of thought, high-salt-tolerant varieties can be selected to broaden the tolerance range. Supernatant liquids from waste systems having higher than normal nutrient solution concentrations could be used with a minimal amount of processing, thus saving time, energy and equipment. A study has been mentioned earlier [11] in which processed sewage water was given to plants as a hydroponic nutrient solution. In this case, the Na^+ and Cl^- concentration was much higher than would be found in a normal solution. On the other hand, the total mineral content was about half. With the addition of iron, and using standard horticultural varieties, tomatoes, cucumbers, lettuce and chrysanthemums of good commercial quality were grown. Though good quality vegetables and flowers were grown with processed sewage water from Calabasas, California, the possible change in the quality of the crop in terms of taste, nutrition and handling will have to be determined for the CELSS type of waste water. The results of the Calabasas experiment [11] can be considered as a very preliminary integration of a waste processing subsystem and a food production (plant cultivation) subsystem.

Integration of Subsystems

The possiblilty of integrating the waste processing subsystem with a higher plant subsystem appears to be feasible from available data. The elemental concentrations of different treated sewage water and sludges are varied, but each can support plant growth (Table 4). On the other hand, it can be said that the tolerance range appears sufficiently wide for plants to grow well on these various media and nutrient solutions (Tables 1 and 4).

Mineral analysis of plants grown on processed sewage water revealed that their roots had higher trace element concentrations than their leaves, indicating increased partitioning in the roots [11]. Further studies are needed to determine the partitioning effects on the various elements within subsystems. When waste is recycled repeatedly through a waste processing subsystem, an accumulation or a biomagnification effect for particular minerals may occur. Not only may there be an accumulation but a depletion may occur in particular subsystems. Binding or complexing into the matrix of a subsystem or organism may bring this about. The high concentration of nickel and chrome in metropolitan sewage may be indicative of possible accumulation problems for CELSS. The source of these two elements is believed to be stainless steel, which may be used extensively in a space station. Other similar situations must be considered.

Summary

The two major requirements of a waste processing subsystem are that it process wastes from humans, food production, and station activities; and that it convert these wastes into forms usable by humans and the higher plant subsystem. Based on the chemical composition studies of representative wastes [1, 2, 3], it appears feasible to produce the required effluent for growing higher plants using as a model the processing method and effluent composition of a metropolitan sewage plant [7, 11, 12]. The range of plant nutrient concentrations in the effluent could be from those of a nutrient solution [5] to those of the Calabasas type composition, which is high in NaCl and low in macronutrients [11]. Definitive requirements for the compositional range of higher plant nutrients cannot be set at this time, since the nutrient tolerance range of candidate plants are as yet undefined for many of the elements.

In the integration of a waste processing subsystem with other subsystems, the optimal operation of the total CELSS system must be considered. The total system may impose constraints and requirements on the waste subsystem that force it into less than optimal operating conditions. Thus, defining the viable operational range of any subsystem becomes important. We stress this concept here because it leads to a particular approach for the CELSS research and defining requirements for a waste management subsystem.

Acknowledgements

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TABLE 1. NUTRIENT CONCENTRATIONS IN NUTRIENT AND SOIL SOLUTIONS

		Nutrient Solution			Soil Solution
Major Elements	Ionic Form	Range in Moles[1]	ppm [1]	ppm [2]	ppm[3]
Nitrogen	NO_3^-	0.005 - 0.010	310-620	224	101-150
Phosphorous	PO_4^{3-}	0.00025 - 0.002	28-190	62	0.-0.03
Sulfur	SO_4^{2-}	0.001 - 0.010	96-960	32	26 - 50
Potassium	K^+	0.002 - 0.010	78-390	235	21 - 40
Calcium	CA^{2+}	0.002 - 0.005	80-200	160	51 - 100
Magnesium	Mg^{2+}	0.001 - 0.010	24-240	24	51 - 100
Minor Elements					
Iron	Fe^{2+}		0.5	1.12	
Boron	BO_3^{3-}		0.25+	0.27	
Manganese	Mn^{2+}		0.25	0.11	
Zinc	Zn^{2+}		0.25	0.131	
Copper	Cu^{2+}		0.02	0.032	
Molybdenum	MoO_4^{2-}		0.01	0.05	
Chlorine	Cl^-			1.77	

1. Levitt, 1974 (6). 2. Epstein, 1972 (5). 3. Concentration range found in largest percentage of samples, Epstein, 1972 (5).

TABLE 2. CONSIDERATION OF NUTRIENT SOLUTIONS FOR HYDROPONIC, AEROPONIC AND "SOIL" CULTURES

FACTORS	HYDROPONIC	AEROPONIC	ROOT MEDIA - "SOIL"
Nutrient System - General Description	Liquid Solution: Bathes plant roots	Mist: Thin film on plant roots	Soil Solution: Thin film on media particles and roots
Amount Required/ Plant	High Volume of solution	Low volume	Moderate-portion stored in rood media
Weight/Plant	High	Low	High
Respiration Oxygen Needs	Requires aeration system	Misting results in areation	Present as result of porous root media
Nutrient Concentration	High, e.g., nitrogen 310-620 ppm	High, e.g., nitrogen 310-620 ppm	Low, e.g., nitrogen 101-150 ppm
Nutrient Sources	Restricted to nutrient solution	Restricted to nutrient solution	Replenished from root media
Supply and Maintenance of Nutrients	Needs frequent maintenance and adjustments Amenable to adjustments	Needs almost daily replenishment of some Amenable to adjustments	Adequate amounts of nutrients can be stored on media matrix Not readily adjusted. additional nutrients can be added
pH	Susceptable to variation of remaining nutrient ratios	Susceptible to variation of remaining nutrient ratios	Buffered by ion exchange capacity of media

TABLE 3. PERCENT OF DRY WEIGHT ELEMENTAL COMPOSITION

ELEMENT	CORN[1]	6 MAN CREW[2] WASTE OUTPUT	MIXED[3] MUNICIPAL WASTE	URINE[4] INORGANIC SALTS	SEWAGE[5] SLUDGE ANALYSIS
O	44.43	25.9	42.2	8.26**	
C	43.57	52.4	50.0	6.9	23.29
H	6.24	8.0	6.7	1.5	
N	1.46	4.7	0.97	8.1	2.0-5.9
K	0.92	-	-	2.43	0.68
Ca	0.23	-	-	2.24	0.25
P	0.20	-	-	0.05	0.8-5.0
Mg	0.18	-	-	0.20	0.5
S	0.17	0.08	0.22	0.69	
Cl	0.14	-	-	5.63	
Fe	0.08	-	-	-	1.23
Na	-	-	-	3.15	1.63
Mn	0.04	-	-	-	0.028
Zn	-	-	-	-	0.1
Ash	*3.07	*8.2	-	-	

