GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: June 20, 1978

Project Title: Technology Integration Analyses for Closed Life Support Systems Applicable to Space Habitats

Project No: A-2158

Project Director: Dr. John L. Carden, Jr.

Sponsor: NASA-Ames Research Center; Moffett Field, Calif. 94035

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Sponsor Contact Person (s):

Technical Matters
(NASA Technical Officer)

P. D. Quattrone
Advance Life Support Project Office, 239-4
NASA-Ames Research Center
Moffett Field, Calif. 94035
415/965-5733

Contractual Matters
(thru OCA)
Dennis R. Brown
Grants Officer
NASA-Ames Research Center
Moffett Field, Calif. 94035

Defense Priority Rating: N/A

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SPONSORED PROJECT TERMINATION

Date: 7/8/81

Project Title: Strategies and Procedures for Integrated Technical Management of Advanced Life Support Systems Development

Project No: A-2158

Project Director: Dr. J. L. Carden, Jr.

Sponsor: NASA-Ames Research Center

Effective Termination Date: 3/31/81

Clearance of Accounting Charges: 4/30/81 (Reporting)

Grant/Contract Closeout Actions Remaining:

- _ Final Invoice and Closing Documents
- x Final Fiscal Report (SF272)
- x Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- x Other Subcontracts 1-A-2158 & 2-A-2158

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A-2158

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

June 12, 1981

Dr. Theodore Wydeven
Project Monitor: NSG 2323
Mail Code 239-10
NASA Ames Research Center
Moffett Field, California 94035

Dear Dr. Wydeven:

This letter will as we have discussed constitute the final report on NSG-2323.

The objective of this program was to prepare a sample of wheat free of clays, silicates, and other refractory materials potentially derived from a soil matrix. The wheat sample was to be ground and made available to other Controlled Ecological Life Support System (CELSS) researchers.

In order to grow the required wheat, a hydroponic plant growth system was set up in a roof top greenhouse on the Georgia Tech campus. The system was large enough to support about 500 wheat plants spaced at one foot intervals. Nutrient solution was supplied to the plants as a film contained in black polyethylene growth tubes. Nutrient flow was interrupted every 15 minutes for a 15 minute period to allow root oxygenation. Figures 1 through 4 give details of the hydroponic system and figure 5 is a photograph of the system in operation. Note the clear polyetheylene film tents erected over the system to prevent dust from settling on the plant leaves.

The nutrient solution used was prepared from a dry mix sold as Hygro-Sol D-11; 3-15-27 by Hygroponics, Inc. of Panama City, Florida. The solution was prepared according to the supplier's instructions. Table 1 gives the nominal nutrient levels claimed by the supplier and those observed in our laboratory using inductively coupled argon plasma emission spectrometry.

The wheat seeds used were obtained from Prof. David Raper of the Soil Sciences Department at North Carolina State University.

They were variety GWO-1809, a semi-dwarf spring wheat. The seeds were germinated in polyurethane "grow blocks" also obtained from Hygroponics, Inc. When the seedlings had developed 1 1/2 to 2 leaves, the grow blocks were transferred from germination trays to the hydroponic system by inserting the blocks through slits in the grow tubes. The wheat seedlings were placed into the growth tubes in early November of 1980 and the wheat plants were harvested in late April of 1981.

Immediately upon harvesting, the plants were taken to the laboratory where the grow blocks were broken away from the root system and briefly rinsed to remove polyurethane fragments and superficial solids. The whole plants were then taken directly to the freeze dryer (Labconco) where they were prechilled with dry ice and lyophilized for 12 hours. The dried plant material was then ground using a Tekmar planetary ball mill. The mill ground the dried wheat very successfully producing a very fine powder. The total mass of ground wheat was 120g.

As you are aware, we performed many environmental measurements during the course of the wheat growth. These included sunlight intensity, temperature, nutrient solution composition, plant growth rate and nutrient solution loss rate. These data may be used as the basis for a future publication.

This report contains the information necessary to document the standard wheat materials prepared by us and available to other CELSS researchers. If you desire further details, I will be happy to supply them to you.

Sincerely,

[redacted]

John Carden, Ph.D.
Project Director

JC/cmh

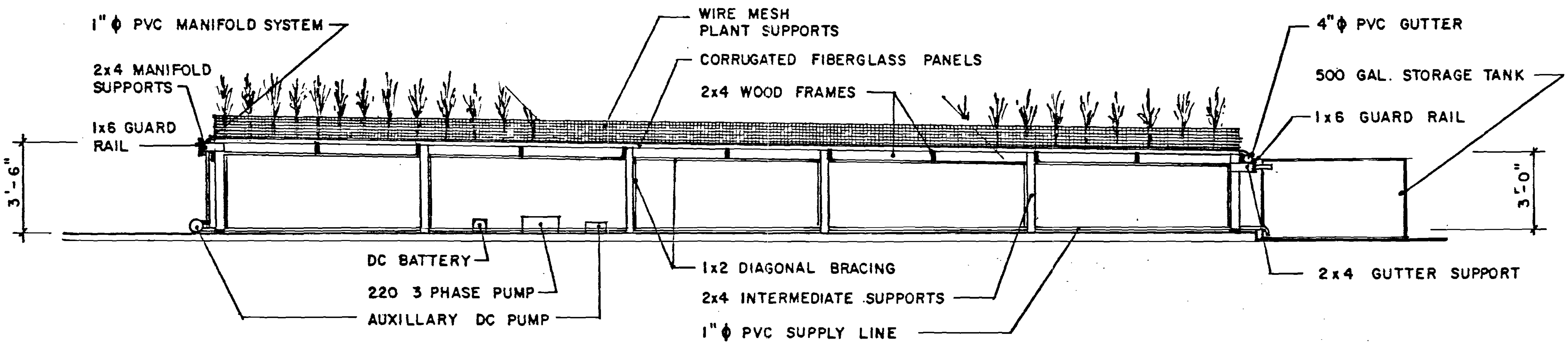
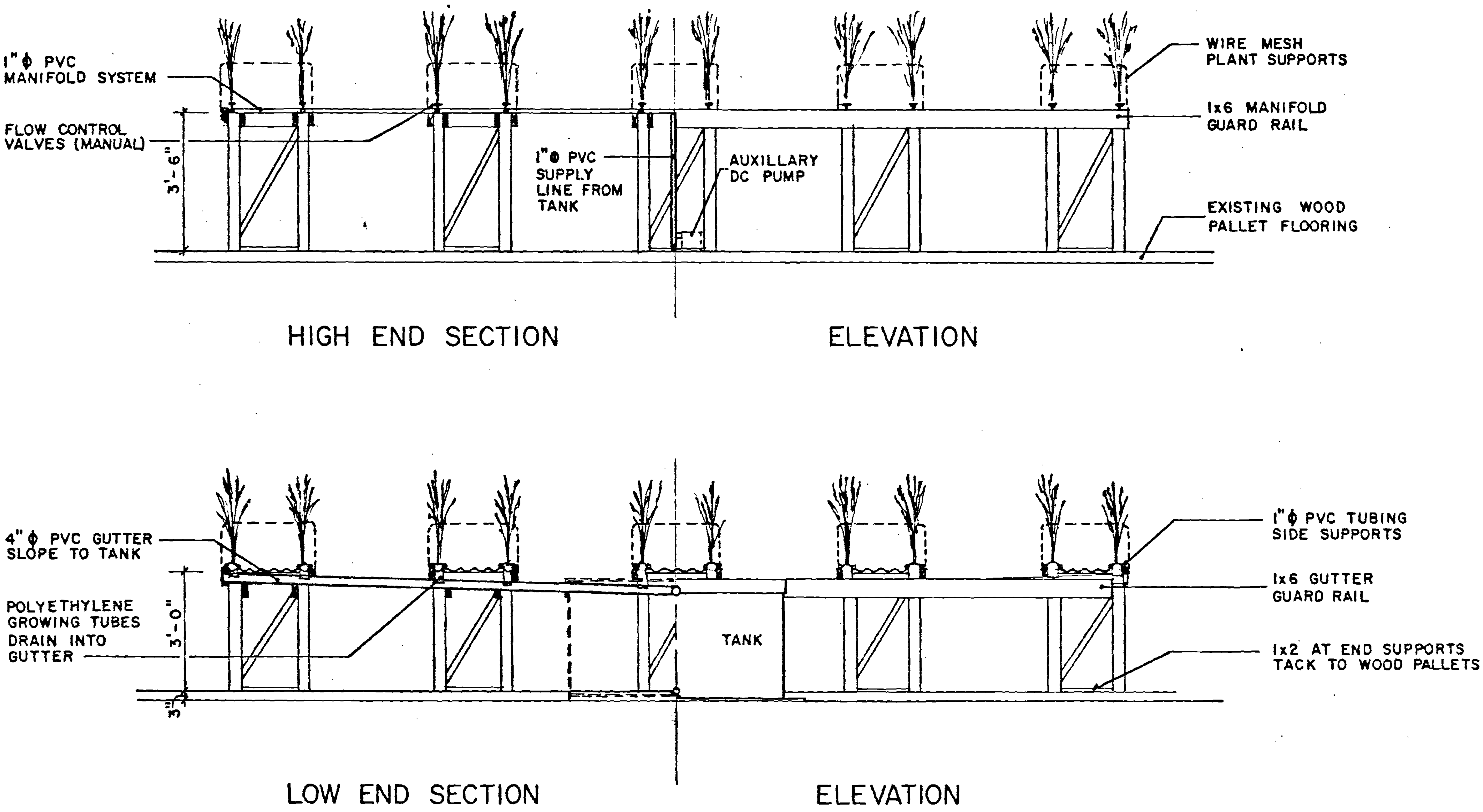


FIGURE 1 LONGITUDINAL SECTION



1"Φ PVC MANIFOLD SYSTEM
FLOW CONTROL VALVES (MANUAL)
3'-6"
1"Φ PVC SUPPLY LINE FROM TANK
AUXILLARY DC PUMP
WIRE MESH PLANT SUPPORTS
1x6 MANIFOLD GUARD RAIL
EXISTING WOOD PALLET FLOORING
HIGH END SECTION
ELEVATION
4"Φ PVC GUTTER SLOPE TO TANK
POLYETHYLENE GROWING TUBES DRAIN INTO GUTTER
3'-0"
3"
TANK
1"Φ PVC TUBING SIDE SUPPORTS
1x6 GUTTER GUARD RAIL
1x2 AT END SUPPORTS TACK TO WOOD PALLETS
LOW END SECTION
ELEVATION

FIGURE 2

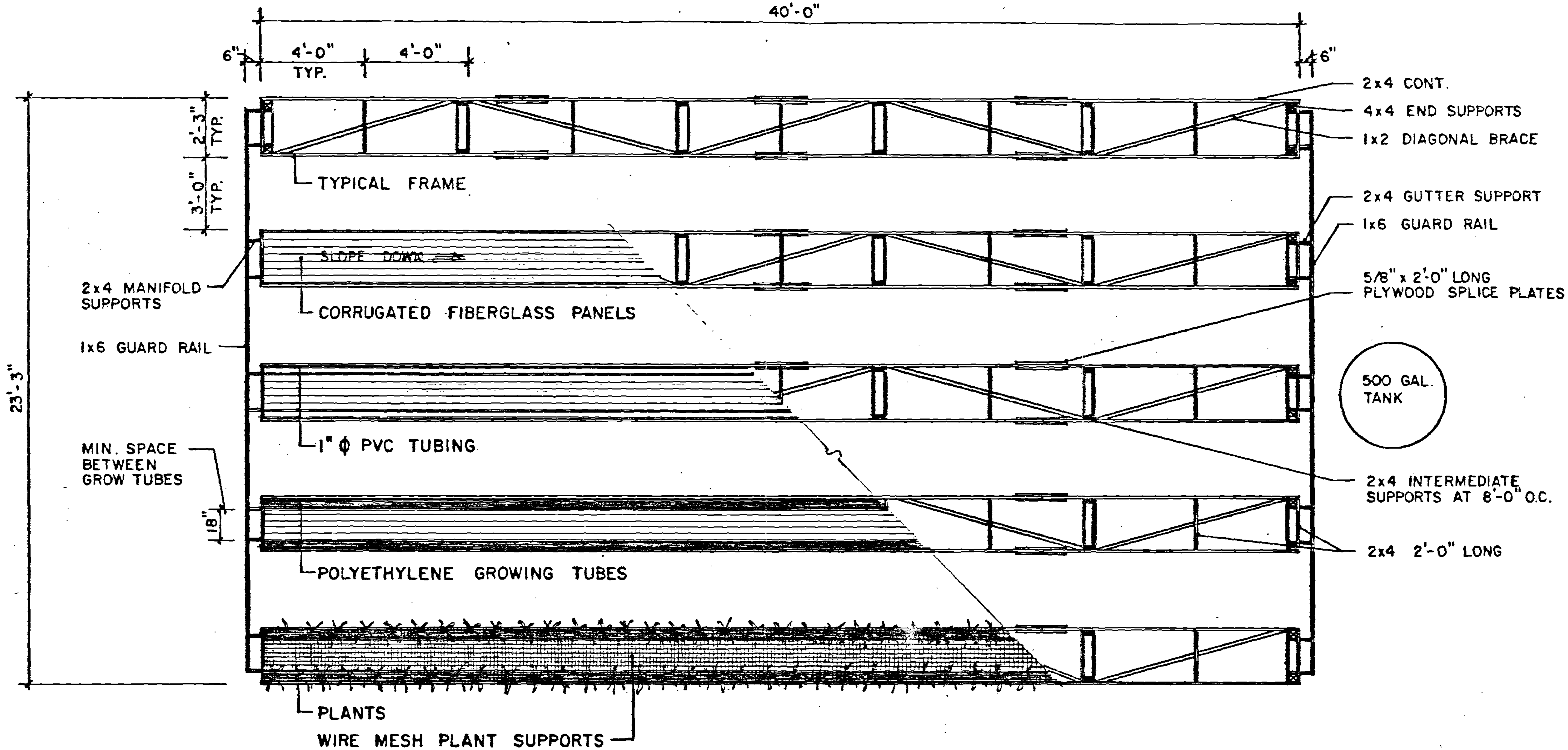


FIGURE 3 FRAMING / CONSTRUCTION PLAN

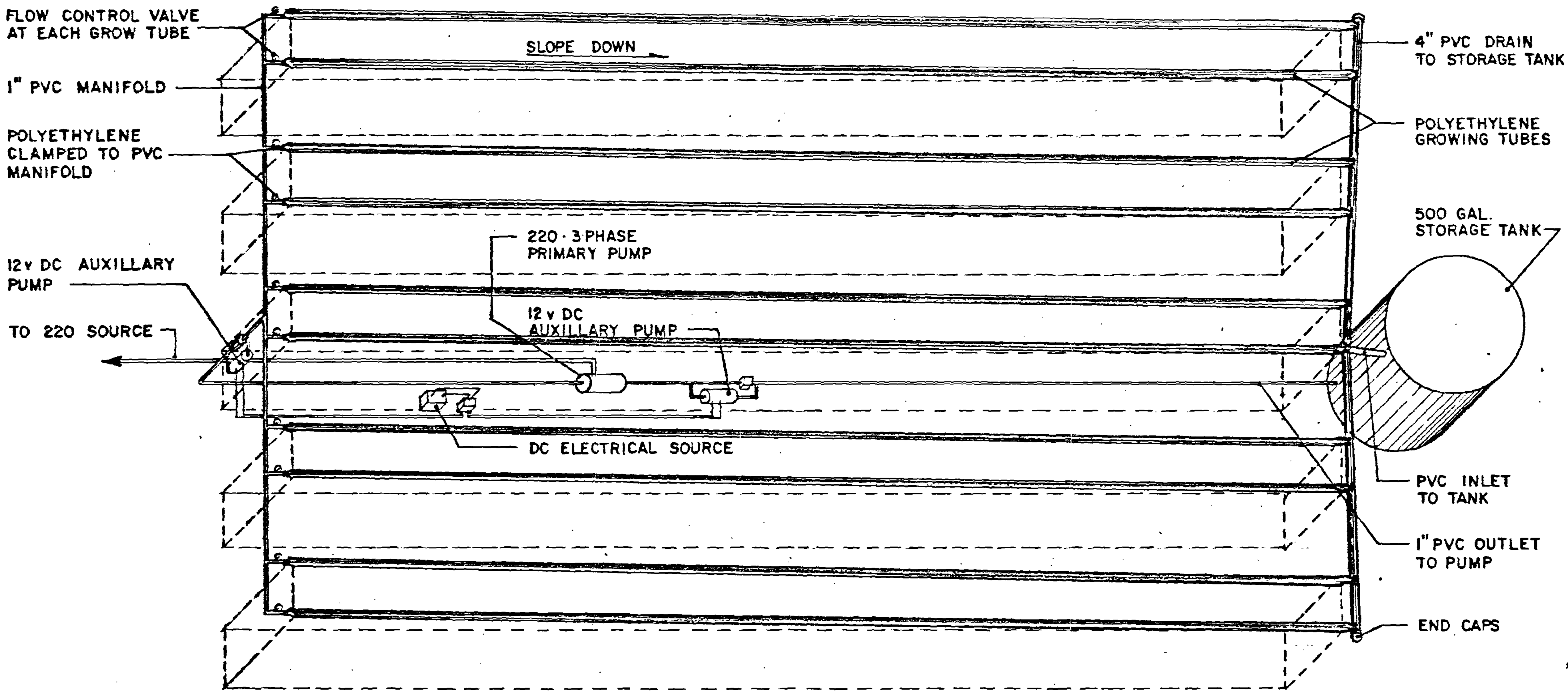


FIGURE 4 PLUMBING / ELECTRICAL DIAGRAM

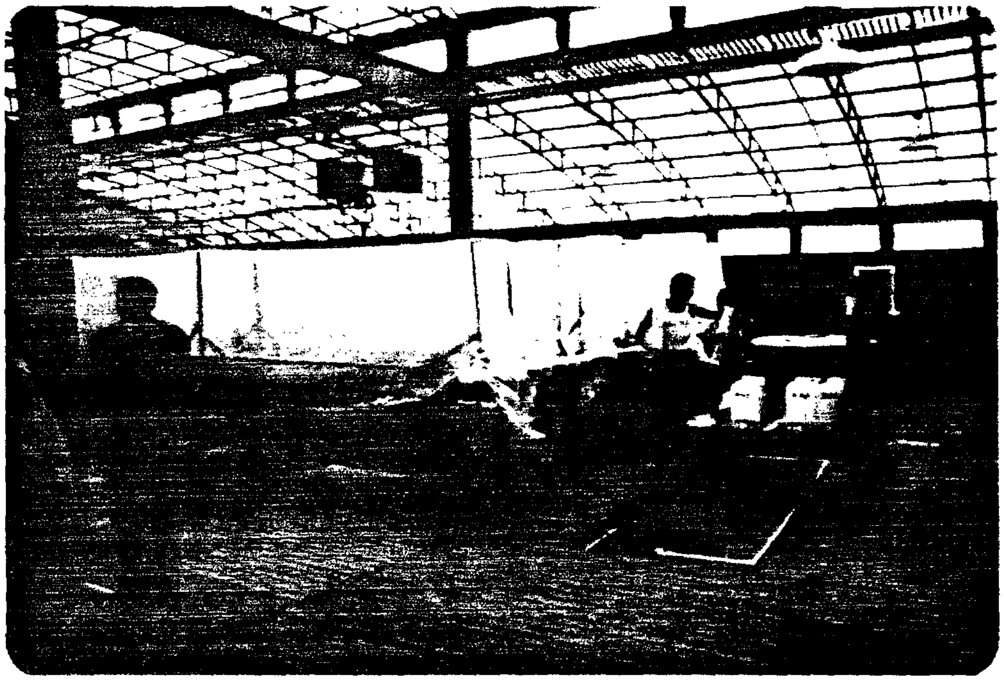


Figure 5. Hydroponic system and crew
in action.