* The equivalent values from corn were lumped together to make a comparison. 3.07 represents the minimum value to compare to the ash from 6-man crew data.
** Urine values are in g/l for comparison
1. Epstein, 1972 (5). 2. Spurlock, et al., 1975 (1). 3. DeRenzo, 1977 (7). 4. Putnam, 1970 (2). 5. Lindstrom, 1974 (12)

TABLE 4. CONCENTRATIONS OF ELEMENTS ESSENTIAL FOR PLANTS AND ANIMALS IN PPM†

ESSENTIAL* ELEMENTS FOR		PROCESSED[1] SEWAGE WATER	DIGESTED[2] SEWAGE SLUDGE	HORTI-CULTURAL[2] SLUDGE	PLANT[3] NUTRIENT SOLUTION
ANIMALS (Human)	PLANTS				
N	N	17	12**		224
K	K	13	5	6**	235
Ca	Ca	66		21	160
P	P	11	4	3	62
Mg	Mg	33		0.8	24
S	S	83			32
Cl	Cl	109			1.77
Fe	Fe	0.1	8	8	1.12
Na	--	45.8		5	
Mn	Mn	Trace		0.1	0.11
Zn	Nz	0.059	0.8	7	0.13
Cu	Cu	0.009	0.4	0.05	0.032
-	B	0.92		0.003	
Mo	Mo			0.001	
Co	-			0.005	
Se	-	0.02			
Ni	-	0.06	0.06	0.08	
V	-			0.002	
Cr	-	0.008	0.25	7	
Si	-		10	40	
As	-	0.001			

* C, H, O Have been left out. Also I, Sn, F for animals
** Values converted from dry weight to dissolved concentration of 0.03% solids in solution for comparison
† Elements not measured were left blank in sludge composition
1. Wallace, et al, 1978 (11). 2. Lindstrom, 1974 (12). 3. Epstein, 1972 (5).

TABLE 5. CONCENTRATION OF NUTRIENTS IN FIVE MEDIA FOR PLANT TISSUE CULTURE[1]

	White (1943)	Heller (1953)	Murashige & Skoog (1962)	Gamborg (1968)	R-2 (1973)
(1) Inorganic macroelements (mM)					
NO_3-N	3.2	7.1	40	25	40
NH_4-N	-	-	20	2.0	5.0
P	0.14	0.90	1.3	1.1	2.0
K	1.7	10	20	25	40
Ca	1.2	0.51	3.0	1.0	1.0
Mg	3.0	1.0	1.5	1.0	1.0
S	4.4	1.0	1.6	2.0	3.5
(2) Inorganic microelements (mg/l)					
Fe	0.70	0.25	5.6	2.8	2.5
Mn	1.8	0.025	5.5	3.1	0.50
Zn	0.68	0.23	2.0	0.45	0.50
B	0.26	0.18	1.1	0.53	0.50
Cu	-	0.007	0.01	0.14	0.05
Mo	-	-	0.10	0.10	0.05
Co	-	-	0.006	0.006	-
I	0.018	0.002	0.63	0.57	-
Al	-	0.006	-	-	-
Ni	-	0.007	-	-	-
(3) Organic nutrients (mg/l)					
Nicotinic acid	0.5	-	0.5	1.0	-
Thiamine-HCl	0.1	1.0	0.1	10	1.0
Pyridoxine - HCl	0.1	-	0.5	1.0	-
Glycine	3.0	-	2.0	-	-
m-Inositol	-	-	100	100	-
2,4-D	-	-	-	2.0	2.0
IAA	-	-	1-30	-	-
Kinetin	-	-	0.04-10	-	-
Sucrose	20g	20g	30g	20g	20g

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WET OXIDATION AS A WASTE TREATMENT METHOD IN CLOSED SYSTEMS

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The chemistry of the wet oxidation process has been investigated in relation to production of plant nutrients from plant and human waste materials as required for a closed life support system. Hydroponically grown lettuce plants were used as a model plant waste, and oxygen gas was used as an oxidant. Organic nitrogen content was decreased 88-100%, depending on feed material. Production of ammonia and nitrogen gas accounted for all of the observed decrease in organic nitrogen content. No nitrous oxide (N_2O) was detected. The implications of these results for closed life support systems are discussed.

The ability to create life-sustaining environments totally separate from the biosphere is of theoretical and practical interest. Whether or not a system can ever be completely self-regenerating, with the only external requirement being energy, is not yet known. However, nearly closed systems with resupply requirements of only 100 g/person-day are conceptually feasible. It is the intention of this research to decrease this requirement.

In this work, only those life support systems that regenerate food by use of higher plants are considered. In addition to being edible, plants produce oxygen and transpire large amounts of water, which can be consumed after collection and purification.

The function of a waste treatment system in such a closed system is to convert waste materials (metabolic wastes and inedible plant matter) into plant nutrients (carbon dioxide, water, and necessary minerals). Wet oxidation is a treatment process that shows promise for closed-system applications.

In wet oxidation, aqueous suspensions of organic matter are heated with oxygen or air at elevated pressure. The operating temperature for wet oxidation is much less than for incineration, presumably because of the lower reactant concentrations in wet oxidation. Liquid water exists under these conditions, hence the name of the process.

Carbon dioxide can be obtained in near-quantitative yield in the wet oxidation of waste materials. The residual organic matter consists primarily of low molecular weight organic acids.

Considerably less is known concerning the fate of organic nitrogen in the process. Ammonia is a major product of the reaction; however, the amounts found do not account for the measured decrease in organic nitrogen content. The extent of this deficit is shown is Figure 1 (data for preparing this figure were taken from Wheaton et al., 1967). A mixture of urine and feces was heated at 500 psi oxygen pressure at the indicated temperature for about 15 minutes. Ammonia and organic nitrogen in the products were measured and compared to their initial values (left ordinate). In all cases the nitrogen content of the residual organic nitrogen and the ammonia product was less than the initial nitrogen content of the waste materials, indicating the formation of other nitrogenous products. At higher operating temperatures, larger nitrogen deficits were found.

The production of other nitrogenous products of wet oxidation has been examined. Neither nitric oxide (NO) nor nitrogen dioxide (NO_2) were detected in the product gases. The liquid effluent has been shown to contain negligible amounts of nitrite and nitrate.

We have found in this work that nitrogen gas (N_2) is a product of the wet oxidation of a variety of waste materials, and that the amount of nitrogen gas produced accounts for the deficits observed in earlier reports.