COMPOSITION OF NUTRIENT SOLUTION

ELEMENT	CONCENTRATION NOMINAL ppm	SOURCE	CONCENTRATION MEASURED ppm
Nitrogen	800	KNO_3 $Ca(NO_3)_2$	750
Phosphorus	52	KPO_4	76
Potassium	284	KPO_4, KNO_3, K_2SO_4	317
Calcium	136	$Ca(NO_3)_2$	
Sulfur	159	K_2SO_4, M SO	130 (low)
Magnesium	47	$MgSO_4$	58
Chlorine	17.6	$MnCl_2$	23
Iron	4.0	EDTA Iron	5.1
Boron	1.5	Solubor	1.6
Manganese	0.5	$MnCl_2$	0.6
Zinc	0.3	EDTA Zinc	
Copper	0.1	HEDTA Copper	0.14
Molybdenum	0.1	Na_2MoO_4	0.07

Table 1. Nutrient solution composition; nominal concentration values from supplier, chemical form, and concentration values as determined in out laboratory by inductively coupled plasma emission spectrometry.

A-2158

GUIDING THE DEVELOPMENT OF A

CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEM

Report on
NASA/Ames Workshop
January 8-12, 1979

Edited by

Robert M. Mason
METRICS, INC.
Atlanta, Georgia

John L. Carden
Georgia Institute
of Technology
Atlanta, Georgia

November, 1979

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ACKNOWLEDGMENT

It is a pleasure to acknowledge the many contributions to this synthesized report. Although their individual contributions largely remain anonymous, this working paper is a result of the efforts of the workshop participants. The success of the workshop was due to the participants' enthusiastic work and to the continued attention to the workshop tasks by Jack Spurlock, who served as overall chairman and leader of group 4, and by the other group leaders: Marc Karel, John Phillips, Mike Modell, and Sidney Draggan. Ben Zeitman coordinated the NASA/Ames facilities and logistics support, and Betty Mason coordinated the non-NASA logistics and facilities support. Nancy Hooper provided extensive editorial support, developing drafts from notes and editing numerous drafts. Pat Junod typed several drafts and the final copy. Phil Quattrone initiated the workshop effort, and the NASA headquarters staff provided useful suggestions in planning and conducting the workshop.

The workshop was supported by NASA as a part of the work under Grant No. NSG-2323. However, opinions, conclusions, and recommendations are those of the workshop participants and do not necessarily reflect the opinion of NASA. The editors are responsible for any errors or omissions in reporting the findings of the workshop groups.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Background

This report summarizes the results of the workshop held January 9-12, 1979, at the NASA Ames Research Center. The workshop was held as part of an effort under Grant No. NSG-2323 from NASA Ames to the Georgia Institute of Technology. METRICS, INC., served as subcontractor to Georgia Tech in the effort.

The purpose of the workshop was to provide the base for an expanded program of research and development of controlled ecological life support systems (CELSS). This purpose had two goals: to establish guidelines for the future development of ecological life support systems and to develop a group of researchers who share a common language and a mutual understanding of the interdisciplinary requirements of the overall program. To achieve these goals, the workshop addressed four objectives:

1. Evaluate a ground-based manned demonstration as a critical milestone in CELSS development;
2. Identify considerations critical to a successful ground-based manned CELSS demonstration (GBCD);
3. Specify information, technology, and capabilities necessary to develop a successful GBCD; and
4. Establish R&D sequences and priorities for CELSS development.

It is apparent that long duration (multiyear) manned space missions would incur almost prohibitively large storage or resupply costs. Consequently, the concepts of recycling waste and growing portions (or all) of the necessary food supply have been considered as alternatives to complete storage or resupply approaches. These concepts include aspects of closed or partially closed ecological systems, and the life support systems based on these concepts have been termed Closed (or Partially Closed) Ecological Life Support Systems (CELSS or PCELSS). Perhaps the single inclusive description, Controlled Ecological Life Support System (CELSS), is most appropriate. This is the terminology used in this report.

These concepts of recycling and controlled ecology have been studied in a series of summer studies and workshops (e.g., see references 1, 2, 3). In addition to these episodic studies, the Bioenvironmental Systems Study Group (BSSG) of the Society of Automotive Engineers has examined these concepts continually over the past several years.[4,5] With increasing evidence that program growth is indicated, additional research in many of the disciplines is likely.

Along with increased research effort, there are increased risks that the overall research effort would be fragmented or that individual efforts would be duplicated. Increased communication among researchers and the responsible program managers could help reduce these risks. Consequently, a workshop to facilitate this communication and to summarize the present state of knowledge seemed especially timely. This workshop was designed to meet these needs.

Approach

Participants. The workshop participants included NASA staff, NASA grantees, and selected individuals who had particularly relevant backgrounds or experience. Participation was by invitation, and invitees were selected through a series of discussions among the editors (who served as workshop organizers), NASA staff, and group chairmen. As the discussions expanded, so did the number of invitees, resulting in over seventy persons being invited to the workshop. Appendix D lists those who were able to actually attend and participate. The participants included both persons who had worked in CELSS-related efforts before and persons who, although their backgrounds were relevant to CELSS, had not been involved in previous research efforts or workshops.

Organization and Schedule. Each workshop participant was assigned to one of six different groups, based on backgrounds and anticipated interests in the groups' areas. The six groups and their respective areas are shown in Table 1; group membership is shown in Appendix C.

The workshop sessions consisted of a mixture of plenary, group, and intergroup meetings. In addition, an executive committee, consisting of the workshop organizers, the workshop chairman and group chairmen,

Table 1. Workshop Group Organization

Group	Workshop Role
1. Nutrition & Food Processing	Identification and assessment of knowledge regarding nutritional requirements and food processing possibilities.
2. Food Production	Identification and assessment of knowledge regarding the growing of food material: options and nutrient requirements.
3. Waste Processing	Identification and assessment of knowledge regarding human and food waste processing options: air, water, and solid waste recycling.
4. System Engineering/Modelling	Identification of role of systems studies and modelling efforts in CELSS design; assessment of interfacing requirements of CELSS components.
5. Ecology	Identification of ecologically desirable approaches to CELSS design; identification and assessment of ecological knowledge necessary for CELSS design and development.
6. Workshop Overview	Monitoring of workshop activity and providing feedback to workshop organizers from NASA program management viewpoint.

the NASA Ames program manager and other NASA Ames managers, and NASA Headquarters staff, met each evening to review progress and make any necessary modifications to the schedule. The schedule which was planned for the workshop is shown in Table 2; principal modifications of this schedule included the deletion of the morning meetings of the executive committee and a delaying and shortening of the intergroup meetings in favor of additional time for intragroup discussions.

In order to assure that the workshop made progress toward all the objectives, the groups were requested to report on objective 1 (evaluation of a ground-based demonstration) by noon on Wednesday. A draft report from each of the groups on the remaining objectives was due at the close of the workshop. (Group 6, the overview group, did not prepare written reports.)

Overview of Report

Each of the workshop groups (with the exception of group 6, the workshop overview group) provided two draft reports during the workshop: one in response to objective 1, an evaluation of the ground-based manned CELSS demonstration, and the other in response to the other three objectives. The remainder of this report presents these group reports, edited for consistency and clarity when necessary, in four sections and appendixes.

The next section presents the groups' evaluation of the GBCD as a milestone for CELSS development. This section provides a collective summary and an individual summary of each of the group's responses.

The third section summarizes the groups' reports on the second and third objectives of the workshop. The second objective was to identify considerations critical to a successful GBCD, and the third objective was to specify information, technology, and capabilities necessary to develop a successful GBCD. Each group identified critical considerations and necessary technologies and then addressed four questions for each of the considerations: why the issue is important; what is currently known; sources of information; and important information gaps.

Table 2. Original Workshop Schedule - January 8-12, 1979

Day	Time	Meeting
Monday	1500	Executive Committee Meeting
Tuesday	0830	Opening Session
	0930	Plenary Session I
	1100	Group Meetings I
	1200	Lunch
	1300	Group Meetings II
	1700	Executive Committee Meeting
Wednesday	0800	Executive Committee Meeting
	0830	Plenary Session II
	1030	Group Meetings III
	1200	Lunch
	1300	Group Meetings IV
	1530	Intergroup Meetings
	1500	Executive Committee Meeting
Thursday	0800	Executive Committee Meeting
	0830	Interaction Meetings
	1200	Lunch
	1300	Interaction Meetings
	1500	Group Meetings V
	1700	Executive Committee Meeting
Friday	0800	Executive Committee Meeting
	0830	Plenary Session III
	1200	Adjournment
	1300	Executive Committee Meeting

The final section summarizes the groups' suggestions on objective 4, establishing R&D sequences and priorities for CELSS development. The recommendations for research are presented in outline form for the issues specified by each group in Section 3.

References

1. "The Closed Life-Support System," Report on a conference held at Ames Research Center, Moffett Field, California, April 14-15, 1966; NASA SP-134.

2. Space Settlements, A Design Study; edited by Richard D. Johnson and Charles Holbrow, report on the 1975 Summer Faculty Fellowship Program in Engineering Systems Design; NASA SP-413; Washington, DC: NASA, 1977.

3. "Life Support," edited by Phillip D. Quattrone, Report on the NASA Office of Aeronautics and Space Technology Summer Workshop, Madison College, Harrisonburg, Virginia; Report available from NASA Langley Research Center, Attn: 418/Charles I. Tynan, Jr., Hampton, VA 23665.

4. "Evaluation and Comparison of Alternative Designs for Water/Solid-Waste Processing Systems for Spacecraft;" Final report on Contract No. NASw-2439 by the Bioenvironmental Systems Study Group of the Society of Automotive Engineers, Inc., J. M. Spurlock, Principal Investigator; July, 1975.

5. "Technology Requirements and Planning Criteria for Closed Life Support Systems for Manned Space Missions;" Jack M. Spurlock and Michael Modell, Final report - Task B (FY1977), Contract No. NASw-2981; January, 1978.

2

EVALUATION OF A GROUND BASED MANNED DEMONSTRATION AS A MILESTONE IN CELSS DEVELOPMENT

Introduction

Each of the six groups was asked to consider the ground based manned CELSS demonstration (GBCD) as a requirement for the development of a successful CELSS. Each group was requested to address, from its own perspective, the following particular questions:

- Critical issues in CELSS development that a GBCD would address;
- Critical issues in CELSS development that a GBCD would not address;
- Considerations on the scope (e.g., population and duration) of the demonstration that the group believes should be imposed for such a demonstration to be meaningful; and
- Suggestions for alternative development routes with an outline of the justifications for these alternatives to a GBCD.

A summary of the workshop findings is presented below. Subsequent sections of the chapter present more information on the individual group's responses to the questions.

Summary of Workshop Findings

Each of the groups believed that a GBCD was a logical milestone in CELSS development. Each believed that the GBCD would be useful for demonstrating actual operations of conceptual designs and components. With the exception of the nutrition group, each group believed that some complete system demonstration, similar to a GBCD, was essential in resolving scientific issues related to CELSS development. (The nutrition group believed that most of the necessary research for assuring proper nutrition could be accomplished without a GBCD). The GBCD was an attractive option for this demonstration in terms of costs and risks.

The GBCD would not address some issues critical to CELSS development. These include:

- Component performance and human behavior in less than 1 g environments;

- Psychological and physiological performance under CELSS conditions in space; and
- Effects of radiation and rotation on component performance and operation.

Nutrition and Food Processing (Group 1)

This group examined research and development requirements to assure an adequate and acceptable CELSS diet and evaluated the GBCD from the perspective of these requirements. To aid in visualizing the criteria for CELSS, the group considered two cases: 1) recycled H_2O and O_2, but no recycling of food; missions might involve up to 20 persons for up to two years; 2) substantial closure, including H_2O, O_2, most carbon, but probably not nitrogen; missions might be multiyear with 50 or more persons.

The group generally agreed that, with some research effort, it will be possible within the foreseeable future to specify diet requirements in terms of chemical composition (carbohydrates, fats, amino acid pattern of proteins, minerals, and vitamins). With this knowledge, there is no intrinsic nutritional merit to any one food.

Nutrient material, whether stored or produced synthetically, agriculturally, or by other biological means, must be incorporated into acceptable foods. A major effort is required to specify and achieve the set of chemical and physical characteristics which characterize food of acceptable variety and quality.

In order to provide maximum flexibility of resource utilization, the diet should consist of engineered foods--foods which meet the nutritional, aesthetic, and other requirements and which are prepared from available components (plant, animal, microbial, plant culture, or synthetic). Research is needed to assure this engineering capability.

The GBCD is a critical requirement, but most research relevant to nutrition and food processing will be accomplished outside the GBCD. The GBCD will be needed to:

1) test interaction of food processing component with other CELSS components;
2) test human responses to the total system, especially in terms of psychology, including food acceptance; and
3) demonstrate total diet control.

The GBCD will not test specific problems related to 0-g. In particular, storage and equipment for conversion of raw material into food and for food preparation may be g sensitive, and human response and food requirements may be affected by gravity level.

The nutrition/food processing group was unable during this workshop to develop guidelines for GBCD size and duration.

Food Production (Group 2)

Group 2's consensus was that a GBCD is a logical early milestone in CELSS development. The critical issues addressed by a GBCD include system closure, component interfaces, waste regeneration/processing, and contaminants. A GBCD also can evaluate approaches to assure system stability, reliability, and safety without the cost and risk of a flight program.

Group 2 emphasized that the GBCD was only one milestone. Other interim objectives and component demonstrations might be accomplished by flight tests and experiments prior to the GBCD, and the group believed that the scope of these interim objectives was more critical than the scope of the GBCD. Subsequent discussions involving the other groups produced a workshop consensus on this point.

Waste Processing (Group 3)

This group concluded that a GBCD was a desirable milestone in CELSS development. The group considered two approaches to waste processing: an approach that produces a plant nutrient solution subsequently used by the plants, and an integrated approach which yields food products without producing the nutrient solution as an interim step.

Assuming a physico-chemical, biological, or hybrid approach to producing a plant nutrient solution from wastes, the GBCD would effectively focus development decisions and effort on several critical issues:

- forms of essential nutrients in effluents;
- closed material balance and recovery of nutrients in usable form from products of waste processing;
- degree of trace material removal (e.g., corrosive compounds, atmospheric contamination) required to avoid antagonism and cross-contaminations;

- control issues associated with transient operation; and
- the detection of subsystem/component interactions.

A GBCD would not adequately address several problems and issues related to waste processing. These issues include:

- materials handling issues (e.g., sedimentation and necessary aeration;
- physiologically produced changes in waste inputs induced by a space environment;
- radiation-induced perturbations in biological subsystems of waste processing; and
- effects of $<1g$ on biological systems.

From the waste processing perspective, the approximate minimum size of the GBCD is three. (Because of transients and variations in waste stream composition over time, the group believed that a small number of persons in the GBCD might present greater problems for the waste processing system than a large number.) The duration of the GBCD should permit several complete cycles of mass through the entire system.

The alternative approach to waste processing is an integrated waste processing system. In this approach, wastes are both decomposed and resynthesized biologically in the same or connecting reactors rather than simply producing a nutrient solution for growing plants. If this approach were followed, the GBCD would address the following issues:

- kinetics of plant growth and oxidation and/or decomposition of wastes (e.g., *Sichornia, Scenedesmus, Spirulina, Lycopersicon esculentum);*
- possible synergistic toxicity of higher and lower plants, such as indicated by Russian experience;
- processing of plant materials for food, minerals for hydroponics, and other needs;
- evapotranspiration rates (rate of water renovation); and
- reactor configuration and system size.

The issues that a GBCD would not adequately address for the first waste processing approach are also relevant to the alternative approach. The desirable size and duration are similar. For the alternative, six persons seem a desirable size, and the duration should be at least three complete mass cycles.

Systems Engineering and Modelling (Group 4)

This group concluded that a GBCD was a desirable milestone in CELSS development. The GBCD would provide an effective means of addressing several critical issues at attractive costs and risks. The GBCD would address the following critical issues:

- validation of CELSS models to provide system performance evaluation as a basis for design improvements;
- refinement of simulation models to account for unanticipated occurrences and system responses;
- focus of efforts on a real integrated system rather than a completely hypothetical concept;
- evaluation of the technology management plan; and
- development of lines of communication among the diverse groups associated with the CELSS program.

The GBCD would not adequately address the effects of reduced gravity, rotation, and radiation on CELSS behavior. It also would not address the issue of human behavior under CELSS conditions in space.

In specifying the scope of the GBCD, the group concluded that the design should provide for:

- off design operation and measurement for CELSS components;
- the monitoring of variables in addition to component model inputs and outputs (this suggests the need for a highly flexible laboratory facility as a part of the GBCD);
- the assessment of leak rates (in and out); and
- use modes by various research groups (this should be based upon a predesign study to weight the protocols of use ranging from dedicated to multitask or parallel).

Ecology-Systems Safety (Group 5)

This group believed that a GBCD is a required milestone in CELSS development. A GBCD could provide:

- data supporting the theoretical basis for system closure (there are no natural, earth-bound ecosystems which are closed in terms of energy, matter, and information);

- a relatively ambitious biological model for in-depth study of the fundamental dynamics of ecosystems, providing information on ecosystem complexity, structure, and functioning;
- safety in development, obviating loss of human life which might occur during an actual CELSS failure;
- a "best case" level of closure which could be relaxed for an actual CELSS when tradeoffs have been adequately identified, providing great flexibility;
- direct and indirect evidence on the performance of the components of a CELSS; and
- a valuable laboratory for the study of applied ecological problems, for example, the behavior of toxic chemicals in ecosystems in terms of chemical localization and effects.

Development and operation of a GBCD would address several critical issues in CELSS development. These issues include:

- the actual feasibility of closure, in terms of costs, degree of failure potential, level of persistence;
- the reliability of mass flow predictions and the impact of uncertainty on system control requirements;
- the necessity for active controls, compartmentalization, and buffers;
- the extent to which component interactions can be controlled (i.e., use of components of GBCD as a set of "biological black boxes");
- monitoring and system testing capability required to identify failure modes of a CELSS or its components (i.e., knowledge of ecological indicators of system dysfunction);
- consequences of alteration of the ecology of various species in a CELSS (and in natural ecosystems); and
- issues pertaining to the structure and functioning of ecosystems, synergistic and antagonistic species interactions, the survival of organisms in gnotobiotic systems, and physiological functions which are usable as indicators of system functioning.

A GBCD would not address issues relating to the influence of the space environment on circadian rhythms which occur in individual species and in total ecosystem processes. Similarly, the GBCD would not address questions of gravitational, rotational, and radiation effects on the biotic and abiotic components of a CELSS.

The ecology group suggested several considerations regarding the scope and design of a GBCD. These considerations are:

1. Coupling of components (biological, physical/chemical, and hybrid) must be followed by a period of equilibration. Consequently, the duration of the GBCD must allow a minimum of two agricultural growth cycles following the equilibration period.
2. The GBCD must be controllable so that at the end of a specified period it will return to an identifiable end state.
3. The GBCD must represent the "worst case" by providing for the largest number of inhabitants within the smallest allowable space in order for the GBCD to demonstrate situations that would never arise in an actual CELSS.
4. Provision must be made for some measure of replicability (e.g., several GBCD) and repeatability (can the GBCD experiment be repeated?).
5. To improve the overall reliability of the design, the GBCD should be composed of several units with each unit a full system capable of performing all of the functions shown in Table 3. The intention is that each unit should be capable of acting as a complete life support system for a specified time period. The units should be as different as possible to increase the reliability of the total system. The units should be designed so that they may be either coupled or disconnected.

Table 3. General Ecological Characteristics Required of All Subsystems in a GBCD or CELSS

Productivity (e.g., food, O_2)
Element Cycling (for nutrition, system structure, and functioning)
Removal of Toxicants
Buffering Capacity
Return to Initial State (or equivalent productivity level) Following Perturbation

3

DEVELOPMENT REQUIREMENTS FOR A SUCCESSFUL GROUND BASED CELSS DEMONSTRATION

Introduction

The five groups were asked to identify considerations critical to a successful GBCD. In addition, they were asked to specify information, technology, and capabilities necessary to develop a successful GBCD. This section summarizes the groups' reports on these two objectives. For each scientific, technical, or developmental issue, the groups considered why the issue is important, what is currently known, sources of information, and important information gaps. Each group considered these issues from its own disciplinary perspective, reflecting its own distinctive conference role (see Table 1 in Chapter 1).

Nutrition and Food Processing (Group 1)

This group's role in the workshop was the identification and assessment of knowledge regarding nutritional requirements and food processing options that would assure an adequate and acceptable CELSS diet. The group considered missions not involving mass closure as well as missions incorporating mass closure. The following issues were specified as necessary technology or capabilities for the development of a successful GBCD.

Missions Not Requiring Closure. Missions not involving closure include those cases which recycle H_2O and O_2 but do not recycle food and nutrients. These missions might involve up to 30 people for up to two years. Of major importance to missions not requiring closure is the storage stability of foods and/or food supplements. For at least a part of the nutritional requirements, stable storage of food (in terms of nutrients, palatability, safety) and food supplements (for appropriately processed foods) would be necessary for several CELSS scenarios. Stability requirements may also remain a critical issue for the ultimate CELSS design.

A summary of the existing knowledge on storage stability of food may be found in documents on Apollo and Skylab and from research reports from Johnson Space Center and Natick Research Labs. Other sources include the MIT report to Ames Research Center* and data within industry. These sources also provide summaries of gaps in available information. Gaps exist in the knowledge of food stability of freeze-dried foods needed to give a 2-year stored diet and in the need to provide esthetic satisfaction by providing additional foods (i.e., thermally processed).

These gaps in information must be closed prior to conducting a GBCD. An integrated demonstration would require a GBCD in order to interact with the human factor, microbial ecology, etc. However, long-term orbital missions may be more appropriate than GBCD. This research has a high significance due to the impact on duration and feasibility of missions.

A second development issue of importance to missions not requiring closure is the analysis of available feeding systems. Potential exists for improving ways to deliver stored food to the mouth. Improvements may be possible in menu design, food service, frequency/service times, and crew station designs.

Data on feeding systems are available from the food service industry, merchant shipping, NASA, and the Navy. The major gap in the data is in adapting to mission requirements. Research must be conducted not only on alternative methods of feeding, but also on the possibility of food preparation in flight and on the minimum organoleptic variety needed for an expected type of crew.

Missions Requiring Closure. Missions involving substantial closure (H_2O, O_2, most C, probably most N) may involve up to 50 people on a multiyear basis.

Any CELSS food production system must meet nutritional requirements whether imposed by steady state or transient physiological conditions. The specifications for nutritional requirements are expressed in terms of the amounts of nutrient material needed to support optimal physiological and psychological functioning. A range of values exists for each nutrient which encompasses minimum needs and maximum tolerances.

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*M. Karel, *et al.*, "Maximizing Storage Stability of Food to be Used for Resupply in a CELSS," MIT Final Report to Ames, July, 1979.

Requirements for fats, carbohydrates, sugars, vitamins, and macronutrient elements are fairly well known. A large body of scientific literature is available with respect to ground based requirements. Expertise in this area is predominantly based in universities although some government laboratories contribute to the field. Precise 0-g information is very limited and exists primarily as internal, unpublished NASA and USSR documents.

Unsolved questions remain on the extent of requirements for polymers of amino acids and sugars, nutrient interactions, microbial interactions, special 0-g needs (particularly for energy), and ground based needs of women with respect to amino acids. It is also uncertain whether all trace elements have been recognized to date, and even among the recognized elements, maximum limits are largely unknown. Requirements for fiber and its chemical characterization remain to be elucidated. The possibility of unrecognized organic nutrient requirements cannot be excluded.

To ascertain that the nutrient specifications proposed for CELSS are optimal, a long-term dietary experiment must be conducted. Healthy human subjects would be maintained for 6-12 months on a diet containing nothing more than the nutrients recognized to be essential and on a nonspecific energy source and fiber. A definitive test depends upon the exclusion of unknown or unessential chemicals. Although complete nutrient formulations have been developed, they have not been tested over prolonged periods. Industry and academic nutrition and clinical departments can provide sources of existing data.

In addition to the specifications of nutrient requirements, criteria for assessing the adequacy of a CELSS diet must be developed. Biochemical, physiological, anthropometric, and psychological criteria are required in order to monitor the well-being of persons maintained on unconventional or controlled diets.

A large array of tests are in use at the present time although little consensus exists with respect to normal values and ranges and optimal combinations of tests. Continuous monitoring systems are largely unavailable and specific tests designed to elucidate problems encountered in specialized feeding situations are quite primitive.

Existing knowledge on criteria for assessment is largely available in academic departments of nutrition and in medical centers concerned with parenteral feeding. 0-g oriented procedures have been developed within NASA. Additional information must be available prior to GBCD.

Other factors influencing diet acceptability must be evaluated early in the development of CELSS since the research results will, along with the nutritional requirements, define the food processing and food service equipment and procedures. In addition, it is likely to affect food raw material production requirements to some degree.

Organoleptic characteristics (taste, color, temperature, texture, form, odor, variety) are known to influence acceptability, but the extent of essentiality and variability have not been quantified. Comparable statements can be made concerning the effects of other characteristics of a diet (physiological state, psychological state, cultural needs, external stimuli, frequency of eating).

Research on these factors must be performed well before the GBCD and will entail seclusion of test subjects. It may in some cases include provisions for a closed environment. The GBCD would be used only to verify the overall research results and the interaction between the food acceptability and the CELSS.

To achieve maximum economy and flexibility in food provision and resource utilization while meeting nutritional and other acceptability requirements, it is necessary to identify or develop the food technology capable of converting raw materials available from the CELSS food production process into acceptable dietary components. Figure 1 summarizes the current state of technology as a function of food component type and diversity of diet *vs.* raw material source. An analysis of the existing technologies may be undertaken for parts of the "map" in Figure 1 initially, and then extended to other areas. The figure also indicates the extent of difficulties in product and process development.

The first task is the development of formula diets from nonconventional ingredients. Potential raw materials include a spectrum ranging from synthetic components to nonconventional biomaterials (yeast, leaf, algae, etc.). The state of the art for this task is primitive, with hospital diets being the major source of data. The second task is the

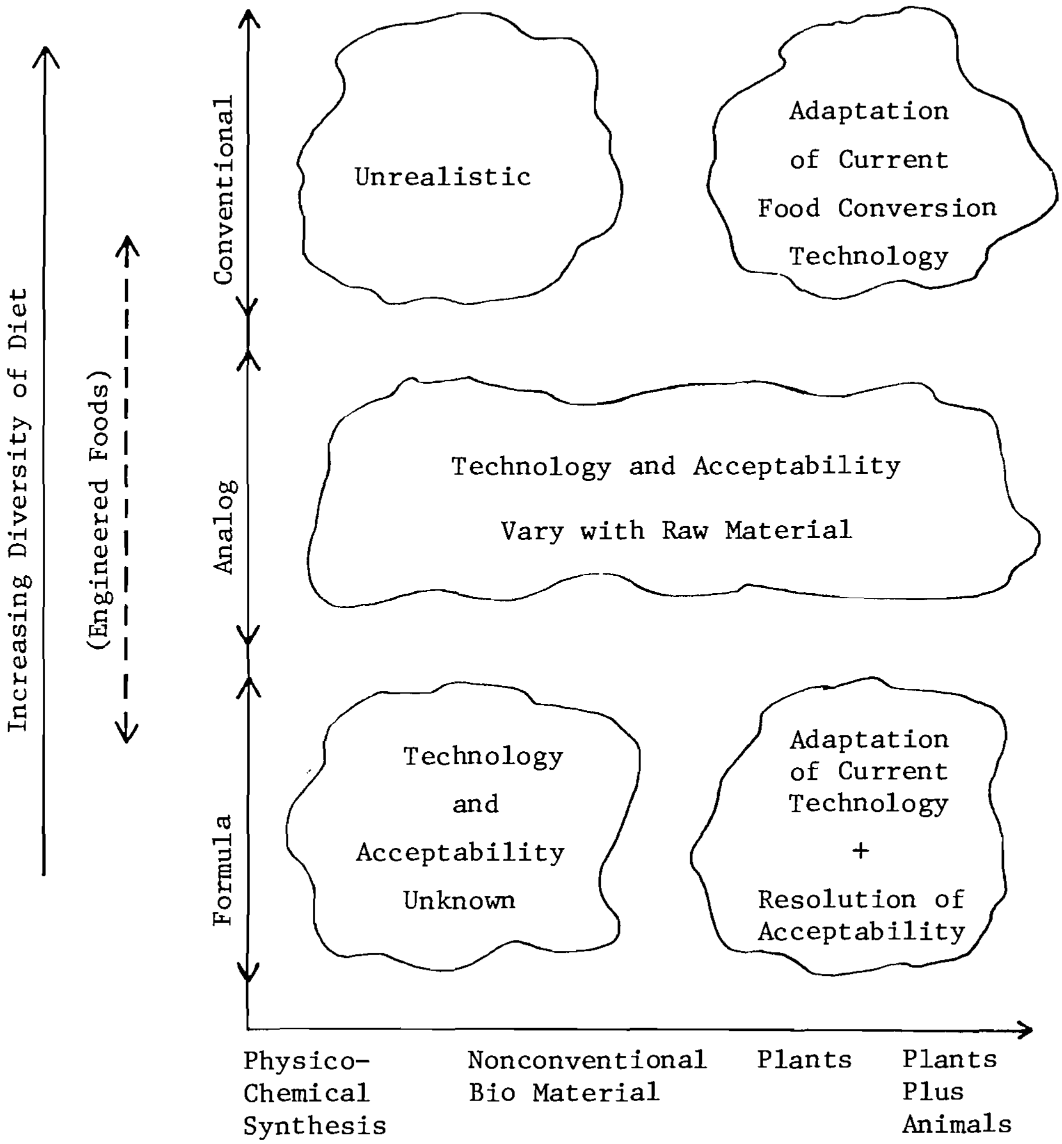

Figure 1. Parameters Governing Product and Process Development

development of conventional foods from a variety of sources, including other engineered foods. Some conventional sources are advanced (i.e., soy milk, oriental "cheeses," fabricated meats, textured vegetable protein, sausages, and candy), with industry and universities providing the major sources of data. However, the state of the art is limited and research is needed on a variety of raw materials.

The state of the art of the third task, developing formula diets from conventional sources, is well developed. Potential problems exist in purification of raw materials but the major problem remaining is adaptation to the mission. The fourth task is the development of a food conversion system for conventional foods from conventional sources, given the constraints of the mission. Except for some components, the state of the art does not exist. This task requires 0-g research.

Food Production (Group 2)

The role of the food production group was to identify and assess knowledge regarding the growing of food materials in a CELSS. The group considered various options for producing food and meeting nutrient requirements.

The food production group assumed that a space-deployed CELSS is at least 15-25 years away. During that time frame, two developments might affect space-deployed CELSS: a) heavy-lift vehicle (HLV) transport systems might reduce lift costs by an order of magnitude; and b) extra-terrestrial sources of bulk life support system elements (C, N, H) from carbonaceous chondritic asteroids may be available. The group believed that the development of the GBCD should not be constrained by space transport considerations.

The problem set appropriately addressed by a GBCD should focus around closure, food regeneration from wastes, and system safety reliability, and predictability. The state of the art of major approaches to food production (plant/animal agriculture, bioengineered foods from microorganisms/chemo-synthesis) is so rudimentary that no approach should be rejected at this time.

In order to evaluate and develop CELSS as a new technology, the food production group believed that the size and mission duration considerations should exceed both the existing and projected state of the art (stored food, absorbed gas, recycled water). The following guidelines were proposed:

--The mission size should be 24 with a duration of at least one year.

--Interim development steps should include closed chamber studies involving:

- plant only, individual species-multispecies;
- animals only, individual-multispecies;
- plants and animals, simple-complex combinations; and
- man and plants (1-man, 3-man, 6-man, 12-man operation of demonstrator, 24-man full-scale demonstrator).

Three options for food production were considered by the group: higher plants/agriculture; microbial and chemical food production; and terrestrial animal/aquaculture animal production. The issues implied by these options are discussed below.

Higher Plants/Agriculture. The group detailed the primary and other functions that higher plants could serve in a life support system. These included the following:

- production of food for humans;
- production of food for animals and substrate for single cell protein or tissue cultures;
- air revitalization including addition of O_2, removal of CO_2, and removal of certain gaseous contaminants as H_2S, SO_2, and NO_x;
- purification of waste water into plant tissues and into air through transpiration;
- conversion of human, animal, and plant wastes into human or animal food;
- redundant food supply; and
- aesthetic value.

Environmental response information has been generated for most candidate higher plants under controlled environments. However, this information is insufficient to be able to predict the maximum productivity for plant species under specialized environmental conditions of any particular closed life support system. Technology is available for systems that can be integrated to optimize cultural and environmental conditions for growth of the candidate plant species.

Nutrient data is available to indicate the range of concentrations under which most candidate plant species will maintain normal growth. Threshold toxicity levels of most micro elements have been established for a few plant species and this information can be a basis for the evaluation of the toxicity levels for candidate species. Nutritional data is available for edible parts and all above ground portions of most candidate plant species grown under field environments and under certain conditions in controlled environments. However, it is unlikely that nutritional data are available for edible parts and above ground portions of most candidate plant species under the specialized environment of the GBCD.

No particular productivity advantage for C-4 plants over C-3* is anticipated in a closed environment system in which carbon dioxide can be provided in excess. In fact, there may be significant disadvantages to utilizing C-4 plants particularly if light levels can not be optimized. The use of plant species that can maintain a continuous constant photosynthetic activity for O_2 production is preferred over species that cease or reduce photosynthetic activity for a period while maturing seed.

Information is available for the utilization of sewage wastes by higher plants. Therefore, systems can be readily developed for evaluating the usefulness of human and plant wastes for candidate plants. It is known that plant systems are capable of utilizing secondary treated waste solutions if a) ionic concentrations are not excessive, and b) the solution contains nontoxic levels of micronutrients: Co, Cu, Zn, Fe, Mn, and Mo. There may be some growth restrictions

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*C-3 and C-4 plants differ in the biochemical pathways by which carbon is incorporated into organic products. In C-3 plants, external carbon dioxide flows through a single pathway, while in C-4 plants, there is an additional pathway which serves to provide a more favorable internal CO_2 concentration.

if major nutrients are not properly balanced. A nitrate source of N would be preferred for most candidate plants, although NH_3-Nitrogen is of potential advantage and even required for certain plant species. The pH of waste solutions could be adjusted over the rather wide range between 4.5 and 7.0 to permit optimum nutrient uptake.

Microbial and Chemical Food Production. The microbial and chemical production of food can provide all of the shopping list of nutrients (including O_2) requested by the nutrition and food processes group. The advantages of the use of such a system are that it:

- is amenable to precise control, optimization, and variation;
- involves the use of compact, high density reactors;
- involves handling of liquids and suspensions, rather than solids;
- has short turnover (maturation) periods and can therefore generate large quantities of biomass in a relatively short time;
- can be switched on and off relatively easily and returns to steady state easily after experiencing a shock;
- is amenable to genetic engineering approaches for synthesis of specific nutrients; and
- constitutes a relatively less labor intensive method of growing food and is amenable to automation.

The disadvantages are that: a) this system presents more complex food processing problems; b) the food might be less acceptable or palatable; and c) catalyst degradation might necessitate the regeneration of catalysts or the maintenance of a store of catalysts.

Microbial photochemical food production systems constitute a completely independent food cycle. Using several small high density reactors can increase the degree of redundancy. The chemical production of food is more resistant to space radiation and impervious to pathogenic cross-contamination. The system is especially amenable to genetic engineering approaches. Special dietary needs such as sulfur-containing amino acids, vitamins, and medicines (antibiotics) can be microbially synthesized this way.

The photochemical and chemical systems serve to regenerate oxygen and remove CO_2. They can be used continuously or programmed to come on stream if and when large transients in concentration of these gases appear. Photoautotrophic microbial systems can efficiently revitalize air to produce oxygen. They also provide unique opportunities for direct chemical or biological control and closure of the nitrogen cycle and limit levels of N_2O, NO_x, N_2 in the atmosphere. Biological or chemical processing of urea, cellulosics, and nucleic acids to useful food products can also be attempted.

In terms of photochemical and chemical systems, the photocatalytic and photoelectrochemical dissociation of water to H_2 and O_2 has been demonstrated. However, the photocatalytic dissociation of CO_2 to CO and O_2 has not yet been demonstrated. The photocatalytic reaction of CO and H_2 is well understood, and the thermal reaction of H_2 and CO to methanol is a commercial process. These techniques have become attractive relative to other conversion routes since a new generation of photocatalysts has evolved.

For biological systems, the continuous culture of large quantities of algae has been confined largely to chlorella. These cultures have been maintained for months under constant input conditions. Even though long running continuous reactors have been developed for algae/ chlorella, perturbation behavior of these systems have not been studied. The transient response to variations in O_2, CO_2, light, etc., have not been evaluated.

A series of large flow reactors have been developed as a result of single cell protein development (feeding on methanol and/or ethanol) for long extended periods. (Problems are with commercial economies, not feasibility.) The large-scale pharmeceutical and single cell industries have accelerated interest in processing and handling techniques. These studies are largely bench scale and have not been used in large-scale preparative processes.

For the nitrogen loop, small-scale chemical reactors for N_2 fixation are being researched and are in a stage of development that is useful for individual farmers. The vast research efforts on the specific steps in N_2 fixation can provide information needed to close the N_2 loop biologically.

Terrestrial Animal/Aquaculture Animal Production. The plan to use animals may provide justification for a larger plant productivity unit, and thus provide flexibility and backup provision for handling emergency situations (e.g., premature harvest of most animals and redirection of plant products to direct human use if a part of the plant production unit should fail). For terrestrial animals, available data are likely to be highly fragmented and scattered and will vary considerably for different species (e.g., data on dairy cattle, pigs, and poultry are likely to be more comprehensive and more relevant than data on sheep, goats, rabbits, etc.) Much of the data will require re-analysis and evaluation because of the unconventional emphasis of CELSS.

Optimum space requirements for most candidate species under conventional production conditions are readily available. However, these are likely to be transferable only where conventional production conditions are very intensive and controlled (e.g., poultry and to some extent rabbits and pigs; less so, dairy cattle, and not at all for sheep and goats). Minimum space requirements for different animal species need to be quantified.

Data on environmental stress on animal species are available but very limited. It seems likely that all problems have not been identified, but two major problems that have been identified are disease and reproductive failure with restricted space and crowding. Reproductive failure involves (at least) failure to ovulate. Data on causes are extremely limited, possibly nonexistent. Effects on immunocompetence are also little known.