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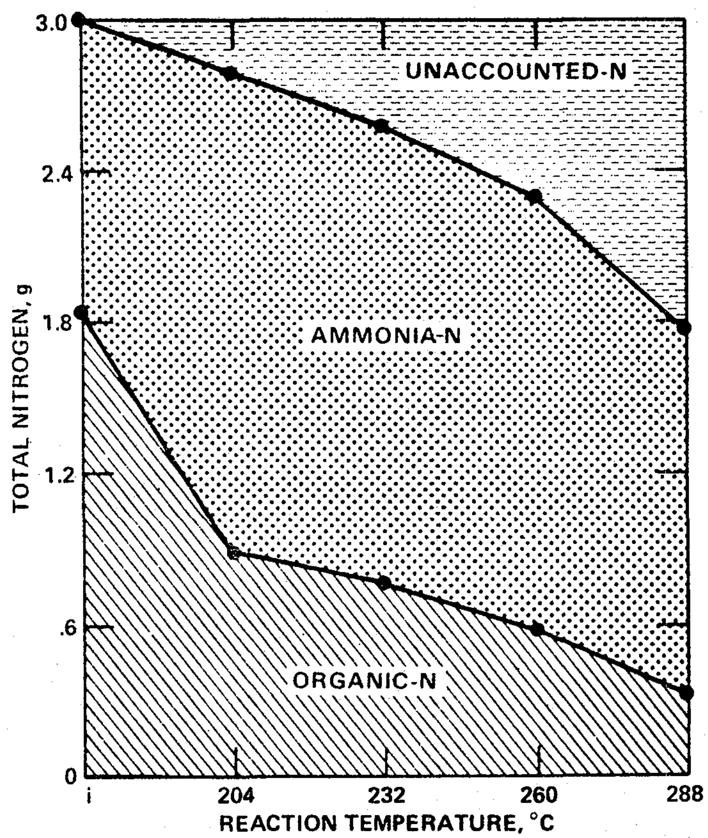

Fig. 1 Amounts of organic nitrogen, ammonia nitrogen, and unaccounted nitrogen found either initially (left ordinate, i) or after reaction of a mixture of urine and feces at 500 psi oxygen, and the indicated temperature for 15 minutes. Data are taken from Wheaton et al., 1967.

SOME ISSUES IN COMPARABILITY OF RESULTS AND ANALYTICAL METHODOLOGY IN CELSS WASTE PROCESSING RESEARCH

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From 1966 to 1975, NASA sponsored incineration research at General Electric Co. and General American Research Division (GARD) and wet oxidation research at Lockheed. When an attempt was made to use the experimental results of these programs to compare critically the processes involved (1), it was found that the input model wastes were sufficiently different to preclude direct comparisons. To optimize the value for critical trade-off analyses of waste processing results obtained in the CELSS program, all researchers are strongly encouraged to use waste materials from a single lot. We have contributed to this effort by providing to CELSS researchers standard waste materials including: human feces and urine, food preparation and processing waste and hydroponically grown wheat.

The human feces and urine were obtained from the Human Nutrition Research Laboratory of the US Department of Agriculture. The feces and urine were excess materials from nutrient balance studies in which the subjects were fed well characterized diets. The feces and urine were collected under carefully controlled conditions, blended, and freeze dried. At Georgia Tech, additional grinding was performed to reduce the aliquot size required to obtain a representative sample. Feces and urine samples were obtained from the USDA in two batches with the final batch being received in May 1981. Approximately 3 kg each of feces and urine are available for CELSS projects.

Professor Marcus Karel of the Department of Nutrition and Food Sciences at MIT prepared a model food processing waste based on the "1974 Thrifty Diet." Resupply from earth of meat, milk, eggs and some fruit was assumed, while conventional oil and sugar processing and wheat milling were included. Detailed information on the model waste is available. The model waste was prepared in two batches. We currently have approximately 1 kg of material from each batch available for CELSS projects. Additional quantities are available from Prof. Karel.

We built a hydroponic system to grow wheat for use as a standard waste material. The rationale for hydroponic growth was to minimize the presence of soil minerals in the standard waste which would not be present in the inedible portions of wheat requiring waste processing in a CELSS. The wheat plants were grown to fruiting, freeze dried, and ground in a planetary ball mill. The total dry mass obtained was considerably smaller than anticipated, perhaps requiring additional crops. For an average plant the freeze dried masses were as follows; roots 23 mg, stalks and leaves 370 mg, and wheat 93 mg. The total freeze dried mass obtained was 120 g.

We are currently in the process of analyzing all these materials for the elements believed essential for plants and/or animals. These elements include H, B, C, N, Na, Mg, Si, P, S, Cl, K, Ca, V, Cr, Mn, and Fe. Analytical techniques being used include inductively coupled plasma emission spectroscopy (ICPES), atomic absorption spectropscopy (AAS), instrumental neutron activation analysis (INAA), and x-ray fluorescence spectroscopy (XFS). It is anticipated that all analyses will be completed by the end of August 1981.

In addition to providing standard waste materials, we have been involved in the evaluation of techniques for chemical analysis applicable to a CELSS. As with many other areas of environmental monitoring and research, the central problem is to be able to quantify a broad spectrum of elements efficiently and reliably in a short period of time. We investigated the applicability of INAA, XFS, ICPES and spark-source mass spectrometry (MS). All of these techniques have some shortcomings for monitoring in a CELSS. Spark-source MS is very fast and can be applied to all elements of interest, but they cannot be reliably quantified. INAA requires radiochemical separations to be applicable to a substantial fraction of the elements of interest and is thus a very slow and tedious technique. XFS suffers from serious matrix problems and does not have adequate sensitivity for most of the trace elements of interest. ICPES can quantify most of the elements of interest, but the sample must be in solution for analysis.

Thus all of these established multi-element techniques have some shortcomings. Based on our review the most promising technique for general environmental analysis is ICPES augmented by furnace AAS for ultratrace components.

The ICPES technique is quite new, with commercial instruments appearing on the market within the last five years. The technique is now commercially available utilizing two distinct types of instruments: simultaneous or direct readers, which use a polychromator to disperse the radiation produced in the plasma and a set of fixed detectors, one for each element of interest; and sequential or scanning systems, which use a monochromator to isolate the emission band of interest at the detector. Simultaneous readers are very fast (and expensive) but lack flexibility since the set of elements which they can detect is fixed.

We have a Perkin-Elmer ICP-5000 scanning system in our laboratory and have used it to analyze a variety of samples related to waste processing. The technique is truly flexible in terms of both the set of elements it can quantify and its linear concentration range. Stability, reproducibility, and reliability have posed serious problems, however, and our instrument is currently being modified by the manufacturer to overcome them.

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AIR POLLUTANT PRODUCTION BY ALGAL CELL CULTURES

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Significance

As man attempts to utilize environments which are increasingly hostile to biological processes, it has been necessary to create artificial environments which can be completely isolated from external environmental stresses. Great success has been achieved in simulating natural environments in closed systems for either humans, higher plants or microbes. In the development of closed systems compatible to a wider range of living organisms, unforeseen problems have become evident. One problem has been reported from the experiments carried out by Kortayev *et al*. (1) and Gitelson *et al*. (2). In a closed system with algal cultures and higher plants, there is a marked reduction in growth of the higher plants, with eventual plant death. The plants appear to recover once the two systems are separated from each other. This suggests the possibility of an air pollutant being introduced by the algal culture into the common air stream. Algae and higher plants are known to produce volatile by-products. The production of even the smallest amounts of toxic substances will accumulate over time in a closed system and would result in injurious effects on the most sensitive component of the closed system. Only after careful identification and evaluation of the production rates of potentially toxic gases by algae will it be possible to recommend changes which would permit the integration of algal and higher plant production units in closed systems.