In terms of gaseous input/output and waste outputs, data are available from metabolism chamber, energy, and carbon/nitrogen balance studies. More data are available on small animals than large, but the vast majority of it relates to animals at maintenance or very low level energy output. Very few are at normal production levels.

Nutrient requirements of conventional agricultural animal species (i.e., cattle, sheep, pigs, poultry) are fairly well known. Less information is available for others (e.g., goats, rabbits) and virtually none is available for nonagricultural species except fragmented data from zoos. Data on chemical/proximate composition and value (e.g., in vitro digestibility) of feed residues and byproducts are limited and very fragmented. Feeding trial information and input/output type data are very limited and confined largely to cereal straws and stovers. Use of crop processing byproducts and noncereal residues (with some exceptions) is not well documented, especially where these constitute a large portion of the feed. Only limited data are available on feeding microbial/algal material to animals, again especially where these constitute a large portion of the diet.

For aquaculture animals, studies on microalgal species are moderately advanced for a few species. Macroalgal species are being studied, but are probably not applicable for CELSS. Studies are needed on single vs. mixed algal species for persistence and stability of output.

Fish ponds with natural food chains and intensive cultures with formulated feed are in commercial use, but additional studies are needed on the feasibility of direct use of wastes. The growth of fish on (sewage grown) algae has been demonstrated (Israel), but the growth of fish on (nutrient solution grown) algae as a sole food has not been demonstrated.

Filter feeding invertebratae (e.g., Daphnia) as an intermediate in the algae-fish system has not yet been demonstrated but is believed to be feasible. Also, freshwater shrimp are a possible edible herbivore/detritivore.

Waste Processing (Group 3)

This group's role was to identify and assess knowledge regarding human and food waste processing options, taking into consideration air, water, and solid waste recycling. From the waste processing perspective, the approximate minimum size of the GBCD is three and the duration of the GBCD should permit several complete cycles of mass through the entire system.

Overall Conceptual Approach. Three elements, carbon, oxygen, and hydrogen, are the major components of the materials required for life support. In a completely closed environment where all foods are grown on board and all wastes are recycled into foods (vegetation and animals), the material balance for these three elements can be closed in a manner analogous to that which occurs on earth.

Carbon in human and animal wastes appears as CO_2 and partially oxidized organics in feces, urine and exhaled breath. If all of the carbon in these wastes are oxidized completely to CO_2, then the net effect of human and animal metabolism plus subsequent oxidation is the exact inverse of photosynthesis:

$$CO_2 + \frac{m}{2} H_2O = CH_mO_n + (1 + \frac{m}{4} - \frac{n}{2}) O_2$$

Since oxygen is consumed in metabolic processes for oxidation, equivalent oxygen is regenerated by plants in turning CO_2 into vegetation. Therefore, the carbon and oxygen balances are simultaneously closed by oxidizing all organic matter in wastes and then growing vegetation for food from all of the CO_2 generated (i.e., from metabolism and waste oxidation). Note that hydrogen transformations from water to food and back to water are also balanced by such processing.

If some foods are not regenerated in space, but are stored on board or periodically resupplied, then there will be a net build up of carbon, hydrogen, and oxygen if they are not removed during waste processing. It is anticipated that these additional quantities of oxygen and hydrogen can be utilized as make-up for inevitable leakage of air and water vapor. Since the CO_2 present in the air is at a concentration significantly below that of oxygen, it is desirable to provide, within the waste processing system, a means for removing excess carbon and storing it in a convenient form (e.g., solid carbon). Since the excess carbon originates as stored food, the maximum quantity of carbon to be removed and stored in waste processing is equivalent to the carbon in the stored food.

Water that does not enter into metabolic processes is essentially used as a carrier fluid, within the living components and externally in the waste processing subsystems. Thus, physical separation processes should be sufficient for transforming water in wastes back into the water inputs of drinking water, sanitary water, and wash water.

The nutrient solutions used for growing plants in controlled growth chambers such as phytotrons invariably contain 12 to 16 elements that are present as inorganic salts and organic chelating agents that are needed to maintain some of the ions in solution. These elements are commonly called macronutrients (K,P,N), secondary nutrients (S,Ca,Mg), or micronutrients (Co,Fe,Mn,Mo,Cu,B,Zn,Na,Cl). We shall herein refer to them as plant nutrients or, when there is need to distinguish between their concentrations, as major nutrients (macro plus secondary) and minor nutrients (micro).

These plant nutrients appear in the waste streams in the form of spent nutrient solution, inedible vegetation, uneaten foods, food processing wastes, human and animal metabolic wastes, and animal processing wastes. One of the major functions of the waste processing system is to recover the plant nutrients elements from the various waste streams and convert them back into forms that can be assimilated back into the food chain by plants.

In addition to the elements present as plant nutrients, there are a number of elements ingested by humans and animals that provide psychological acceptability of food or adequate nutrition. Notable in the former category is table salt, which is conventionally relatively pure NaCl, although some KCl impurity can be tolerated without introducing noticeable bitterness. The latter category includes many elements that are known or suspected to be essential for proper nutrition (e.g., I). A complete list of elements and required concentrations will be developed by those concerned with habitat nutrition.

It is anticipated that these elements and compounds, with the exception of table salt, will be required in trace quantities. These elements will be referred to herein as diet supplement elements. When NaCl is excluded from the list, we shall call them trace diet supplement elements. On earth, they are ingested either as minor components of animal and plant foods or as supplements in vitamin capsules. In a CELSS environment, they could also be ingested from plants, provided that they are included in the plant nutrient solutions and provided that sufficient quantities become incorporated in the edible portions of plants. Similarly, they may be incorporated in the drinking water provided that their concentration does not affect the taste-acceptability of the water. Alternatively, they can be separated from the waste streams, packaged in capsule form and ingested as a diet supplement. Since very small amounts of the trace diet supplement elements are required, adequate supplies of these could be brought on board at the outset and used on a once-through basis. However, the concentrations of these elements would continue to build up. Since it is known or suspected that excessive quantities of some of these elements are harmful to health, the maximum acceptable limits might be exceeded for long mission durations. The length of mission beyond which recycle becomes essential is dependent on the ratio of maximum acceptable limit to recommended dietary requirement, which is amenable to analysis. Such analyses should be undertaken at an early date by those concerned with modeling and nutrition. Since extensive experimental studies on the ways plants take up these elements will have to be performed before we can determine if they can be recycled via plant nutrient solutions, it is necessary to plan now for the contingency that these elements will have to be recovered from waste streams and returned as diet supplement capsules.

Note that organic components of diet supplements, such as vitamin pills, do not need to be addressed explicitly by waste processing. It can be safely assumed that they will be ingested from stores brought on board at lift-off and will be converted to CO_2 and H_2O along with other organic wastes.

There will invariably be a number of other extraneous elements that enter the water or air cycles due to corrosion or wear of machinery. It is anticipated that these extraneous elements will appear at trace levels, but that they will build up within the loops if provisions are not made to prevent their appearance or remove them during waste processing. It is also anticipated that efforts to minimize their appearance will be made by placing constraints on materials of construction. However, in order to provide for inevitable and unplanned events and build ups, methods for removing these extraneous trace elements will have to be incorporated in the waste processing system.

Waste Processing Subsystems. The functions of the waste processing subsystems of CELSS are to turn all wastes back into the inputs required to sustain life and to remove contaminants that may be harmful or impair functioning of the living components of the habitat. The major inputs required to sustain human life are food, oxygen, drinking water, sanitary water, and wash water. The major waste outputs include a) solids (human and animal feces, inedible vegetation, uneaten foods, food processing wastes, and animal processing wastes); b) liquids (human and animal urine, spent nutrient solutions, and spent wash water); and c) gaseous (O_2 from plants, CO_2 from humans and animals, water vapor, and off-gases).

Two constraints are important to waste processing. The first is to minimize the cross-contamination between different living components by maximizing isolation (avoid mixing plant atmosphere with human atmosphere by, e.g., separating O_2 from plant atmosphere and transferring only this O_2 to humans, etc.). The second constraint is to maximize redundacy of waste processing subsystems by the function served. Multiple approaches to oxidation of organics should be used.

Many important tests/demonstrations are needed along the way to a full system GBCD. The need for diversity/isolation of different subsystems (e.g., plant and animals) plus the advantage of treating different wastes separately (e.g., plant wastes would contain no NaCl nor trace elements from diet pills) means that waste processing subsystems could be developed and tested on a smaller scale and without a complete CELSS. The existing technology has never been evaluated within the CELSS concept. Early design analyses of complete systems are needed. Whole new waste processing methods may need to be invented and developed.

Typically, subsystems evolve to a mature form in a series of research and development steps that involve progressive technological improvements and increased understanding of the nature of the processes that comprise the subsystem. In past experiences with physicochemical subsystems, there has been a tendency for hardware and mechanical developments to outpace the basic understanding of the processes involved. This, in many cases, has resulted in more costly development than would otherwise be necessary. It is felt that this situation can be minimized or avoided by obtaining as much understanding as possible about the operation and performance of a subsystem at each step of development.

The following subsystem technologies have been researched and developed to varying degrees:

- oxidation of organics by incineration;
- wet oxidation of organics;
- biological oxidation of organics;
- integrated algal bacterial systems;
- higher plants grown on urine;
- wash water recycle;
- atmosphere decontamination;
- carbon dioxide and oxygen extraction; and
- recovery of plant nutrients and trace metals from solid and liquid streams.

None of these technologies has been studied previously in terms of adaptation to the specific requirements of the CELSS concept. For example, the three alternative oxidation processes (incineration, wet oxidation, and biological oxidation) are well-developed technologies for terrestrial applications; the first two have also been researched by NASA for limited space applications. However, even for what is normally considered "well-developed technologies" on earth, a significant amount of R&D is required to determine how readily they will fit the needs of a CELSS waste treatment process.

Precise measurements and characterization of system inputs, outputs, and operating parameters are required so that detailed mass and energy balances may be obtained. These data are required to establish the engineering interfaces and the design of accompanying subsystems. For example, the concentrations and types of organics in the off-gas, which are a function of operating temperature and mode of operation, will define the need for subsequent catalytic oxidation of the off-gas. The degree to which N_2 is formed during the oxidation of organic nitrogen will determine the need for a separate nitrogen-fixing subsystem in the overall processing scheme. The forms and concentrations of metals in the ash, which may be a function of oxidation temperature, will have ramifications on the methods used to solubilize and separate the ash components in the preparation of plant nutrients.

Incineration is a well established terrestrial technology that has been researched by NASA as a means for consolidating wastes in short-duration space missions. However, past studies have not developed the data required to evaluate this technology for CELSS application. The selection of appropriate control parameters and monitoring needs will require the development of special instrumentation to a flight qualified status.

Wet oxidation of organics, or the Zimpro process, is a developed terrestrial technique that has been researched by NASA for limited space flight applications. Both solid and liquid wastes can be processed by oxidation with the final products consisting of CO_2, a NaCl-KCl mixture for use in food preparation, and a mineral plant nutrient solution or the dried plant nutrients.

Figure 2 illustrates the components, the flow of materials, and the processes of this system. Urine is processed separately, and by a different oxidative procedure, from the other wastes in order to a) recover the NaCl for human consumption, b) prevent salinization of the hydroponic solution, and c) provide alkaline components to neutralize the acidic products of the wastes treated with a catalyzed wet oxidation process.

The proposed system operates as a batch-type reactor rather than a continuous flow-reactor. This choice is based on considerations of safety, engineering simplicity, and reliability, and a decrease in variable treatment parameters needed to maintain quality control of the products. In order to evaluate the proposed system, the following steps are suggested:

- identification of laboratories competent in wet oxidation processing for research and development;
- consultation to determine the suitability of proposed salt mixture for human consumption;
- consultation to determine the suitability of plant nutrients for hydroponic use;
- identification of plant growth facilities for testing plant nutrient solutions;

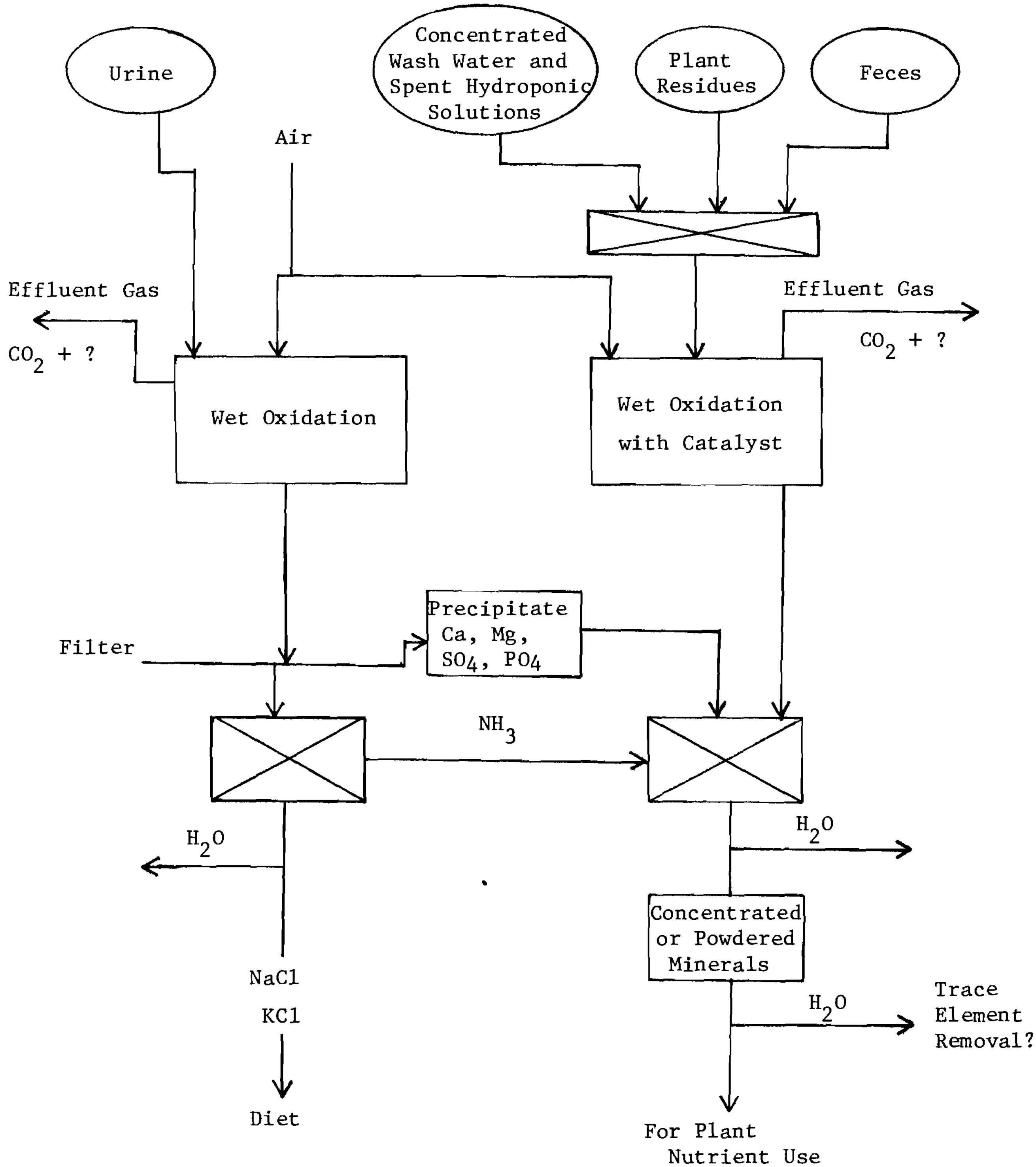


Figure 2. Wet Oxidation

- consultation to determine appropriate approaches to providing pure oxygen (rather than air) from CELSS;
- identification of analytical requirements for R&D;
- review of research on wet oxidation processing;
- identification of problems of commercial users of wet oxidation processes for possible relevancy; and
- identification of wastes or simulated wastes to be used in R&D.

Biological oxidation of organics is a well-developed terrestrial technology for secondary treatment of sewage. It is commonly called the activated sludge process.

A critical issue is whether or not the microbial treatment process will be stable under anticipated transient stresses. To answer this crucial question, one must first determine the following:

- the values of pH, temperature, solids concentration, and other state variables which will give "optimal" steady state performance (removal of carbonaceous material, etc.);
- the major microbial species present and how they react;
- the nature of the gases vented; and
- for all important elements, the removal rates from solution and accumulation in the biotic component.

Knowing these items, the base case can be perturbed by shock loadings of flow volume, overall solids-loading, and by step changes in the concentrations of key elements. The changes in effluent quality and the character of the microbial population can be determined and potentially, a useful mathematical model developed. What are the effects of pH control failure or temperature fluctuations? Do the source or quantity of dilution water affect stability and performance?

Some soluble refractory organic compounds (i.e., chemical oxygen demand, or COD) will be "purged" from the stream by precipitation from the liquid with the solid residue stored. It is unclear that such a "purge" would reduce soluble COD to acceptable levels. The nature and source of such compounds would need to be determined.

An integrated algal bacteria system has been suggested as a candidate for CELSS applications. The process step of incinerating the algae back to CO_2 can be eliminated, and this may be an alternative to oxidation of bacterial buildup in biological waste treatment.

It is known that all systems work to some extent, a low temperature distribution is acceptable, and the elimination of all bacteria is unnecessary. It is not clear how such a process will fit into a complete CELSS waste processing system. The end uses of the algae produced need to be defined. Unknown factors include light sources, algae as food, refractories produced in bacteria oxidation, incineration residues, and toxicants.

Another waste treatment process is based on using higher plants to grow directly on the soluble waste products (urine, dissolved matter in wash water, etc.). Preliminary research has demonstrated that certain vascular plants can recycle minerals from human waste while producing high quality protein and essential vitamins. The vascular aquatic plants used in these studies may contain as much as 4% sodium chloride on a dry weight basis. Additional research should be conducted screening large numbers of different type vascular plants for their capacities and efficiencies to grow and recycle minerals directly from human waste in the form of edible plant material.

Used wash water is relatively uncontaminated. It contains predominantly inorganic salts, urea, and cleansing agents. It can be processed for storage and subsequent reuse as wash water by pasteurization to control bacteria and odor formation. Wash water represents over 80% of the total water requirements, and an efficient means for treating spent wash water is essential.

Three systems (or some combination thereof) appear to be good candidates for wash water processing: reverse osmosis (hyperfiltration), multifiltration, and selective floculation-precipitation. Commercial reverse osmosis and multifiltration units have been on the market for a number of years. However, they are generally for small-scale usage or for cleaning up water only sufficiently for discharge to receiving streams. These units generally cannot tolerate elevated temperatures. Prior studies by NASA did not address the adaptation of these technologies to CELSS requirements. Spacecraft-applicable reverse osmosis technology is relatively immature, having only recently been accelerated from the small-scale, feasibility stage to a full-scale preprototype system. Consequently, some additional technology development will be required to improve fabrication techniques, increase life characteristics, etc. There have been no long-term tests of an operating system.

Atmospheric decontamination, or the removal of trace contaminants from the human and plant atmospheres, is essential within a CELSS environment. In order to minimize the dangers of cross-contamination, ecologists have recommended that each of the subsystem atmospheres be treated separately.

Previous NASA efforts in atmosphere decontamination involved catalytic oxidation and/or adsorption to purify the atmosphere of humans. The adaptability of these or other technologies to the CELSS requirements needs to be studied.

Carbon dioxide and oxygen extraction may be necessary to minimize cross-contamination between atmospheres of the CELSS subsystems. It may be necessary to separate CO_2 from human and animal atmospheres and feed the concentrated CO_2 into the plant atmosphere. Similarly, O_2 would be removed from the plant atmosphere and fed into human and animal parts of the habitat.

NASA has developed a number of systems for removing CO_2. However, none of these systems have addressed the special requirements imposed by CELSS. There has been little, if any, prior work in space applications relative to oxygen extraction.

Plant nutrient and trace metals have to be recovered in a form suitable for reuse. More or less extensive separation of these nutrients will be required, depending on (1) whether one, or more than one, nutrient solution composition is required for plant growth, and (2) whether "fresh" minerals are periodically introduced into the recycle loop by the use of supplementary diet "pills." Nutrients are separated from such solutions always as salts, rather than the individual elements.

Methods are now available whereby the theoretical feasibility of the steps required in any proposed separation can be explored on paper.

This is possible because the chemistry of these ionic systems is reasonably well known, and because of recent work which makes it possible to predict activity coefficients and solubility diagrams for the systems involved.

The design of a salt separation system depends upon the composition of the feed solution to be processed, on the salts to be separated, and on the purity desired for each of these salts. Any desired separation can usually be accomplished by selective crystallization and extraction, provided that the necessary processing equipment and sufficient energy are available. However, the processing schemes involved for some separations may be very complex and therefore may be impractical for CELSS operation. No generalized process design can be proposed for each separation. Specific designs unique to each feed and to each desired separation must be developed.

Systems Engineering/Modeling (Group 4)

This group identified the role of systems studies and modeling efforts in the CELSS program. The group considered the desirable scope of the GBCD, and the discussions emphasized issues relating to the interfacing requirements in the process of CELSS development and in the CELSS design.

In considering the scope of the GBCD, the group concluded that the design should provide for the monitoring of variables in addition to component model inputs and outputs. The design should also provide for off-design operation and performance measurement for CELSS components, for the assessment of leak rates (in and out), and for different use modes by various research groups. This suggests the need for a highly flexible laboratory facility as a part of the GBCD.

The process of CELSS development requires considerable discussions among researchers from several disciplines and program management that assures effective program integration. These requirements can be supported by an effective information storage and exchange methodology. Such a methodology, developed by identifying the information needs associated with disciplinary and component interfaces, could also provide a basis for program management decisions. The support of CELSS development thus incorporates two critical factors: program integration and the integration of the actual CELSS design, operation, and control.

In order to achieve effective program integration, the following information is needed:

- characterization of design options (scenarios);
- specification of data voids that limit establishment of evaluation criteria (feedback);
- specification of data quality necessary to achieve required evaluational quality; and
- method for evaluating recommended design scenario candidates (guide for establishing priorities for R&D).

Analyses of requirements for CELSS design, operation, and control are needed as well as analyses which include simulations of operational behavior and control strategies to achieve stable operation. These analyses will require the following:

- establishment of a data base;
- specification of hardware/software requirements;
- information from and for R&D;
- specification of functions (performances) information; and
- specification of data quality and establishment of (degree of) confidence (limits).

General Modeling Approaches. The sole means of providing the level of control essential for the successful operation of CELSS is through dynamic mathematical descriptions of the functions of all system components, including the biological. Many of the techniques of modeling and process control are well documented. However, none have approached the degree of complexity required by CELSS. The sources of information are moderately well documented, and the expertise in the areas of sensing and control theory is well identified.

Significant gaps exist in the theory of control of nonlinear systems. Theoretical development in this area must and can be defined. Similarly, assessment of the quality and meaningfulness of sensory strategies and data is not immediately possible and will require theoretical development. However, the problem is well defined and investigative efforts are known to be underway in this area.

Little or no data are currently available concerning the actual input/output flows of systems within CELSS. In order for these data to be timely, accessible, and acceptable to the community of CELSS researchers, they should be developed according to a set of mutually agreeable guidelines for data acquisition.

CELSS will operate as a tightly controlled mass recycling system. It will contain two major easily separable biological componets, man and his food sources, as well as a series of physical and mechanical components, including those capable of chemical processing. The GBCD is envisioned as a unit, or series of units, that will operate with a practicable minimum of external mass input and hence a maximal degree of recycling and closure.

The operation of CELSS will require highly structured control strategies that will function to maintain homeostatis, or some defined states. Such control requires constant analysis of the state of the system, integration of all information relevant to system state, and a strategy for applying specific corrective actions (control). Application of control also requires detailed knowledge of the location of all mass in the system, and the ability to predict future system state. The sole means of providing the level of control essential for the successful operation of CELSS is through dynamic mathematical descriptions of the functions of all system components, including the biological.

CELSS will require the development of a series of mathematical models. This series will ultimately be integrated to provide system control. At the first level, descriptive models must be designed to acequately represent the flow of materials through various parts of CELSS: through the human, food production and waste processing components of the system. To develop these, input and output flow rates must be known, as must limits, capacities, and tolerances. The accuracy with which flow rates must be known for the purpose of a descriptive model will provide a framework for validation--a process that will require comparison with a real functioning system, model alteration, and adjustment of parameters.

A descriptive model will provide a subject for examining control strategies. Control will consist essentially of specific alteration of flow rates, and will be, in itself, a subject of research inquiry, both theoretical and practical. Among those topics that must be considered are timing and duration, and the subsequent system responses to specific control operations. It will be necessary, therefore, to develop an initially separate control model, applicable to a descriptive model, but with the fundamental purpose of beginning the identification of control strategies.

Control strategies will be dependent upon sensed data: information that in toto will represent the system state. Sensing strategies will require the development of additional models, with the purpose of attempting to evaluate the meaningfulness of the sensed data. The flow of sensory information must be integrated and interpreted.

Concurrently with the simultaneous development of descriptive, sensing, and control models, methods must be developed for integrating them and for applying them to small, operating, physically closed systems. This permits a comparison between the simulations performed with mathematical models and operations of real systems.

A Modeling and Design Development Strategy. Following the establishment of a (chemical) diet requirement for man, a sequence of development stages may be envisioned. At the first stage, one may postulate a number of agricultural options, each of which meets the human requirements. For example, a set of six options might be established:

- two options based only upon plants;
- one plant and terrestrial animal option;
- one plant and aquatic animal option; and
- two unconventional (e.g., algal based, chemical synthesis) options.

With man outside the metabolic loop, each option would establish two items (Figure 3) which would frame initially the nature of the waste processing response:

1) an agricultural waste stream which, with man out of the metabolic loop, equals total agricultural production (biomass), and
2) a nutrient demand vector which should include the desired chemical composition, tolerance limits, velocity, etc.

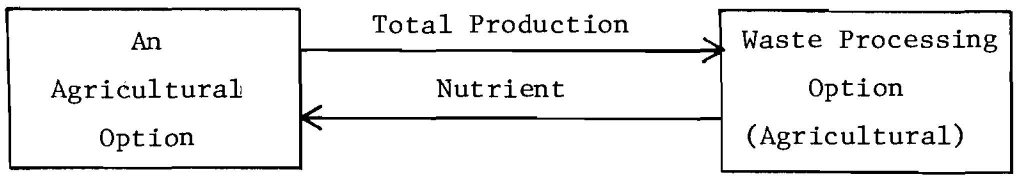


Figure 3. Simple Two Component CELSS Model

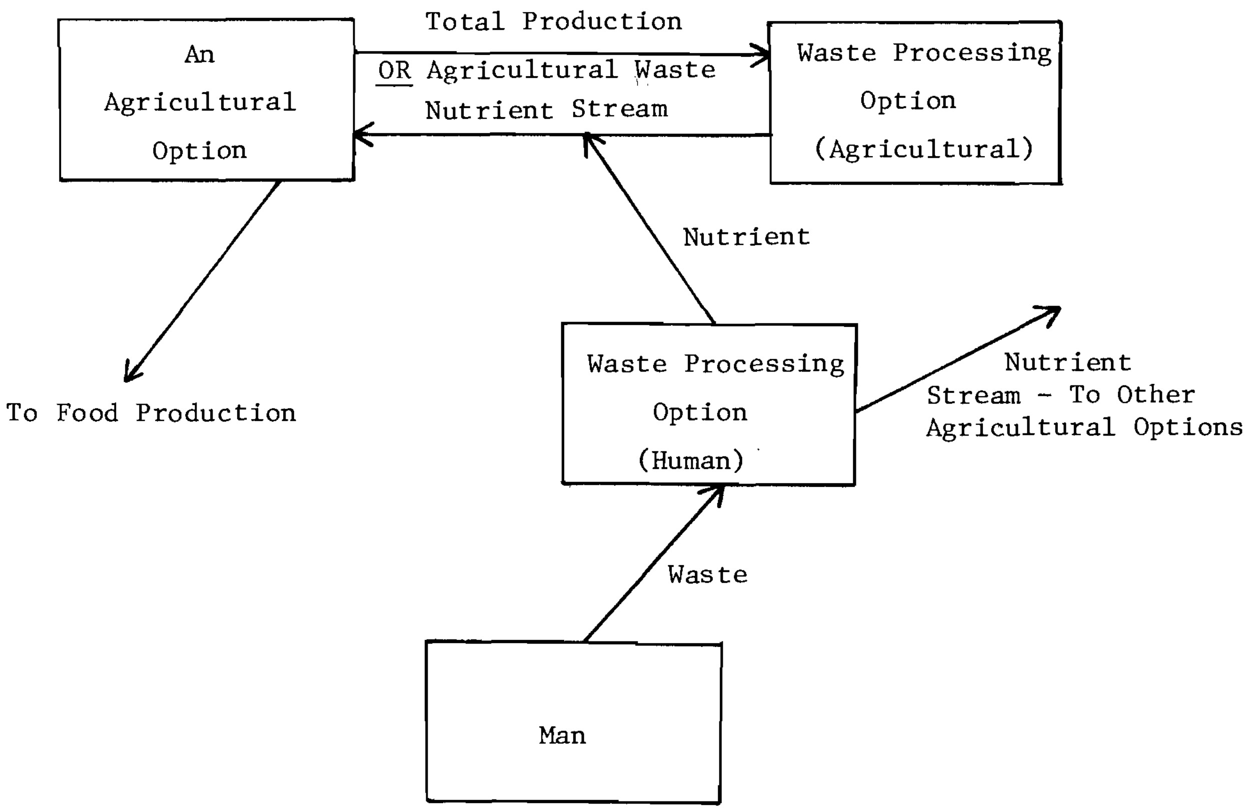


Figure 4. Simple CELSS Model with Hypothetical Human Waste

This initial stage might be viewed as an elementary loop which must be balanced. Even in this simple system, several interesting points could be tested by both simulation and experimentation:

- cycling times;
- buffering requirements;
- production smoothness demands;
- resiliency characteristics;
- unforeseen sinks/toxin accumulations;
- effects of transients;
- interfacing protocols; and
- instrumentation and control requirements.

Because of the desire to have successful off-design operation, it is important to be able to balance the two plant/animal options with the animals removed from the metabolic link.

A second stage now can be addressed. By using (only) the established diet requirements and not any specific agriculture production module, one can formulate a second partial loop describing the human waste stream (Figure 4). Subsequently, one could take an initial step towards understanding the integration of the total system (Figure 5) by varying the fate of human wastes, coupling man into the metabolic loop of different agricultural modules while leaving him decoupled from other agricultural modules. Several additional issues could then be analyzed:

- system balance under a changing rate of agricultural production and human wastes (i.e., putting man in the metabolic loop) with different agricultural modules;
- risk analysis of man acting as a vector for cross-contamination between different agricultural modules;
- time element build-up with man in the loop;
- trade-off (initial) analysis of compartmentalization and isolation protocols; and
- control policy analysis and simulation.

The next stage would be to close the partial loop introduced in the second stage by introducing the food processing options. Specifically, for each agricultural option, establish a food production submodule (Figure 6). Under this form, the complete system integration could be

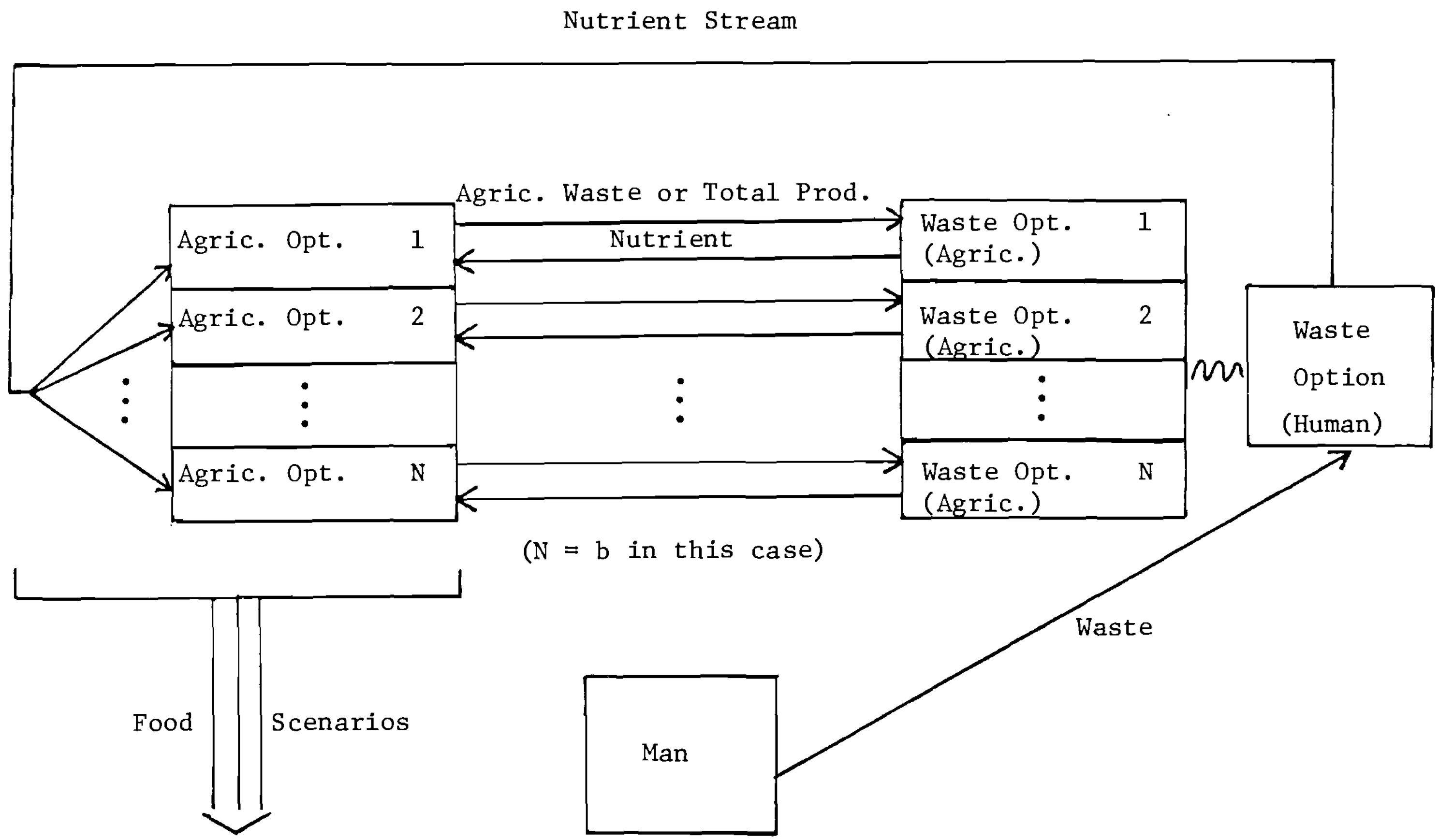
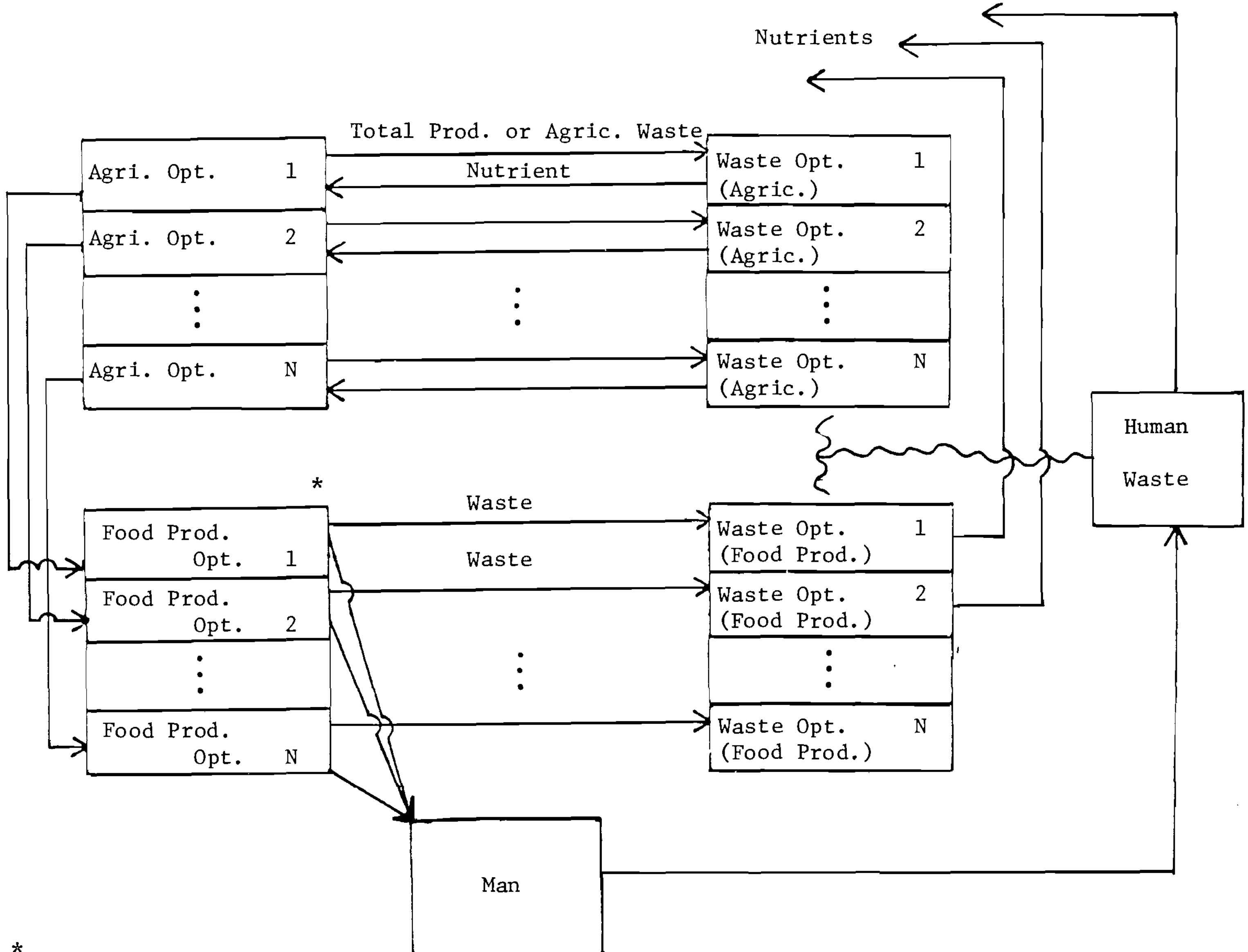


Figure 5. Model for Testing Impact of Coupling Human Waste Stream into Food Production Options



*Includes stores by option

Figure 6. Closed CELSS Model Showing Options

tested and evaluated. Furthermore, the storage policies (including food processing requirements and trace nutrients) could be considered within the system structure. Detailed tradeoff analysis could then be made. System stability, controllability, resilience, and observability could be tested. Also, unforeseen sinks and toxin build-up could be tested.