Research Findings

Axenic cultures of *Euglena gracilis* var. *bacillaris* and *Chlorella vulgaris* Beijerinck (Berlin strain), have been grown in culture volumes ranging from 250 ml to 15 l. The effluent air from these cultures was passed to either gas washing bottles or to plexiglass chambers which contained wheat or bean seedlings. The plants were kept watered and illuminated throughout the fumigation.

Euglena gracilis

Phytotoxic gases were produced from actively growing cultures of both wild type (photosynthetic) and aplastidic (nonphotosynthetic) strains of Euglena, which were grown on heterotrophic media. Following fumigation with effluent gases from 24 h, bean seedlings showed several signs of injury: A) wilting of leaf blades which was followed by complete desiccation that started in the intervenal regions; B) initial chlorosis of mid-petiole stems which ended with their collapse; and C) anthocyanin accumulation along main stems coupled with collapse of cortical stem tissues. Wheat seedlings, similarly exposed, developed chlorotic areas along the distal third of the leaves, which was followed by collapse of the entire leaf within 24 to 36 h post-fumigation. With a wild type culture of 15 l cell densities less than 2 x $10E^{06}$ cells per ml did not produce any evidence of phytotoxic gases in the effluent air. Phytotoxicity occurred only at culture densities greater than this. Maximum phytotoxicity occurred when cell densities reached 6 x $10E^{06}$ cells per ml, which occurred at approximately the early stationary phase of growth.

Chlorella vulgaris

Similar injuries appeared on plants exposed to effluent gases from Chlorella cultures which were grown photoautrophically. However, unlike Euglena cultures, injury symptoms were apparent only when the volume of the Chlorella culture was large (28 l, grown in two bottles connected in series) and when the exposure was for several days. Maximum production of phytotoxic gases occurred during periods of active cell division rather than the non-dividing periods as was observed for cultures of Euglena.

Identification of Toxic Gas(es)

Mercuric cyanide (4% w/v) and lactic acid (1.0 N) solutions effectively trapped the phytotoxic gases from the effluent air from a 15 l Euglena culture. The toxic gases could be released from these solutions by adding KOH until the pH was neutral or alkaline. Solutions of base (1 N NaOH) were ineffective as a trap.

The primary phytotoxic gas is not ethylene, since none of the typical symptoms of ethylene injury were observed on the bean seedlings. Hydrogen cyanide is also an unlikely candidate, since a base trap, which should be highly effective in removing cyanide gas, failed to prevent injury. An organic sulfide is a prime candidate as the primary pollutant.

Studies in Progress

1. Histological studies are in progress to identify the initial

sites of tissue and cell injury in bean plants fumigated with effluent gases from cultures of Euglena.

2. The acid and mecuricyanide soluble gases will be further characterized by mass spectrometry and gas liquid chromatography.

3. Although the primary pollutant is probably an organic sulfide, there is the possibility of pollutant interaction with ethylene and nitrogen oxides, especially in terms of the expression of injury symptoms in higher plants. The production rates of ethylene, nitrogen oxides, and cyanide from algal cultures will be determined and considered in terms of the total air pollutant mixture from algal cultures.

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MINERAL SEPARATION IN A CELSS BY ION-EXCHANGE CHROMATOGRAPHY

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Introduction

An important part of a closed ecological life support system (CELSS) is the ability to process waste materials into forms suitable for recycling, so that the accumulated residues of one compartment become suitable raw materials for another compartment. In addition to C, H, and O, an elemental materials balance must include N, P, K, Ca, Mg, S, Mn, B, Cu, Zn, Al, Cr, Ni, and possibly Se. Pb and Hg may have to be monitored and removed. Also, the ionic form of the element may have to be changed from the output of one subsystem to the input of another.

There are several problems involved in the balance of recycled minerals: (1) the prevention of NaCl buildup in the plant nutrient solution to the point where it reduces plant growth; (2) assurance that humans receive the minimum daily requirements of both macro- and trace minerals; (3) assurance that the plant nutrient solution has the optimum concentrations of macro-, micro-, and trace minerals needed for optimum growth; and (5) the control or removal of extraneous mineral species that enter the food and nutrient recycle loops from corrosion, wear, or other sources of contamination.

In order to recycle all the minerals in a CELSS system, it will eventually be necessary to consider all sources of mineral wastes, including those obtained from human waste products, inedible plant material, and minerals from materials wear and corrosion. However, the experimental work reported here was directed to the identification of operational parameters pertinent to ion-exchange chromatography separations, and it was limited in scope to sodium, potassium,and calcium separations.

Experimental

The experiments were performed with 9-mm-diameter ion-exchange columns and conventional column accessories. The cation separation beds were packed with AG 50W-X2 strong acid cation-exchange resin in H^+ form and 200-400 dry mesh particle size. In some experiments, a "stripper" bed was placed in series with the cation separation bed to neutralize the acid eluent and allow the eluted cations to be detected conductometrically. The stripper beds were packed with AG 1-X8 strong base cation-exchange resin in OH^- form and 200-400 dry mesh particle size. Columns, column accessories, and resins were obtained from Bio-Rad Laboratories, Richmond, CA. The feed solution was pumped into the top of the cation separation resin bed by a peristaltic pump (Buchler Polystaltic Pump or Harvard Apparatus Variable Speed Peristaltic Pump). Conductivity readout on the effluent from the stripper column was done with a Radiometer Copenhagen CDC 334 flow-type cell and a CDM3 meter (London Co., Cleveland, OH). Determinations of elemental concentrations in collected samples were done with a Perkin-Elmer model 603 atomic absorption spectrophotometer.

Results and Discussion

In Fig. 1, the peak elution volume, V, has been plotted against column length for experiments in which Na^+ is removed from the column by various concentrations of acid eluent. Column volume, which is proportional to column length in these experiments, is also shown. The data shows a linear relationship between V and column volume, with increasing positive slope as the concentration of eluent decreases. According to chemical equilibrium theory applied to ion-exchange reactions [1]:

$$V/X = (Dg)\ (r) + e \qquad (1)$$

or

$$V/X = Dv + e \qquad (2)$$

Then

$$V = X\ (Dv + e) \qquad (3)$$

and a plot of V vs X should be linear if Dv and e are constant. The linear plots in Fig. 1 show that equilibrium theory is being followed and it would be reasonable to interpolate data or do limited extrapolation to longer or shorter columns.