Note that this approach follows closely the Ecology Group's idea of using different, completely functioning ecosystems. There undoubtedly will be numerous iterations between and within different stages and models.

Ecology-Systems Safety (Group 5)

The role of this group was to identify ecologically desirable approaches to CELSS design. They also identified and assessed the ecological knowledge necessary for CELSS design and development.

Several considerations were suggested regarding the scope and design of a GBCD:

- Coupling of components (biological, physical/chemical, and hybrids) must be followed by a period of equilibration. Consequently, the duration of the GBCD must allow a minimum of two agricultural growth cycles following the equilibration period.
- The GBCD must represent the "worst case" by providing for the largest number of inhabitants within the smallest allowable space in order for the GBCD to demonstrate situations that would never arise in an actual CELSS.
- The GBCD must be controllable so that at the end of a specified period it will return to an identifiable end state.
- Provision must be made for some measure of replicability (e.g., several GBCD) and repeatability (can the GBCD experiment be repeated?).
- To improve the overall reliability of the design, the GBCD should be composed of several units with each unit a full system capable of acting as a complete life support system

for a specified time period. The units should be as different as possible to increase the reliability of the total system. The units should be designed so that they may be either coupled or disconnected.

There are no natural earth-bound ecosystems which are closed in terms of energy, matter, information, etc. A GBCD would provide data supporting the theoretical basis for system closure. It would represent a "best case" level of closure which could be relaxed when tradeoffs were adequately identified. The GBCD would provide:

- a relatively ambitious biological model for in-depth study of fundamental dynamics of ecosystems;
- required preventive measures to obviate loss of human life that might occur in CELSS failure:
- direct and indirect evidence on performance of components of a CELSS;
- a valuable laboratory for study of applied ecological problems such as behavior of toxic chemicals in ecosystems in terms of chemical localization and effects;
- a test of the predictability of mass balance maintenance; and
- a test of how conditions within the CELSS can be stabilized and kept within required limits.

Research will profit from use of simulation modeling (biological and mathematical). However, the state of the art of ecosystem modeling must be improved. Factors such as size and complexity (i.e., the variety of biotic and abiotic components) will affect the behavior of any ecological system. Fundamental ecosystem processes such as nutrient and energy cycling may be observed as indicators of the health of the system. Techniques such as energy analysis as developed by H. T. Odum, et al, will prove useful here.

The output of the International Biological Program (IBP) would provide substantial information on processes occuring in ecosystems and observed from a holistic perspective. The IBP Information Center (Environmental Sciences Division; Oak Ridge National Laboratory; P. O. Box X; Bldg. 1505; Oak Ridge, TN 37830) should be able to provide information and the location of other sources.

The Environmental Sciences Division at ORNL is now doing an eco-toxicology study for the U. S. Environmental Protection Agency (EPA). The intent of the study is to disclose reliable indicators of dysfunction in ecosystem processes which occur above the species level of biological organization. The study will review the literature on model ecosystems (i.e., microcosms). The ORNL contact is Dr. R. Milleman (same address as above) and the EPA contact is Dr. V. Nabholz, Office of Toxic Substances, TS-792, Washington, DC 20460.

The following paragraphs discuss the major information requirements for a successful GBCD.

Microbiological Impacts. Human effects and interactive human/microbial effects must be considered. In addition, microbial effects on the ecology of the GBCD and on the total (biotic and abiotic) GBCD must be considered. Any ground based demonstration should recognize the ubiquitous distribution of microorganisms and how their diverse activities and interactions affect ecosystems. To this end, it is proposed that a strategy be developed to control and to monitor the presence and activities of microorganisms inside the module. This approach need not demand an enumeration of all microorganisms, but rather be prepared to anticipate and identify how their activities might impinge on an ecosystem. It may be desirable and possible to produce, through choice and directed natural selection, particularly useful benign and competitive microbial communities to be included in the GBCD and the CELSS.

Model Development. Model development must be closely coupled with the development of laboratory experiments. Models are necessary for the planning and development (in a technological and engineering sense) of the GBCD. Models may be used for purposes of simulation, prediction, and analysis necessary in GBCD and CELSS development. The modular concept (described below) lends itself well to model development.

Monitoring Strategies. Ecology as both a theoretical and an empirical science provides many, but at this time not all, criteria necessary for an adequate set of monitoring parameters. The GBCD must provide intensive monitoring capability above that to be accomplished in an actual CELSS to provide extensive baseline and background information on the potential states and responses of an actual CELSS.

Monitoring will be continuous or periodic depending on:

- the relative hazard of the substance to the biota (including man) if it departs from some restricted range of concentration or level;
- the relative hazard to the functioning of the GBCD system; and
- the time scale (i.e., residence time of contaminants in various compartments and their response time).

Monitoring strategies should be developed for both expected and unexpected situations (e.g., illness or disease in human inhabitants or their supporting biota). Agents capable of producing irreversible (deleterious) changes should be monitored with sufficient frequency to provide warning of the impending change well in advance of the event.

Any ecosystem or GBCD system will fluctuate within a range which can be described by a set of "fingerprints." Monitoring strategies should provide for the development of "fingerprints" to provide a range of diagnostic, analytical output patterns to identify system changes which are allowable within a range of tolerances previously observed in the GBCD.

Modular GBCD (and CELSS) Concept. A life support system must have the following six functions:

- productivity (e.g., food, atmosphere, etc.);
- element cycling (e.g., N,S,P,C transformations);
- resiliency (i.e., return to original state or desirable states following perturbation);
- toxicant removal;
- buffering capacity (i.e., short-term homeostatic control); and
- persistence.

The requirements of safety and reliability suggest that the most desirable design for CELSS would be to have several modules, each capable of fulfilling complete life support for the people and fulfilling the functions given.

Each module will be made of compartments, each fulfilling a specific role (e.g., food production, waste treatment). These compartments would be capable of being regeneratable, isolatable, and controllable. The fluxes in and out to other compartments would be subject to control. It is most desirable for these separate modules to be as different from each other as possible. That is, the constituents of compartments fulfilling the same function in two different modules would be as different as possible. For example, food production in one might be aquatic based, in another terrestrial. This would minimize the possibility of failure of two modules for the same reason. For example, one module might be more resistant against a sudden temperature increase due to mechanical failure, while another more resistant to build-up of carbon dioxide.

Whether this kind of redundancy is possible depends on restrictions of mass and economics. Whether it is necessary depends on an evaluation of acceptable risk to the people and the reliability of each module (as determined by experiments).

Modules could also be connected and could, when desirable, share compartments for some time periods. The advantages of the multiple module concept are safety, reliability, quality (i.e., food and environment diversity), and the use of alternative technologies. Disadvantages include weight, cost, and complexity.

Criteria for Choice of Species. The ecology group suggested the following criteria for choosing species for a GBCD:

- produce a minimum of waste and toxic materials (per unit of useful production);
- show minimal sensitivity to environmental factors;
- have minimal demands on the overall system;
- be relatively clean, or pathogen-free (i.e., a partial gnotobiont);
- possess simple, straightforward requirements for sexual reproduction (i.e., not have requirements for pollination which are difficult to fulfill), or (probably preferable) reproduce asexually or without the need for pollen transfer by a process extrinsic to the plant;
- be highly inbred (at least in a seed stock line) (undesirable evolution therefore will be most easily controlled);
- be highly prolific; and
- exhibit short time to maturation of whatever the product is desired (e.g., seed, root, leaf, meat).

RESEARCH RECOMMENDATIONS

Introduction

The fourth objective of the workshop was to establish R&D sequences and priorities for CELSS development. In response to the scientific, technical, or developmental issues presented in the previous section of this report, the groups identified needed research on each issue. These recommendations are presented in the following section in outline form for each group according to the issues they discussed.

Nutrition and Food Processing (Group 1)

Storage Stability of Food:

1. Demonstration of freeze-dried food storage stability (2 years)
2. Utilization of space vacuum for food storage
3. Analysis of environmental storage techniques.

Analysis and Development of Feeding Systems:

1. Menu design
2. Food service
3. Frequency of eating
4. Crew station design.

Specification of Specific Nutritional Requirements:

1. Conduct a long-term (6-8 months) dietary experiment, maintaining healthy human subjects on a diet containing nothing more than the nutrients recognized to be essential and a nonspecific energy source and filler. Exclude unknown or unessential chemicals.

Criteria for Assessment of Health Status in Response to Diet:

1. Normal values and ranges
2. Optimum combinations of tests
3. Continuous monitoring systems
4. Problems associated with specialized feeding situations.

Other Factors Influencing Diet Acceptability:

1. Investigation of how a formulated or simple food stuff can be made acceptable on a long-term basis. Consider importance of frequency of eating, textural variation, flavor variation, preparatory conditioning, and organoleptic variation.
2. Determination limits of tolerances for texture and basic flavors (sweet, sour, bitter, salty, etc.).
3. Evaluate effect of nonfood sensory stimulation on the demands of organoleptic properties.
4. Investigate effect of various stages (levels) of mental activity on an individual's acceptance of a food system.
5. Development of monitoring requirements to assess continuing acceptability of a diet.
6. Investigate behavior modification as means of increasing acceptability of a diet.
7. Identify interrelations between factors affecting acceptability.
8. Evaluate psychological needs for diet to be desirable as well as acceptable.
9. Evaluate relationship between diet acceptability/ desirability and task performance.
10. Determine degree of flexibility in diet content required during long-term exposure.
11. Investigate need for preconditioning gut microflora before exposure to CELSS diet.

Identification or Development of Food Technology:

1. Analysis of existing technologies in areas identified in Figure 1 (page 20). This should precede research in areas listed in 2 below.
2. Research and development in following areas to meet mission requirements:
   (a) formula diets derived from nonconventional ingredients: acceptance of diet unknown.

(b) analogs of conventional foods and other engineered foods from a variety of sources: technology is advanced with respect to some conventional sources; long lead time and high probability of use.

(c) formula diets from conventional sources: technology well developed and may only require adaption to mission; can be done after mission is specified; few problems are expected.

(d) conventional foods from conventional sources: technology requires adaptation to mission.

3. Additional factors to be considered for any food technology under investigation:

   (a) evaluation of gravitational sensitivity of any technology considered for flight CELSS.

   (b) determine requirements for supporting chemical production/ recycling to provide necessary oils, solvents, bases, etc., for technology under consideration.

   (c) characterize waste stream from food processing system.

   (d) demonstration of adequate sanitation during storage, processing, and service of foods.

   (e) determination of labor requirements for routine implementation of given technology.

4. Other research areas:

   (a) requirement for provision of emergency food storage capability.

   (b) alternative ways of utilizing "crops" if food processing system fails.

<u>Food Production (Group 2)</u>

<u>Higher Plants/Agriculture</u>:

1. Projects of absolute and immediate necessity. (Must begin in Year 1).

   (a) develop criteria for the selection of plant species and cultivars for use in the GBCD.

(b) perform studies in order to maximize the primary productivity of autotrophic plants in terms of food and oxygen generating capacity. This would include:

- determination of the conditions and plant characteristics that provide the highest oxygen and primary productivity per unit area and unit time. Factors as cultural procedures, habitat characteristics and nutritional requirements for the plants should be studied and optimized. The environmental factors should be determined for maximum yield efficiency in terms of human food vs. total dry matter produced. These studies should be undertaken with separate candidate species that maximize photosynthetic tissue production; maximize metabolite storage in seeds; and maximize metabolite storage in root or stem organs. For predictive value there should be the construction of dynamic population growth models as an integrator of all other information. The studies should include a characterization of the food value of various candidate species grown under the environmental conditions projected for the life support system. Another part of the program would be an investigation of methods of propagation of candidate plants to insure maximum efficiency and stability in a CELSS.
- a program of selection and development (breeding) of cultivars of candidate plants possessing high productivity as well as a high proportion of edible portions and high nutritive value should be initiated.

(c) evaluate the potential of plants to utilize human and plant wastes as nutrient sources.

(d) initiate a program to determine stress factors and the effects of these stresses on the plants. This would include a determination of the reasonable environmental extremes that most candidate species could tolerate and still produce acceptable levels of oxygen and primary productivity. It should also include determination of the compatibility of a common nutrient solution for multiple species of plants. Included will also be an identification and quantification of the effect of stress factors on secondary plant products such as organic and inorganic effluents from plants (and algae) and the possible role of such effluents as stress factors (toxins) themselves. There should also be a study to determine compatibility of multiple species in one enclosed compartment.

2. Subsidiary projects (should begin by Year 4 or 5).
   (a) study the effects of additives such as exogenous growth regulators on productivity.
   (b) evaluate the long-term effects on plants with growth in a recirculating completely controlled unit, supplied with balanced nutrients and required atmosphere. Follow with studies incorporating recirculating waste utilization and then with studies incorporating animal(s) in the system to simulate a human.
   (c) determine the capability of plants removing toxic contaminants from the CELSS atmosphere as H_2S, NH_3, NO_x, SO_2, etc.
3. Projects and goals which could be initiated after several years (should begin by Year 6-10).
   (a) study the role of hypogravity on the productivity of food plants.
   (b) as time goes on, there should be integration and coordination with the other components of the food production unit, such as microorganism production and animal production.
4. Additional recommendations:
   The development of this basic program can start out as projects in individual laboratories with coordination in plant growing and chemical analysis procedures to be utilized, plant data to report, and statistical analysis procedures to follow. As more integration is required, the work might begin to be concentrated more and more in a central(s) laboratory to provide necessary complex facilities and integration between scientists in different disciplines. As the program proceeds, there should be increasing coordination with flight tests of critical components of the food producing unit.

Microbial and Chemical Food Production:

1. Short-term (begin in FY 79).

   (a) photochemical synthesis:

   - photocatalytic dissociation of water to H_2 and O_2 and CO_2 to CO and O_2.
   - photoelectrochemical approaches to the above processes.
   - demonstration of concept, yield, sustained reaction, high catalyst turnover rate, and low decay rate.
   - achieve high yields (20-25%) and stability of catalysts or photoelectrodes.

   (b) microbial systems:

   - analysis of algae and single cell protein reactors currently under operation, reactor setup and extended continuous reactor operation in a flow mode, with continuous nutrient injection and material extraction.
   - design of prototype reactors and study of transient response to changes in O_2, CO_2, etc., shocks, and perturbation in experiments running for periods of up to one year.
   - setup of small reactor to demonstrate the concept of production of special nutrients using genetically engineered organisms.
   - nitrogen loop experiments by analyzing microbial nitrogen fixation and denitrification processes.
   - concept demonstration studies in extraction and separation (physical and chemical) technologies and demonstration of state of the art in these areas. Review relevant technology in concentration of single cell proteins for further processing and possibility of preliminary chemical and physical separation of nucleic acid, cellulose, etc.

2. Long-range (not listed by priority).

   (a) chemistry:

   - enhance O_2 production via photocatalysis. Increase the efficiency of O_2 production, CO production, and MeOH production by homogeneous photochemical and photoelectrochemical processes.

- production of key food nutrients by chemical processes (glycerol or even ethanol).

(b) biology:

- strain selection and engineering for microbial production of more palatable, easily processed and handled food products. These microbial species would be selected for greater digestability and nutrition.
- general selection of new microorganisms or procedures for new applications to do new job or possible new jobs. Such a field is tissue culture.
- long-range applications of monitoring technology to detect acids of N and develop chemical and biological scrubbers.
- measure and model material and energy balance in these systems. What are the outputs?
- long-range studies on the application of extractive, separative,and procession technology.
- the use of various feedstocks for the various processes, i.e., what can be done with CO_2, cellulose, nucleic acids that can all be used as feedstocks.

Terrestrial Animal/Aquaculture Animal Production:

1. Are alternatives to animals satisfactory? E.g., if all plant materials can be processed as human foods and/or reconverted to plant nutrients by waste processing, and if vegetarian diets with stored trace nutrients are satisfactory, there is minimal justification for animal production.
2. Are the benefits of animal production greater than the advantages of alternate techniques?
3. Consideration of direct use of waste products by edible detrital feeders (kill pathogens in food processing/cooking). Paper study should include feeding studies--heavy metals (or other toxicants) that are not digested or assimilated may not be problems.

4. Input/output of animals will depend on particular feed components which may be different in CELSS application than in conventional. Recommend start with conventional diets and fine tune with special diets as they may be developed.
5. Input/output (especially gaseous) studies should include aquatic microorganism species. N_2S, CO, N_2O, N_2, NO_x, etc., should be included.
6. Modeling studies on causal interactions in animal digestive/metabolic functions are underway and should be applied to CELSS.
7. Intensive production systems appropriate for CELSS may include subsystem components operating at submaximal efficiency for reasons of stability or optimization of total system efficiency.

Waste Processing (Group 3)

Need Early Demonstrations:

1. Regeneration of plant nutrients from plant wastes (spent nutrient liquor and inedible portions of plants). Objectives:
   (a) to close the material balance with respect to inorganics in a phytotron.
   (b) to test first generation waste treatment methods of recycling inorganic nutrients from plant wastes (e.g., to determine the form, concentration, and distribution of elements in oxidizer off-gas and residue).
   (c) to define complete analytical schemes necessary to accomplish (a) and (b).
   (d) to determine the extent to which unanticipated elements enter the loop (e.g., from corrosion) and to determine their effects on plant growth.
   (e) to determine the rate of uptake of nutrients by plants during different phases of growth and thereby define the methods of replenishing nutrients to the feed solution.
   (f) to determine the distribution of nutrients between edible and inedible portions of the harvest.
   (g) to determine the extent to which fixed nitrogen is lost by conversion to N_2 in oxidation.

2. Separation and recovery of plant nutrients, table salt, and trace elements from urine. Objectives:
   (a) to design, build and test a system for concentrating urine (e.g., by evaporation) to a slurry or solid that is oxidized, to purify the water vapor and recover inorganics from the urine concentrator, and to recover and separate plant nutrients, table salt, and trace elements from the oxidizer products.
   (b) to close the material balance with respect to C, H, O and inorganics.
   (c) to define complete analytical schemes necessary to accomplish (a) and (b).
   (d) to determine the extent to which unanticipated elements enter the loop.
   (e) to determine the acceptability of the plant nutrients for growing plants and table salt for human/animal consumption.
   (f) to determine the variability of composition of urine from day-to-day with a given population and/or from one population to another.
   (g) to determine the extent to which fixed nitrogen is lost by conversion to N_2 in oxidation.
3. Separation and recovery of plant nutrients and trace elements from feces. Objectives:
   (a) to design, build and test a system for collecting and oxidizing feces and sanitary wipes and to recover and separate plant nutrients and trace elements.
   (b) to close the material balance with respect to C, H, O and inorganics.
   (c) to determine the extent to which fixed nitrogen is lost by conversion to N_2 in oxidation.
   (d) to define complete analytical schemes necessary to accomplish (a), (b), and (c).
   (e) to determine the extent to which unanticipated elements enter the loop.

(f) to determine the acceptability of the plant nutrients for growing plants.

(g) to determine the variability of composition of feces from day-to-day with a given population and/or from one population to another.

4. Recycle of wash water. Objectives:

   (a) to design, build, and test a complete system for recovering and reusing 95-99% of the water used for washing clothes and bathing for a population of 20 people and to produce a concentrate of contaminants in the wash water.

   (b) to obtain a reliable data base on the concentrations of contaminants in wash water.

   (c) to close the material balances with respect to H_2O, organics and inorganics.

   (d) to determine optimal cleansing agents/detergents that are compatible with the wash water recycle system.

   (e) to define analytical schemes necessary to accomplish (a), (b), and (c).

   (f) to determine the extent to which unanticipated elements enter the loop.