In Fig. 2, V is plotted as a function of the reciprocal of acid eluent normality. Some scatter of points was introduced by plotting data at one position for a nominal column height, whereas the true column height varied with the acid eluent concentration.

The relationship between V and the reciprocal of acid eluent normality follows equilibrium theory [1,2]. The relative concentrations in the column can be expressed by a selectivity coefficient, K, as

$$K^{M^+}_{H^+} = \frac{[M^+]_{resin}\,[H^+]}{[H^+]_{resin}\,[M^+]} \qquad (4)$$

This can be related to the weight distribution coefficient, Dg, as

$$Dg = \frac{[M^+]_{resin}}{[M^+]} \qquad (5)$$

Combining equations (4) and (5):

$$Dg = K^{M^+}_{H^+} \frac{[H^+]_{resin}}{[H^+]} \qquad (6)$$

Substituting equation (6) into (1):

$$V/X = K^{M^+}_{H^+} \frac{[H^+]_{resin}}{[H^+]} (r) + e \qquad (7)$$

or

$$V = X\,K^{M^+}_{H^+} \frac{[H^+]_{resin}}{[H^+]} (r) + Xe \qquad (8)$$

Since $[H^+]$resin is in great excess over $[M^+]$resin in these experiments, $[H^+]$resin remains almost constant, and V is proportional to $1/[H^+]$. The plotted relationship (Fig. 2) can be used to interpolate peak elution volumes with various concentrations of acid eluent and for limited extrapolation to higher and lower acid eluent concentrations.

In Fig. 3 the same data is plotted as log V vs log HCl eluent concentration (N). The log-log plot also follows from equilibrium theory. The distribution coefficient, Dg, for a solute, B, present in trace amounts, compared to a solute, A, present in large excess, can be expressed [2] as

$$Dg = \left(k_A^B\right)^{(1/a)} \frac{[A]_{resin}^{b/a}}{[A]} \qquad (9)$$

when k_A^B is defined by

$$k_A^B = \frac{[B]_{resin}^{a}}{[B]^{a}} \; \frac{[A]^{b}}{[A]_{resin}^{b}} \qquad (10)$$

Since A is present in large excess, equation (9) can be simplified to

$$Dg = (\text{constant}) \frac{1}{[A]^{b/a}} \qquad (11)$$

Equation (11) can be conveniently plotted in logarithmic form; log Dg vs log [A] gives a straight line with slope -(b/a).

When two or more trace components are present, such plots can be useful in predicting the effect of eluent concentration on separation.

Equation (11) can be substituted into (1) to give

$$V/X = (\text{constant}) \frac{1}{[A]^{b/a}} + e \qquad (12)$$

or

$$V = X\,(\text{constant}) \frac{1}{[A]^{b/a}} + eX \qquad (13)$$

For the data obtained in this study, the values of eX are small compared to V. Therefore a log-log plot of V vs 1/[A] yields straight lines (Fig. 3). The slopes should be -1 for the replacement of Na^+ by H^+, but the observed slopes were all > -1, averaging -0.9. This plot is also useful for interpolation and extrapolation of experimental conditions.

The relationships shown in Fig. 1-3 also held for data in which an anion-exchanger stripper column was used in series with the cation column and the effluent ion concentration was monitored conductometrically.

Successful separation tests are shown in Fig. 4 and 5 for Na^+ and K^+ and Na^+, K^+, and Ca^{++}, respectively. Very small overlaps of the Na^+ and K^+ fractions were observed. For the test results shown in Fig. 5, a step change in eluent concentration was made after the K^+ elution and before the Ca^{++} elution.

Although it is premature to design the type of ion-exchange chromatography mineral separation system that might be needed for a CELSS, a preliminary estimate can be made of the size of a unit system. Based on the peak elution volumes seen in these experiments and the maximum amount of minerals expected in human wastes, about 12 liters of cation-exchange resin, loaded at 5% capacity, would be needed to handle sodium and potassium separation from one man day of human waste. Scaling from present elution techniques with 0.1 N acid, the total throughput volume of acid eluent needed would be of the order of hundreds of liters. A system in which the eluent was continuously recovered from the eluate would be needed to minimize the outstanding eluent volume.

Summary and Conclusions

An approach was made to mineral recycle in closed systems by means of ion-exchange chromatography separations. Experiments carried out on laboratory-scale ion-exchange columns verified the application of equilibrium theory and obtained parameters related to the possibility of scale-up operations. The feasibility of separation of Na^+, K^+, and Ca^{++} at low concentrations was also verified. From work to date, ion-exchange chromatography separations appear viable as a means to recycle minerals in a CELSS.

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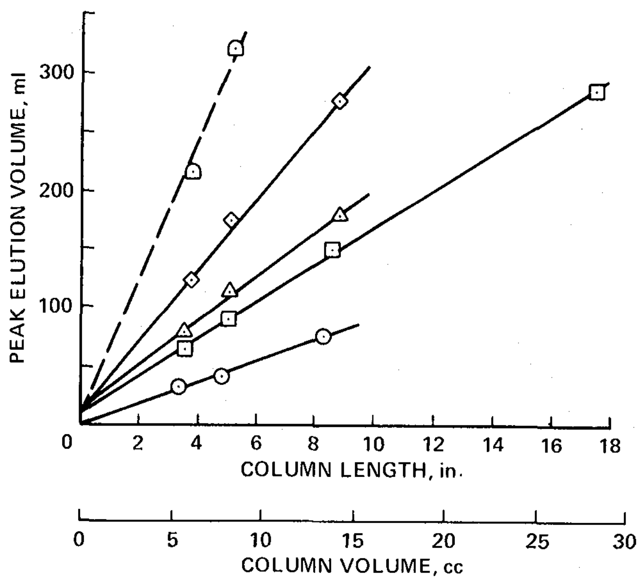

Fig. 1 Sodium elution from cation-exchange column — peak elution volume as a function of column length, AG 50W-X2 resin, 0.9 cm diameter, 2.5 ml/min flow rate, 0.04 meq/mm column exchange capacity, ○ 0.2 N HCl eluent, □ 0.1 N HCl eluent, △ 0.075 N NCl eluent, ◇ 0.05 N HCl eluent, ⌂ 0.025 N eluent, 0.001 meq NaCl on 7.62-15.2 cm columns, 0.01 meq NaCl on 20.3-45.7 cm columns, ⌂ line drawn using average y intercept of ◇ and △ lines.