5. Purification and control of phytotron atmospheres. Objectives:

   (a) to design, build, and test a system to remove atmospheric contaminants, control humidity, and remove oxygen from phytotron atmospheres.

   (b) to close the material balance with respect to CO_2, O_2, and H_2O.

   (c) to define complete analytical and control schemes necessary to accomplish (a) and (b).

   (d) to determine the extent to which unanticipated elements enter the loop.

   (e) to determine the extent to which plant nutrients are released into the atmosphere.

6. Purification and control of atmospheres for humans and animals. Objectives:
   (a) to design, build and test a system to remove atmospheric contaminants (including bacteria and viruses), control humidity and remove CO_2 from human and animal habitats.
   (b) to close the material balance with respect to O_2, CO_2, and H_2O.
   (c) to define complete analytical and control schemes necessary to accomplish (a) and (b).
   (d) to determine the extent to which unanticipated elements enter the loop.
   (e) to determine the extent to which organics, inorganics, bacteria, and viruses are released into the atmosphere.

Alternative Subsystem Technologies. Definition studies should be undertaken by NASA for each of the alternative subsystem technologies that have been identified to date. Each of these definition studies would have the following objectives:

1. To review prior work (terrestrial and space applications) on the subsystem technology.
2. To develop a process design that clearly shows how the subsystem technology can be adapted into a complete CELSS waste processing system and, in so doing, identify the auxiliary processing requirements with appropriate interfaces.
3. To identify the major issues and unknowns that bear on whether the subsystem technology can meet the specific requirements of the CELSS concept.
4. To define an experimental program plan that would address the major issues and unknowns so identified in 3.
5. To prepare a preliminary process design evaluation with estimates of resources required (i.e., weight, power, volume, etc.) for two levels of mission duration and size of habitat population.

From a review of the results of these studies, NASA should be in a position to determine which alternative subsystem technologies are conceptually sound within the CELSS context and which show the most promise with respect to the optimum disposition of resources. In this manner, NASA could develop a prioritization for subsequent R&D. The objectives of such subsequent R&D should be evident from the results of the definition studies with regard to objective (4) above. These definition studies could be completed in a 12-18 month time frame.

Oxidation of Organics by Incineration:

1. Review of existing literature on reactors and catalysts.
2. Characterization of input wastes including water content, elemental breakdown, handling techniques, sustaining combustion, oxygen mixing, etc.
3. Need for a gas phase catalytic oxidizer.
4. Detailed characterization of output streams.
5. Establishment of laboratory analytical techniques and instrumentation, including leaching, solvent extraction, scrubbing, wet chemistry, atomic absorption spectroscopy, gas/liquid chromotography, gas chromotography-mass spectroscopy, X-ray diffraction, etc. These techniques would be employed not only to achieve an elemental breakdown, but also to establish the various elemental states and compounds, both organic and inorganic.
6. Establishment of a complete mass and energy balance.
7. Steady state, off design and transient performance.
8. Identification of control parameters and instrumentation requirements.
9. Monitoring requirements and instrumentation.

Wet Oxidation of Organics:

1. Study the parameters and products of the wet oxidation process (time, temperature, pO_2, mass balance, effluent gas and liquid composition, fixed catalyst composition, etc.).
2. Study material composition and corrosion parameters of equipment.
3. Evaluate subsystems for removal of undesirable effluent gases and regeneration of subsystem.

4. Evaluate requirement for complete removal of residual organic compounds from processed solutions (further treatment may not be necessary if they are biodegradable and not toxic in subsequent use, i.e., acetate).
5. Study parameters of precipitate and NH_3 removal and NaCl-KCl purification from oxidized urine.
6. Evaluate toxicity of NaCl-KCl mixture derived (from real urine) with animals.
7. Evaluate plant nutrient solutions for plant productivity.
8. Study equilibria of plant nutrient solutions with 10^{-2} to $10^{-9.5}$ bars pCO_2 for possible changes.
9. Evaluate trace element accumulation in plant nutrient mixture and design methods for removal if necessary.

These suggested analyses are not ordered in priorities or sequence partly because the funding level is unknown and some analyses are obviously far more expensive than others. The completion of all analyses should permit a preliminary engineering model design for further evaluation.

Biological Oxidation of Organics:

1. Determine if the microbial treatment process will be stable under anticipated transient stresses. The base case can be perturbed by shock loadings of flow volume, overall solids-loading, and by step changes in the concentrations of key elements. The changes in effluent quality and the character of the microbial population can be determined and potentially, a useful mathematical model developed. What are the effects of pH control failure or temperature fluctuations? Do the source or quantity of dilution water affect stability and performance?
2. How are soluble refractory organic compounds handled (i.e., COD)? Some soluble COD will be "purged" from the stream by precipitation from the liquid with the solid residue stored. It is unclear that such a "purge" would reduce soluble COD to acceptable levels. The nature and source of such compounds would need to be determined. Must the whole culture at times be dried?

3. Does selective adsorption by the biological process create material balance problems?
4. How can a three-phase system be aerated in a zero-gravity environment? Mixing may be more efficient and "energy cheaper." Should pure O_2 or air be used? (Probably O_2 if readily available.)
5. What transformations take place in the equilization tank?
6. What type of reactor scheme is best? (Hardware)
7. Should the waste treatment scheme provide for nitrogen-fixation when animals are present?
8. Are schemes for refeeding animals converted animal wastes feasible in a CELSS?

Integrated Algal Bacterial Systems. Clarify the following:

1. Some strains of algae are better candidates as a food source than others.
2. If animals are in the system, algae becomes more attractive as an animal food source.
3. It may be used to generate a stored product of waste treatment when some foods are supplied from storage.

Higher Plants Grown on Urine:

1. Plant screening for selective mineral removal.
2. Proof of acceptability of edible portions for human consumption of those plants grown directly on human waste--processing requirements.
3. Reliability.
4. Trace contaminant removal and/or buildup.
5. Microbial monitoring.
6. Mass balance (solid and gaseous).
7. Degree of salt removal.
8. Physico-chemical means.
9. On-line monitoring requirements.
10. Viruses.
11. System's tolerance to perturbations.

12. Will nitrogen fixing be needed to reclaim lost nitrogen?
Tradeoff study between the use of physico-chemical means and the use of nitrogen fixing organisms to reclaim lost gaseous nitrogen. Reliability, etc.

Wash Water Recycle:

1. Reverse osmosis:
   (a) extensive testing must be performed to characterize and improve, as required, the following:
      - component life;
      - reliability;
      - chemical additive requirements;
      - mass production techniques for module formulation;
      - long-term trace buildup; and
      - scaling factors for larger systems.
   (b) Parallel development of alternate membranes should be pursued.
2. Multifiltration/Floculation-Precipitation:
   (a) the following should be investigated:
      - development of high temperature ion exchange resins;
      - identification and quantification of applicable floculants; and
      - feasibility of resin regeneration.
   (b) an optimum system configuration should then be determined and all expendibles and any trace buildups should be quantified by long-term testing.
3. General:
   (a) cleansing agents to be used should be identified.
   (b) when the rest of the waste treatment scheme is better defined, a tradeoff should be done on the penalty for occasional system blow-down vs. that for processing to a higher degree of purity.
   (c) Large-scale tests of operating systems should be made with continuous recycle of representative wash water. Particular attention should be given to the degree of water recovery, the ultimate disposition of contaminants removed, and chemical additive requirements.

Atmospheric Decontamination. Review NASA's previous work on atmosphere decontamination, current literature, and recent developments in the associated technologies, and define subsystems which are compatible with a complete CELSS waste processing system.

Carbon Dioxide and Oxygen Extraction. Review the literature and previous NASA studies on removal of CO_2 and O_2 from atmospheres and develop conceptual designs of subsystems that will meet anticipated CELSS requirements.

Recovery of Plant Nutrients and Trace Metals:

1. Define the separations to be accomplished in terms of the following findings:
   (a) determine the composition of the feed liquor. Desirably, this would come from the "plant" group, but if necessary, the probable composition would be estimated.
   (b) establish the composition of the product solutions (or the dry salts to be prepared) for supply to the hydroponic growing solutions. Note any salts. Partial removal would presumably be necessary to avoid reaching toxic levels.
2. Develop "paper" schemes (processes) for each of the proposed separation. This would involve working with equilibrium solubility diagrams at various temperatures developed for each system. If one or more of the micronutrients is to be in part removed, then precipitation based on chemical means may be desirable.
3. Conduct laboratory tests to confirm the accuracy of the key predictions on which the above separational schemes are based. Follow by procedure modification, if needed. These laboratory tests can be on a test tube scale.
4. Conduct a pilot operation for each scheme, answering the following questions:
   (a) is the precipitate filterable?
   (b) does it form promptly?
   (c) does it cling to the vessel walls and so introduce other handling problems?

(d) are there foaming problems?

(e) are compositions as expected?

Since the quantities for a 1-to-3 man mission are not great, much of this work might be done on a "dishpan scale."

Systems Engineering-Modeling (Group 4)

Principal Roles and Objectives of Systems Analysis Effort:

1. Program integration:

   Development of a management information/management decision support system for planning, evaluating, and improving CELSS R&D program planning. Includes: a mechanism to estimate relative cost of achieving particular levels of knowledge; communication system to provide research progress and results in acceptable format to program managers (and similar information to other researchers); a mechanism to assure that impact of research results on other project/program phases are understood, evaluated, and utilized properly.

2. CELSS design, operation, and control:
   (a) methodology required for levels of simulation (modeling capacity);
   (b) providing resources for proposals:
   - currently available,
   - easily modified,
   - R&D required; and

   (c) subdivision of tasks or subtasks (depending on integrating capabilities).

General Modeling Approaches:

1. Establishment of investigatory working groups to identify quantity and quality of input data:
   (a) control theory--develop a consistent theory of control for nonlinear operating systems;
   (b) sensing theory--develop theory of analysis and weighting of sensory data with protocols for continuous updating sensitivity analysis;

(c) control/sensing integration--develop research chambers capable of accepting control and sensing functions;

(d) sensory analysis in mass spectrometry, gas chromatography, specific ion electrodes, flame ionization analysis, etc.; and

(e) modeling languages.

2. Decisions must be made on:

(a) input data format;

(b) methods of evaluating data bases;

(c) physical location of data bases;

(d) computer operating systems to be used;

(e) possibility of centrally located computer system facilities and distributive network--initiate purchase; and

(f) addressing analog to digital conversion modes.

3. Start general, refined descriptive model and consider loci of specific submodels.

Except for the first 12-18 months, schedules are not presently possible. It is recommended that within six months a panel of advisors be formed to address the problem of commonality of languages, operating systems, and modeling languages.

Ecology-Systems Safety (Group 5)

Justification for a GBCD as a Prerequisite to the Development of an Actual CELSS:

1. Determination of mass balance equations with respect to number of inhabitants and following characteristics: productivity, element cycling, removal of toxicants, buffering capacity, and return to initial state following perturbation.

2. Use of physical/chemical systems to increase control and reliability of systems: use biological systems for functions which cannot be done efficiently otherwise.

3. Study of toxicity effects and where toxicants will localize in CELSS.

4. Development of species data bank with respect to: effects of the environmental stresses, productivity, and potential food

sources (including exotic, tropical, and major agricultural species).

5. Further development of closed model ecosystems to build theory of closure; improve knowledge of role of connectance between biotic components.
6. Development of mass balance calculations and mathematical models for simulation, subsequent prediction, and analysis.
7. Evaluation of monitoring techniques.
8. Experiment with closed ecosystems (closed to materials) and partially closed ecosystems in laboratory and field (natural) situations:
   (a) to aid studies of closure failure rates and causes;
   (b) to study time course of failures;
   (c) to study stability characteristics, internal connectance and structure:
   (d) to study modes of system re-establishment following failure;
   (e) to define control strategies required to prevent failure:
   (f) to study relation of system size and complexity to failure rates.

APPENDIX A

INDIVIDUAL RESEARCH RECOMMENDATIONS (GROUP 2)

QUANTITATIVE ANALYSIS OF BIOMASS PRODUCTION AND COMPATIBILITY STUDIES OF EARLY MATURING SOYBEAN CULTIVARS FOR GBCD

Jagmohan Joshi, U. of Maryland

Justification

Soybean is one of the recommended plants to be grown in GBCD. This has been clearly shown by various investigators in the earlier studies conducted for NASA. In CELSS, it is very important to know the total amount of biomass produced by each crop. Since "cells" requires complete recycling of all resources, this information is very important both for chemical engineers and waste treatment engineers.

Procedure

Six early maturing soybean cultivars will be selected for this study and an effort will be made to quantify the total biomass into two components (i.e., edible and nonedible). Plants will be grown in controlled environmental growth chambers under hydroponic conditions. This will enable the accurate inventory of all plant parts.

Nutrimal analysis of different plant parts will be done including edible parts (seeds) and nonedible parts (leaves, stems, branches, and roots). Seed yield efficiency analysis (seed weight/nonseed weight) will also be done to characterize efficient cultivars. Nutrimal and seed yield efficiency analyses will also be done on plants grown in the open field conditions. This information will shed some light as to whether or not the controlled environments have any effect on the nutrimal quality of the crop and whether these CEA have any influence on the ratio of seed dry matter weight to nonseed dry matter weight and I believe that such information will be very useful for GBCD.

Compatibility studies with other food plant species will also be done. Soybeans will be grown with lima beans, Mung beans, white potatoes and sweet potatoes. The effect of association between these crops and soybeans will be studied. The major consideration here is the production of total biomass. This information will be useful for GBCD because it will shed some light whether or not we can grow these plants in the same compartment.

The approximate cost will be \$50,000/year. The duration of the project will be one year.

CHARACTERIZATION OF CHEMICAL/PROXIMATE COMPOSITION AND VALUE OF CROP RESIDUES AND BYPRODUCTS AS POTENTIAL SOURCES OF LIVESTOCK FEED

Anthony Bywater, UC

Background and Relevance

Data exists on proximate composition and indexes of feed value (e.g., *in vitro* digestion coefficients) for a number of crop residues and byproducts produced in conventional agriculture. However, this data is scattered and highly fragmented and it is anticipated that there will prove to be numerous data gaps both with respect to individual products and in terms of the range of products analyzed to date. If residues and byproducts are to be utilized efficiently in animal production, there is a clear need for collation and vigorous analyses of available data, identification of data gaps and experimentation to fill these gaps. Residues and (particularly) byproducts normally contain essential nutrients either in forms which are of limited availability or which show marked imbalances in comparison to animal requirements. Quantification of nutrient contents and availabilities is thus essential to formulation of rations containing balanced quantities of available nutrients sufficient to promote desired levels of animals performance whatever those may be.

These data are required wherever residues and byproducts are to be used in animal feeds - whether in a CELSS or in conventional agricultural production. It seems likely that if animals are to be included in a CELSS, their primary function will be conversion of nonhuman edible products from higher plant and microorganism elements of this system to high quality food of high acceptability to humans. This implies that a high proportion, if not all, of the animal rations will be composed of such products accentuating problems of nutrient imbalance and availability. Information requirements described are clearly fundamental to successful inclusion of animals in a CELSS as it is not possible with present data to quantify input/output coefficients with such high residue/byproduct feeding regimes.

Collection of these data would yield tremendous immediate benefits within conventional commercial livestock production. Current concern with the high levels of grain and other human edible crop products fed to animals has increased interest (and pressure) to investigate efficient utilization of residues and byproducts in animal production. These materials represent a greater volume than the human edible crop products produced by conventional agriculture and clearly are a vast resource of potentially utilizable energy and protein. Successfully converted to animals products, they would provide millions of dollars of agricultural revenue.

Approach

Research should proceed in three stages:

1) Collation and analysis of existing data;

2) Collection of missing data identified in 1); and

3) Formulation and testing (feed trials) of sample rations.

Available data on residue and byproduct composition and value exist either as "secondary" data published in the literature or in personal data files of individual workers (many of whom can be identified fairly readily). Collation of data therefore involves literature search and personal correspondence with selected individuals.

Collation of data simply in tabulated form seems unlikely to yield maximum benefit particularly in view of inherent variability associated with these feeds. We have available a number of causal and predictive computer models and data analyzing techniques concerning characterization of feed nutritive value, digestive functions, and digestion end product patterns, absorption and metabolism by ruminant and nonruminant livestock. These techniques allow rigorous identification of critical parameters in utilization of alternative feedstuffs and have been designed and will be used for research such as described.

Depending on the scope of available data, it is anticipated that stage 1 described above will require at least one year of effort. Time frames for stages 2 and 3 clearly depend on the extent of data deficiencies identified in stage 1.

Funding

Funds required are:

1 professional (post doctoral fellow) + 1 technician (including departmental overhead and salary)	$40,000
Computer costs, postage and miscellaneous	10,000
University overhead (currently set at 30%)	15,000
	$65,000

(Alternative Research Topic - A. Bywater)

QUANTIFICATION OF SPACE REQUIREMENTS AND IDENTIFICATION OF ENVIRONMENTAL STRESS AND BEHAVIORAL PROBLEMS DUE TO SPACE LIMITATION AND CROWDING OF LIVESTOCK

Relevance

It is known that space limitations and crowding of livestock lead to problems associated with immuno-competence and disease and ovulation problems and reproductive failure. Causes of these problems are unclear and it seems highly probable that there are additional problems yet to be identified in this context particularly where unconventional diets may be fed. If the possibility of inclusion of animals in CELSS exists, this clearly represents a crucial information requirement as basis for a go/no go decision. It is my understanding that some data relevant to this area are available particularly with respect to pigs and poultry but the data is sparse. Collection of existing data and identification of critical experiments in this area are of high priority. Benefits in the medium term to planning of CELSS developments are clear; benefits in the short-term particularly in the form of spinoffs to commercial agriculture exist but are perhaps not as substantial as those to be gained by evaluation of byproduct and residues as potential feed resources.

Approach and Funding

As this topic is outside my area of specialization, it is difficult to provide precise descriptions of procedure or budget estimates. However, a paper search clearly represents an approximate starting point and based on the fact that available data are more limited than with the previous proposal (feed evaluation) a very rough estimate of cost is suggested as $40,000, derived in a similar way to that for the previous proposal. Further experimentation and costs clearly depend on findings of the paper search; rough estimates of costs are (minimum) $50,000 set up (special facilities, animals, instrumentation and equipment) plus $50,000 annual operating cost (feed, personnel, overhead).

RESEARCH RECOMMENDATIONS

Olle Bjorkman, Carnegie Institute

In my view the top research imperative is to find the means to maximize the primary products or byproducts of the autotrophic part (plants, algae) in terms of food and O_2 generating capacity under the limitations of light and other environmental constraints expected in a real closed space habitat. In order to achieve this goal, we need to conduct the following studies which are largely experimental:

1. Investigate growing conditions (light, temperature, CO_2, O_2, water and nutrient relations, etc.) and plant characteristics that would provide the highest possible productivity.
2. Select and breed plants which combine these possible edible portion and nutritional value.

It should be emphasized that many of these selection criteria may be very different from those applied in conventional terrestrial agriculture. The most important stress factors in natural environments can probably be eliminated in the closed space environment but new stresses and limitations may be imposed instead. Therefore:

3. Identify these possible limiting factors and investigate how their impact may be minimized both by modification of the environment or by altering the ability of the plants to cope with them.
4. In the characterization of what constitutes ideal plants for the present purpose, it is important to investigate the advantages and disadvantages of plant growth mode and life cycle (continuous - indeterminate _vs_. short-lived - determinate growth, perennial _vs_. annual) as well as of modes of propagation (sexual - vegetative, etc.). The mode of growth of the plant should be considered in relation to the cycle time and the buffering capacity (e.g., O_2 and organic C) of the total system.