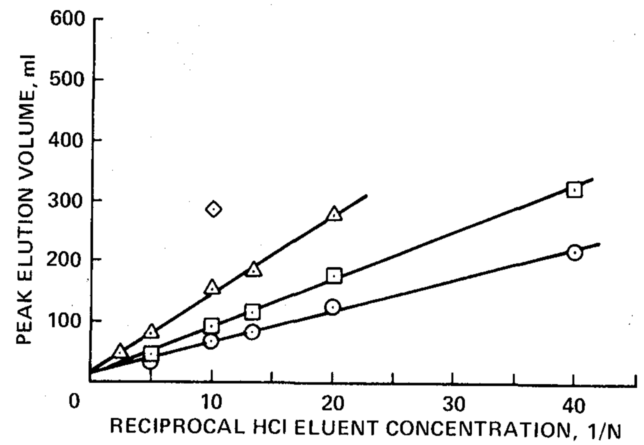

Fig. 2 Sodium elution from cation-exchange column — peak elution volume as a function of reciprocal of eluent concentration, AG 50W-X2 resin column, 0.9 cm diameter, 2.5 ml/min flow rate, 0.04 meq/mm column exchange capacity, ○ 8.9 cm column, □ 12.7 cm column, △ 21.6 cm column, ◇ 44.4 cm column, 0.001 meq NaCl on 8.9 and 12.7 cm columns, 0.01 meq NaCl on 21.6 and 44.4 cm columns.

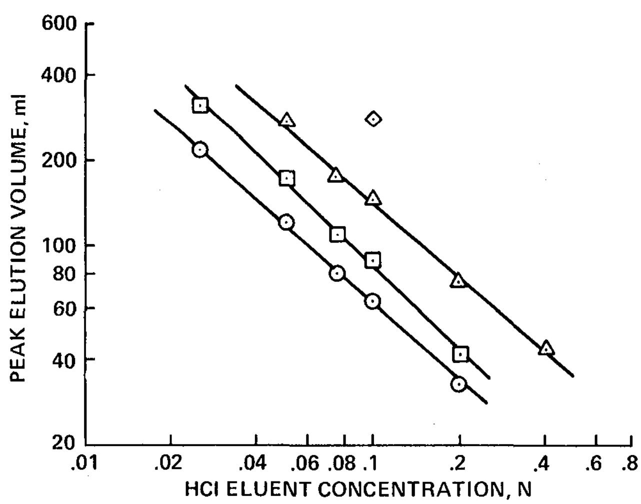

Fig. 3 Sodium elution from cation-exchange column — log-log plot of peak elution volume and HCl eluent concentration, AG 50W-X2 resin, 0.9 cm diameter column, 2.5 ml/min flow rate, 0.04 meq/mm cation exchange capacity, ○ 8.9 cm column, □ 12.7 cm column, △ 21.6 cm column, ◇ 44.4 cm column, 0.001 meq NaCl sample on 8.9 and 12.7 cm columns, 0.01 meq NaCl sample on 21.6 and 44.4 cm columns.

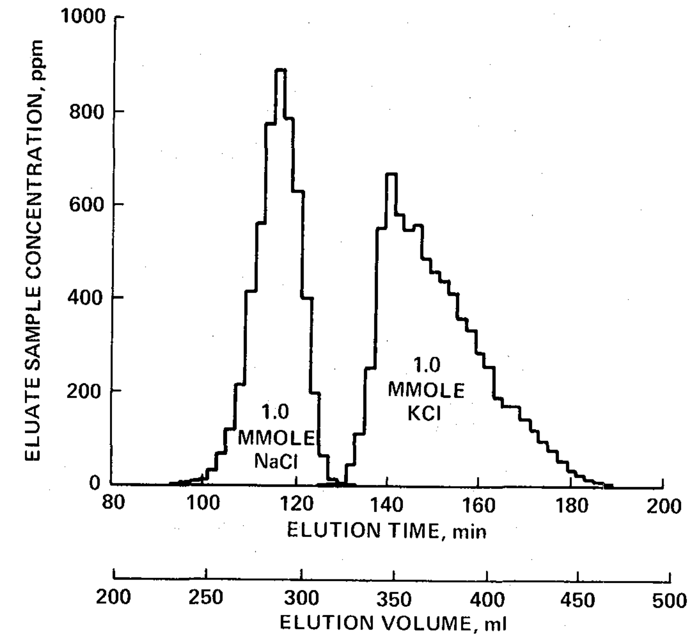

Fig. 4 Separation of sodium and potassium by elution from cation-exchange column, 44.4 cm AG 50W-X2 resin column, 9 mm diameter, 19.8 meq column capacity, 2.47 ml/min flow rate, 0.1 N HCl eluent, sample concentration determined by atomic absorption analysis.

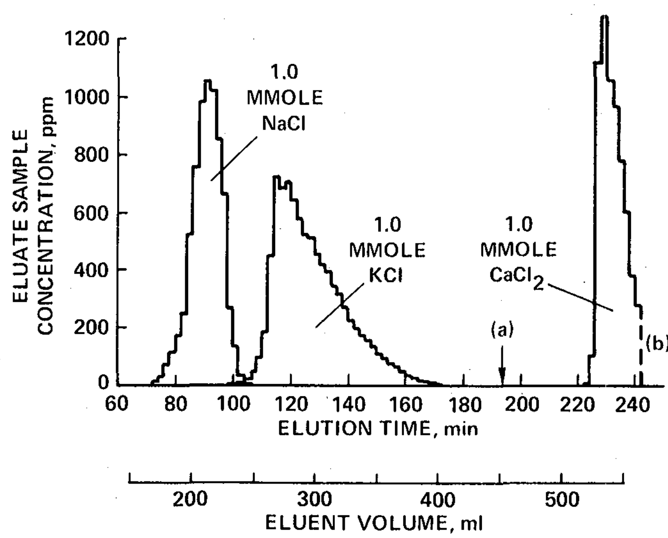

Fig. 5 Separation of sodium, potassium, and calcium by elution from cation-exchange column, 41.7 cm AG 50W-X2 resin column, 9 mm diameter, 19.0 meq column capacity, 2.33 ml/min flow rate, start with 0.1 N HCl eluent, change to 1.0 N HCl eluent at (a), test terminated at (b), sample concentration determined by atomic absorption analysis.

LIST OF SYMBOLS

a	absolute value of charge on A
A	sorbable ion present in large excess
b	absolute value of charge on B
B	sorbable ion present in trace amounts
Dg	weight distribution coefficient; ratio of total amount of sorbed solute per g of dry resin to its concentration (total amount per ml) in external solution
Dv	volume distribution coefficient; ratio of total amount of sorbed solute per ml of column or bed volume to its concentration (total amount per ml) in external solution
H	hydrogen ion
k_{A}^{B}	selectivity coefficient
$K_{H^+}^{M^+}$	selectivity coefficient
M^+	metal cation
V	eluate volume at which solute concentration emerging from bottom of column is at a maximum; elution peak volume, ml
X	a geometric column volume, ml; area of resin bed (square cm) times height of bed (cm)
e	fractional interstitial void volume of column
r	bed density of column, g dry resin/cubic cm of column

[ ]	concentration in external solution
$[\ ]_{resin}$	concentration in resin phase

LIST OF PARTICIPANTS AND RESEARCH INTERESTS

David Auslander
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Most of our work focuses on dealing with systems having a large degree of uncertainty. This includes modeling, control, state estimation, resource allocation, simulation. The connection of all this to CELSS is in the design of systems whose performance goal is survival.

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My interest in CELSS is in the general area of the analysis of system behavior with particular emphasis on problems of system control. For the last several years I have been developing and using a mass balance, computer-based model of an idealized closed life support system, and I am presently planning to construct a laboratory-based closed system, utilizing algae and small animals, to use to validate the model and for general experimental analysis of the behavior of such systems.

---***---

Vern Ballou
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I am currently engaged in the evolution of the mineral separation needs arising in a CELSS system due to a) the difference in composition of potential waste product solutions and optimum plant growth nutrient solutions, and b) possible toxicity problems from the build-up of corrosion and wear products of operating systems or mission oriented industrial processes and experiments. Consideration is being given to the feasibility and advantages of a number of separation techniques, while current experiments involve ion-exchange chromatographic techniques.

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Daniel B. Botkin
Environmental Studies Program
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Research interests include: ecosytem ecology; interrelations among large mammals, terrestrial vegetation and mineral cycling; ecological models.

Re CELSS: Theoretical ecological constraints on systems that suggest life over long periods.

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William F. Campbell
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Current research directions include: Ultrastructural, physiological, histo- and cytochemical effects of environmental stresses (temperature, UV-irradiation, SO_2, salinity) on plant species. Extremes of temperature, drought, and salinity constitute the most common stresses endured by plants in Utah and other semi-arid regions. We have learned that management of water and fertilizer allows plants to grow on marginal lands with respect to water and soil salinity. Our ultrastructural cytochemical work indicates that environmental stress (UV-irradiation) inhibits ATP formation at the membrane level of chloroplasts in etiolated pea plants. In the CELSS project, we will apply developed techniques as well as new approaches now being developed.

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Analytical Chemistry of Environmental Materials:
Development of efficient quantitative techniques for elemental analysis of environmental samples. Techniques:

- -- inductively coupled plasma emission spectrometry (ICPES)
- -- flame and furnace atomic absorption spectrometry (AAS)
- -- instrumental neutron activation analysis (INAA)
- -- x-ray fluorescence spectrometry (XFS)

Major problem areas:
-- sample preparation -- interference/matrix effects

Other interests include quantitative organic vapor monitoring using activated charcoal absorbers; preparation of reference quality materials for evaluating measurement protocols and standardizing experiments; and control and disposal of hazardous chemicals.

---***---

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Conceivable approaches to the construction of a CELSS range within two extremes: 1) reliance on natural ecological controls, and 2) reliance on mechanical and chemical computer-controlled systems. I am interested in narrowing the range of possible approaches, by considering both the limits of natural ecosystem stability, as well as the applicability and theoretical limitations of control systems theory.

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Franklin Fong
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My research interests concern the areas of biochemical and physiological mechanisms in higher plants that affect a) air pollutant resistance and b) long-term stress acclimation. Current studies involve: 1) description of injury symptoms produced in higher plants by exposure to algal effluent gases; 2) characterization and identification of the phytotoxic air pollutants from Chlorella vulgaris and Euglena gracilis cell cultures.

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Bert Hansen, III
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Direct research interests center around modeling specific biological processes from a thermodynamic viewpoint (energy: entropy as well as mass balances). Current efforts are focused on anaerobic digestion. Of additional interest are the areas of integrating the sub-systems, especially waste and food sub-systems, and monitoring the Soviet work in areas related to CELSS.

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We are studying various nutritional aspects of vegetarian diets composed of candidate plant species for the CELSS. Such diets are deficient in the elements I, Na and Cl and in the vitamins B_2 and B_{12}. The Ca content is marginal and the skewed Ca/P ratio may have long-term adverse effects. The high fiber content and the presence of metal chelators reduce the bioavailablity of trace metal.

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1) The regulation of N (NO_3^-, NO_2^-, NH_4^+ urea) assimilation by plants, including rate-limiting steps in the overall integrated pathway, and rate limiting steps within each reaction; closely linked utilizaton of photosynthetic electrons for NO_3^- and NO_2^- reduction; regulation of N reduction in darkness. 2) Regulation of turnover of ribulose bisphosphate carboxylase, a major storage sink for N assimilation; proteinases catalyzing N assimilation; relation to yield and quality by affecting photosynthesis.

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Marcus Karel
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We are currently involved in two research projects under NASA sponsorship. The <u>first</u> deals with evaluation of engineered foods for PCELSS, CELSS and GBCD. The present phase of the research has the following objectives:

1) Evaluation of feasibility of developing acceptable and reliable engineered foods from a limited selection of plants grown in a PCELSS, supplemented with nutrients from other sources microbially produced, or a limited amount of resupplied dehydrated foods or food components. This evaluation includes analysis of physicochemical compatibility or components.

2) Evaluation of engineering capabilities for production of foods and processing under GBCD and eventually, CELSS conditions, and for integration of regenerative and resupplied components.

3) Evaluation of research tasks and specification of research and development approaches for adapting present technology to food technology under space conditions.

The <u>second</u> project has its objective definition and physical preparation of a model of food processing wastes from a food technological operation in PCELSS. This model is used by our collaborators (Dr. Modell at MIT and Dr. Spurlock at Georgia Tech) to test waste recycling concepts.

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Robert Kaufmann
Complex Systems Research Center
O'Kane House
University of New Hampshire
Durham, NH 03824

I am interested in the operation of systems and the use of models as a tool for gaining this type of knowledge. My recent work has focused on the interaction between physical and biological systems (e.g., economic system). CELSS interests me because it offers a chance to examine two system characteristics, material closure and control, that will become increasingly important to the interaction of human systems with their encompassing natural systems.

---***---

William H. Lenharth
Research Computing Center
Pettee Brook Offices
University of New Hampshire
Durham, NH 03824

My research interests generally involve the application of a systems approach to complex, interdisciplinary problems. This may entail both hardware- and software-mixed solutions. Specific areas of interest include computer systems modelling, simulation modelling, atomic control engineering, and systems/industrial engineering.

---***---

Robert D. MacElroy
Mail Stop 239-4
NASA-Ames Research Center
Moffett Field, CA 94035

Principal research interest in the CELSS program are in the area of control: Can environmental conditions be manipulated in such a manner that plant physiology can be specifically controlled? To approach this problem I have been involved with Schwartzkopf, Moore, Averner and Stofan in developing a chamber in which one can reliably and specifically alter CO_2 and O_2 concentrations, temperature, humidity, etc., and observe the effects on the growth and development of plants.

Other interests in the CELSS area include information dissemination, computer modelling and simulation, and the use of computers in information transfer.