Points 1 and 2 above have highest priority and research can be started immediately. It would probably have to continue until well beyond the achievement of the first real space habitat. The recommended funding level for the next 10-year period for the above research is estimated to be $1 million to $5 million per annum. During the first few years most of this research may be funded through a competitive grant program but it seems desirable that a more coordinated and institutionalized research program be set up as the development of the CELSS progresses and the problems become more specialized.

ALGAL STUDIES RELATED TO CELSS

Richard Radner, Martin Marietta

The continuous culture of large quantities of algae has been confined largely to Chlorella (mainly for historical reasons). These cultures have been maintained for months under constant input conditions; the transient response to variations in (O_2), (CO_2), light, etc., have not been evaluated.

The use of Chlorella aboard a CELSS as a food production/gas regeneration system has some drawbacks (e.g., the rather substantial cell wall makes this algae difficult to process, the production of N_2O during the process of NO_3 reduction, etc.)

The question of which alga or suite of alga species (varieties, strains, etc.), must be reexamined. These studies should address issues such as:

1. Growth and production characteristics;
2. Production of culture byproducts (e.g., N_2O, trace organics, glycallate). The production of significant quantities of N_2O should be addressed early in the research project because of its impact on air quality and closure of the nitrogen cycle;
3. Possible use of N_2-fixing blue-green algae, which could serve to close the nitrogen cycle as well as a food production/ gas regeneration system;
4. Nutritional and food processing characteristics (toxins, cell wall).

Continuous cultures of these algae (as well as the more traditional Chlorella) should be evaluated with respect to anticipated CELSS conditions (e.g., stability, and responses to transient perturbations in (O_2), (CO_2), light, temperature, etc.) The startup/shutdown characteristics of the culture should also be evaluated; this system would be ideal to make rapid adjustments in gas composition.

These studies would be relevant to several aspects of CELSS such as:

1. Food production from algal sources from the viewpoint of both nutrition and food processing;
2. The use of algal culture to control (O_2) and (CO_2);
3. Evolution of contaminants by algal cultures;
4. Closure of the nitrogen cycle.

This project could be open-ended and flexible. Significant progress could be expected in certain aspects of the topic at a cost of $50K-$100K/year.

STUDY OF ALGAL CULTURES ALONE AND AS COMPONENTS OF MORE COMPLEX AQUATIC COMMUNITIES IN A CELSS

Frieda B. Taub, Univ. of Washington

Purpose

1. Comparison of single *vs*. mixed algal cultures for persistence and stability of output over constant *vs*. nonconstant environmental condition.
2. Closure of aquatic communities (algae plus other trophic levels) to determine the characteristics necessary for a community to survive under material closure (light supplied; heat removed).

Methods

1. Test continuous and batch cultures of single and mixed species of algae to determine:
   a) if competitive exclusion will result in a single dominant (see studies by S. Kilham and D. Tilman);
   b) if the environmental conditions (temperature, light, nutrient concentrations and ratios) determine the dominant species of algae;
   c) if initial algal concentrations determine the dominance species of algae;
   d) if CO_2 input/O_2 output is more constant over a wide range of environmental conditions in mixed cultures than in a single culture.
2. Material closure is theoretically possible in aquatic communities in which the algal biomass is consumed by animals and microbes which provide recycling. Our laboratory has experience in synthesizing aquatic communities which exhibit many ecological properties and processes and which have survived in a sealed fashion for the brief periods for which they were tested (approximately one week - the systems were still healthy,

but the systems were still open for gas monitoring). These systems can be used as prototypes to research such questions as:

a) persistence and survival of aerobic systems as a function of size, nutrient budget, and storage capacity for O_2 (in gas phase vs. liquid phase) and C as CO_2^- bicarbonate-carbonate or as organic material;

b) scale necessary to support fish.

Equipment

Monitoring of O_2 and CO_2. We have experience with lab-sized fermenters (New Brunswick Brand), but would need additional and larger units. Also, infrared CO_2 may be more appropriate (the New Brunswick records pH and the assumptions generally made to convert pH to CO_2 changes are not valid if other reactions which change pH are also going on.)

Applications to Earth

A better understanding of water pollution problems may result since the algal species usually considered for space applications are closely related to species which are dominant in pollution situations.

Budget (Approximate) Year 1 of 3

Salaries:	
Principal Investigator - 1 month	$ 3,000
Research Technologist or Post Doctoral - 1 full time	15,000
Graduate Students - 2 half time	15,000
Hourly (undergraduate)	2,000
Electronic Technician (part time)	4,000
	$39,000
Equipment: O_2/CO_2(pH) monitoring	22,000
Supplies and Services: Glassware, Chemicals, Electrodes, Computer Services, Computer Use, Office & Secretarial Services	10,000
Travel: to Ames, to Scientific Meeting (PI + Student)	1,500
Benefits: 15% of S&W	5,850
Indirect Costs: 55% of S&W	21,450
	$99,800

Years 2 and 3: Inflation increases in salaries, decreases in equipment.

SPECIFIC TOPICS

R. C. Valentine, UC

I. Role of Nitrogen Fixing Crops in GBCD

A. Efficient combinations of host legume/symbiont
B. Storage and preparation of inoculum
C. Green leaf character in soybeans
D. Genetic engineering of N_2 fixation (H_2 uptake plasmid)
E. Azolla-dnabaena azollae as a rapidly growing plant for GBCD: analysis of world collection for productivity

II. Genetic Engineering of Single Cell Reactors for GBCD

A. Construction of highly amplifiable plasmids for biosynthesis of elevated levels of key nutrients (vitamins, amino acids, macronutrients)
B. Genetic engineering of autotrophic (H_2+CO_2) bacteria for synthesis of micronutrients and efficient CO_2 fixation

III. New Horizons and Genetic Engineering of Biological Denitrification and Closure of the N-Loop for GBCD

A. Source of N_2O and NO_x from biological systems: a new organism for answering the "intermediate" question
B. Potential for biological N_2O scrubbers from genetically engineered organisms

IV. Genetic Engineering of Stress Tolerant Plasmids for Microorganisms

A. Salt tolerant plasmids and synthesis of massive quantities of organic osmoregulators in Ne salty environment
B. Chill tolerant plasmids

V. Genetic Engineering of Energy Production (H_2 Synthesis) from Water by Blue-Green Algae

A. H_2 uptake (H up) plasmids
B. Genetic derepression of hydrogenare and nitrogenare

APPENDIX B

INTERACTION OF WASTE PROCESSING GROUP WITH OTHER GROUPS

Interaction of Waste Processing Group with Other Groups

A. Interaction with Ecology Group

1) Nutrient solution does not have to be sterile, but pathogenically sterile.
2) No objection to direct growth of plants on human waste.
3) Information available on mineral, heavy metal max. on portable water from recycling systems. No information on organics.
4) One nutrient broth would not be optimum for the total system. Selective salt separations would be desirable.
5) Ecologists had a modular concept with each module as different as possible; implying four different waste processing systems.

B. Interaction with Diet/Nutrition Group

1) Need 5g Na/day.
2) K/Na ratio 1:1 (may be off by a factor of 2).
3) Maximum specifications on many micronutrients are not known.
4) Diet specialists assumed that vitamin/mineral supplements would be externally supplied - plant group will address the issue of supply.
   - Can't wait for years of research on micronutrient supply from edible plant portions;
   - Plant people did not consider complete mineral removal from nutrient solutions with excess solutions returned to waste processing;
   - Plant people assumed extensive salt separations in the waste processing.
5) Minimum food additives mostly in the form of organics (EtOH, etc.).
6) Fat breakdown products will be added to the atmosphere.
7) Can supply gross elemental composition of the human diet.
8) Anti-view on use of algae for food.
9) Nucleic acids can be removed.
10) Low protein diets in space desirable.

C. Interaction with Plant Group

1) Definitely interested in growing plants directly on human waste.
2) Confusion on the inclusion of animals in food production - Executive Committee does not support the inclusion of animals in the GBCD due to prior trade-off studies.
3) Possible to use a single nutrient solution as growth media - however, confusion as to definition of single nutrient solution. Plant people considered single source as a multiple pure compound.

4) Most plant people wanted pure N in form of NO_3^-. However, did not consider using part NH_4^+ for N supply as well as pH adjustment. Group discussion: pH of nutrient solution with respect to NO_3^- is cation selection (Ca, Na, etc.). Thus pH of growing plants will depend on differential cation uptake.
5) Plant nutrient solution should be pathogenically sterile.

D. Interaction Between Ecology and Waste Processing

1) Multiple systems are desirable, but not necessarily required.
2) Does the Waste Processing group consider having 2 or 3 different GBCD such as biological, physicochemical, hybrid, etc.? Answer: yes, within trade-offs - priority and cost limitations.
3) One unknown - do plants take micronutrients up into the edible plant portions and concentrations necessary to sustain humans without having to artificially supply these to the diet?
4) In all of these systems there is a possibility of purging.

APPENDIX C

GROUP MEMBERSHIP

GROUP 1: NUTRITION, DIET AND FOOD PROCESSING

Marcus Karel, Leader
J. Peter Clark
G. W. Hoffler
Stephen Kreitzman
Paul Rambaut
U. D. Register
Quinton Rodgers
Dwayne Savage
Richard Sauer
Paul Singh
Frances Zeman

GROUP 2: FOOD PRODUCTION

John Phillips, Leader
Olle Bjorkman
Anthony Bywater
Paul Deal
Mordecai Jaffe
Jagmohan Joshi
Cary Mitchell
Richard Radner
David Raper
Ronnie Roberts
Frieda Taub
T. W. Tibbitts
Judith Thomas
John Tremor
Ray Valentine
Leon Zalkow
Pete Zill

GROUP 3: WASTE PROCESSING

Michael Modell, Leader
Dot Fricks
Amitava Gupta
Bert Hansen
Fritz Meissner
Ed Merek
Rebecca McDonald
William Mueller
William Oswald
Eugene Petersen
David Putnam
Michael Schuler
William Wolverton

GROUP 4: SYSTEMS ENGINEERING-MODELING

Jack Spurlock, Leader
David Auslander
Mel Averner
John Carden
Albert Liabastre
Robert MacElroy
Robert M. Mason
Berrien Moore

GROUP 5: ECOLOGY-SYSTEMS SAFETY

Sidney Draggan, Leader
Ed Balish
Daniel Botkin
Lawrence Hochstein
Bassett Maguire
Adrian Mandel
Walter Mason
Bernard Patten
Gary Sayler
Mel Silverman
Lawrence Slobodkin

GROUP 6: OVERVIEW

Paul Buchanan
Minno Dastoor
Richard H. Green
Thora Halstead
William Knott
Robert W. Krause
William Mueller
Bruce Peterson
Dan Popma
Phil Quattrone
Frank Samonski
Giulio Varsi
Calvin Ward
Richard Young
Ben Zeitman

APPENDIX D

NAMES AND ADDRESSES OF WORKSHOP PARTICIPANTS

AUSLANDER, DAVID
Dept. of Mechanical Engineering
UC-Berkeley
5120 Etchevery Hall
Berkeley, CA 94720
Telephone: 415-642-4930

BALISH, EDWARD
Dept. of Medical Microbiology and Surgery
University of Wisconsin Medical School
Room 179 Medical Science Bldg.
Madison, Wisconsin 53706
Telephone: 608-263-1670

BJORKMAN, OLLE
Carnegie Institution
Dept. of Plant Biology
290 Panama
Stanford, California 94305
Telephone: 415-325-1521

BOTKIN, DANIEL
Wilson Center
Smithsonian Building
Washington, D.C. 20560
Telephone: 202-381-5260

BYWATER, ANTHONY C.
University of Calif. at Davis
118 Animal Science
Davis, California 95616
916-752-1259

CARDEN, JOHN L.
Georgia Institute of Technology
Engineering Experiment Station
Room 231 Baker Bldg.
Atlanta, Georgia 30332
Telephone: 404-894-3450

CLARK, J. PETER
ITT Continental Baking Company
Process Development & Engineering
P.O. Box 731
Rye, New York
Telephone: 914-967-4747 Ext. 142

DRAGGAN, SIDNEY
Div. of Policy Research & Analysis
The National Science Foundation
1800 G Street, NW Room 1240
Washington, D.C. 20550
Telephone: 202-632-7810

JAFFE, MORDECAI J.
Department of Botany
Ohio University
Athens, Ohio 45701
Telephone: 614-594-5434

JOSHI, JAG
University of Maryland
Eastern Shore
Princess Ann, Maryland 21583
Telephone: 301-651-2200 Ext. 274

KAREL, MARCUS
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Telephone: 617-253-6744

KRAUSE, ROBERT W.
College of Science
Oregon State University
Corvallis, Oregon 97331
Telephone: 503-754-4811

KREITZMAN, STEPHEN
Emory School of Dentistry
Emery University
1462 Clifton Road
Atlanta, George 30322
Telephone: 404-329-6769

LIABASTRE, ALBERT A.
School of Chemical Engineering
Georgia Institute of Technology
Atlanta, George 30332
Telephone: 404-894-2874

MAGUIRE, BASSET
University of Texas, Austin
Austin, Texas 78712

MASON, BETTY
Metrics, Inc.
290 Interstate North
Suite 116
Atlanta, Georgia 30339
Telephone: 404-955-1975

MASON, ROBERT M.
Metrics, Inc.
290 Interstate North
Suite 116
Atlanta, Georgia 30339
Telephone: 404-955-1975

MASON, J. WALTER
University of Alabama in Birmingham
Department of Public Health, SOM/SPAH
Division of Environmental Health
204-A Tidwell Hall
University Station
Birmingham, Alabama 35294
Telephone: 205-934-4993

MEISSNER, H. P.
Department of Chemical Engineering
Room 66-542
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Telephone: 617-253-4589

MITCHELL, CARY A.
Department of Horticulture
Purdue University
West Lafayette, Indiana 46207
Telephone: 317-749-2261

MODELL, MICHAEL
Chemical Engineering Department
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Telephone: 617-253-4595

MOORE, BERRIEN
Systems Research Group
O'Kane House
University of New Hampshire
Durham, New Hampshire 03824
Telephone: 603-862-1763

OSWALD, WILLIAM
University of California at Berkeley
Berkeley, California
Telephone: 415-642-0835

PATTEN, BERNARD C.
Department of Zoology
University of Georgia
Athens, Georgia 30602
Telephone: 404-542-8134

PETERSON, BRUCE
Marine Biological Laboratory
Woods Hole, Massachusetts 02543
617-548-3705

PUTNAM, DAVID
Umpqua Research
Route 1, Box 333a
Myrtle Creek, Oregon 97457
Telephone: 503-863-5201

PHILLIPS, JOHN
Arizona Research Associates
317 East Jacinto St.
Tucson, Arizona 85705
Telephone: 602-623-4679

RAPER, C. DAVID
North Carolina State University
Department of Soil Science
Box 5907
Raleigh, North Carolina 27650
Telephone: 919-737-2644

REGISTER, U.D.
Department of Nutrition
School of Health
Loma Linda University
Loma Linda, California 92354

ROBERTS, RONNIE S.
Chemical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
Telephone: 404-894-2889

ROGERS, QUINTON
Department of Physiological Sciences
School of Veterinary Medicine
University of California at Davis
Davis, California 95616
Telephone: 916-752-3086

SAVAGE, DWAYNE
Department of Microbiology
University of Illinois
131 Burrill Hall
Urbana, Illinois 61801
Telephone:

SAYLER, GARY
Graduate Program in Ecology
University of Tennessee
Knoxville, Tennessee 37916
Telephone: 615-974-3065

SHULER, MICHAEL
Department of Chemical Engineering
340 Olin Hall
Cornell University
Ithica, New York 14853
Telephone: 607-256-7577

SINGH, R. PAUL
Dept. Agricultural Engineering
University of California at Davis
Davis, California 95616
Telephone: 916-752-0811

RADMER, RICHARD
Martin Marietta
1450 South Rolling Road
Baltimore, Maryland 21227

SLOBODKIN, LARRY
University of New York
Stony Brook, New York 11794

SPURLOCK, JACK
Applied Sciences Laboratory
Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332
Telephone: 404-894-3414

TAUB, FRIEDA
College of Fisheries (WH-10)
University of Washington
Seattle, Washington 98195
Telephone: 206-543-2100

THOMAS, JUDITH
North Carolina State University
Dept. of Soil Science
Box 5907
Raleigh, North Carolina 27650
Telephone: 919-737-2778

TIBBITTS, T.W.
University of Wisconsin
1575 Linden Drive
Madison, Wisconsin 53706
Telephone: 608-262-1491

VALENTINE, RAY
University of California at Davis
Plant Growth Laboratory
Davis, California 95616
Telephone: 916-752-6164

WARD, CALVIN
Dept. of Environmental Science & Engin.
Rice University
P.O. Box 1892
Houston, Texas 77001
Telephone: 713-527-4086

ZALKOW, LEON H.
School of Chemistry
Georgia Institute of Technology
Atlanta, Georgia 30332
Telephone: 404-894-4045

ZEMAN, FRANCES J.
University of California at Davis
Department of Nutrition
129 Everson Hall
Davis, California 95616
Telephone: 916-752-3388

LIST OF NASA PERSONNEL AT CELSS WORKSHOP

NASA HEADQUARTERS	WASHINGTON, DC 20546		
DASTOOR, MINNO	Code SB		
HALSTEAD, THORA	Code SBL-3	202 755 3733	FTS 8 755
POPMA, DAN	Code SBS-3	202 755 3723	
YOUNG, RICHARD	Code SBL-3	202 755 3732	
JOHNSON SPACE CENTER	HOUSTON, TX 77058		FTS 8 525
FRICKS, DOT	Code EC3	713 483 3343	
RAMBAUT, PAUL	Code SD3	713 483 5457	
SAMONSKI, FRANK	Code EC3	713 483 4823	
SAUER, RICHARD	Code SE3	712 483 2759	
JET PROPULSION LAB	4800 Oak Grove Drive PASADENA, CA 91103		
GREEN, RICHARD H.	Code 169-527	213 354 6703	FTS 8 792
GUPTA, AMITAVA	Code 67-201	213 354 5783	
HANSEN, BERT	Code 125-159	213 354 6378	
VARSI, GIULIO	Code 125-159	213 354 3790	
MUELLER, WILLIAM	Code 84	213 354 2420	
PETERSEN, GENE	Code 125-159	213 354 7286	
AMES RESEARCH CENTER	MOFFETT FIELD, CA 94035		FTS 448
AVERNER, MEL	Code 239-10	415 965 5573	
DEAL, PAUL	Code 239-10	965 5572	
HOCHSTEIN, LARRY	Code 239-10	965 5938	
MAC ELROY, ROBERT	Code 239-10	965 5573	
MANDEL, ADRIAN	Code 239-7	965 5061	
MEREK, ED	Code 239-9	965 5768	
QUATTRONE, PHIL	Code 239-4	965 5733	
SILVERMAN, MEL	Code 239-9	965 6180	

TREMOR, JOHN	Code 236-5	965 5731
ZEITMAN, BEN	Code 239-10	965 5748
ZILL, PETE	Code 239-10	965 5759

KENNEDY SPACE CENTER, FL 32899 FTS 823

BUCHANAN, PAUL	Code MD	305 867 2585
HOFFLER, G. W.		
KNOTT, WILLIAM	Code MD-B	305 867 3152

NATIONAL SPACE TECHNOLOGY LAB, NSTL Station, MS 39529 FTS 494-3155

MC DONALD, REBECCA	
WILVERTON, B.C.	NSTL Station, MS 39529