General scientific interests include computer-modelled molecular interactions, the origin of life, the origin of biological codes, including the genetic code, and self-assembled structures such as collagen and membranes.

Background: overwhelmingly biological.

---***---

R. M. Mason
Metrics Research Corporation
180 Allen Road, Suite 200S
Atlanta, GA 30328

Program and System Integration Efforts

1) Modelling: economics of regeneration vs. resupply and of alternative regenerative approaches:

-- Tradeoff studies for shaping research strategies

-- Evaluation of potential value of alternative technologies

2) Mathematics of stable/long-lived systems:

-- Ecological parallels to organizational strategies.

-- Information flows in complex and dynamically stable systems (e.g., minimum data requirements for monitoring system "health" and controlling system behavior).

3) Program Integration Efforts (solutions to issues resulting from the management of an interdisciplinary research program):

-- Face-to-face information exchanges (meetings, conferences, workshops), formal and informal.

-- Common data bases for assuring compatible research efforts, especially modelling and systems control efforts.

-- Routine information exchange, both among CELSS researchers and between CELSS and related research programs.

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C. A. Mitchell
Department of Horticulture
Purdue University
West Lafayette, IN 47907

Candidate Species Selection: Cultural and Photosynthetic Aspects.

In cooperation with food scientist J. E. Hoff and nutritionist J. M. Howe, we have been selecting traditional crop species which will satisfy minimum human nutritional requirements for a CELSS, and for which we have considerable cultural information. We are preparing to grow selected crops hydroponically in highly controlled environments, and to supply the harvested biomass to the nutritionists for analysis of nutritional quality. We also are establishing the capability to measure photosynthetic rates and relative growth rates for small crop canopies of selected species growing under hydroponic conditions and varying levels of CO_2, light, and temperature.

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Michael Modell
Department of Chemical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

My research centers on developing chemical processes for solid waste and wastewater treatment. The emphasis has been in recovering resources from wastes. Terrestrial applications of my work include (1) regeneration of activated carbon by supercritical CO_2 desorption and (2) aqueous phase oxidation of organics with recovery of inorganic salts and power.

I have worked with various NASA groups on evaluaton of alternative waste treatment methods for prolonged manned space flight.

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Berrien Moore III
Complex System Research Center
O'Kane House
University of New Hampshire
Durham, NH 03824

My research interests are in the area of mathematical modelling, particularly at the system or subsystem level for the purpose of buffer size estimation and analysis of control characteristics. We are currently focusing upon food production (plant growth) and beginning to consider plant-animal interactions.

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Richard Radmer
Martin Marietta Laboratories
1450 South Rolling Road
Baltimore, MD 21227

My primary research interest is photosynthesis and related processes. Emphasis has been on 1) the reaction steps associated with photosynthetic O_2 evolution, 2) the competition between CO_2, O_2, and NO_3^- for light-generated reducing equivalents in algae, and 3) rate and efficiency limitations associated with photosynthetic processes. CELSS-related work is being directed toward the development of an algal culture system for air regeneration and food production.

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C. David Raper, Jr.
Department of Soil Science
North Carolina State University
Raleigh, NC 27650

Plant growth and development can be viewed as the integration of physiological and morphological responses to environmental factors within the interdependency of functional relationships. In developing mathematical models to describe plant growth responses, we have concentrated on the interdependency of the carbon (or energy) supplying function of the shoot, through photosynthesis, and the nitrogen and water supplying function of the roots. An environmentally promoted change in the function of one necessitates an adaptive change in the function of the other, either through an alteration in rates of physiological processes or a modificaton of morphological development. Physiological processes such as photosynthesis or specific uptake rates of nitrogen are considered reversible, with a short response time, while morphological processes such as leaf and root initiation and elongation are considered irreversible, with a prolonged response time. Based on this conceptual relationship between plant functions, we are developing a dynamic model to describe plant growth as balanced flows of carbon (energy) and nitrogen through the plant system in response to temperature, photosynthetically active radiation, CO2 levels, nitrogen availability in nutrient solution, and pH of the root zone.

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Claire Reinhold
Complex Systems Research Center
O'Kane House
University of New Hampshire
Durham, NH 03824

My current work is with simulation modeling of plant growth, developing new and altering existing models for use in the context of a closed chamber. Once we have working models we plan to perform factorial experiments on them to get an idea of their control characteristics.

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Frank B. Salisbury
Plant Science Department
UMC 48
Utah State University
Logan, UT 84322

Current research directions include: the clinostat as a gravity compensator and the role of mechanical stresses in clinostating; the gravitropic responses of green dicot stems, including gravity perception, transduction, and the mechanics of the bending response; and plant detection of the change from light to darkness in photoperiodism, emphasizing light levels and spectral distribution (e.g., during twilight). The project being initiated at present (part of CELSS) is to seek ways to achieve maximum yield of wheat in a controlled environment that includes high light and CO_2 levels, controlled spectral quality, humidity, temperature, mineral nutrients, and special cultivars.

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Steven H. Schwartzkopf
Mail Stop 239-10
NASA Ames Research Center
Moffett Field, CA 94035

My major research interests are the application of control theory to ecological systems, and simulation modelling of ecological systems. I am especially interested in using simulation models to investigate the concepts of internal control (homeostasis) and stability as applied to the behavior of natural and artificial ecosystems.

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Paul Stofan
Mail Stop 239-10
NASA Ames Research Center
Moffett Field, CA 94035

I propose to continue development and refinement of a growth chamber for plants that approximates the expected constraints of space. Second, I propose to continue development of plant remote-monitoring equipment not available commercially. Third, I propose to assemble the support apparatus needed to operate the growth chamber successfully.

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T. W. Tibbitts
Horticulture Department
University of Wisconsin
Madison, WI 53706

Interactions of light, temperature, humidity and carbon dioxide for control of growth and development of plants with particular concern for physiological injuries, as tipburn and intumescences, that are serious problems in controlled environments. Present research thrusts are with calcium-related tipburn of lettuce, identificaton of contaminants causing plant injuries, and identification of the best types of HID lamps for plant growth.

I have taken a special interest in the development of guidelines for measuring and reporting environmental conditions in controlled environment studies, and in the development of quality assurance procedures to insure repeatable growth in controlled environments.

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T. Wydeven
Mail Stop 239-4
NASA Ames Research Center
Moffett Field, CA 94035

I am the manager for the CELSS waste management program sponsored by NASA Ames. I also have two specific research interests: a) exploring wet oxidation as a method for treating CELSS wastes, and b) minerals separation by ion-exchange chromatography and other candidate minerals separation concepts.

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15. Supplementary Notes

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16. Abstract

This report consists of 17 papers presented at a meeting in May 1981 concerning research and development of controlled ecological life support systems (CELSS). Topics covered include: CELSS program overview, system control, plant physiology, plant selection, food production, food processing, and waste management.

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