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Task 1 Report
Initial Assessments of Life Support Technology Evolution and Advanced Sensor Requirements

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ADVANCED LIFE SUPPORT ANALYSES (Contract No.: NAS8-38781)

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INITIAL ASSESSMENTS OF LIFE SUPPORT TECHNOLOGY EVOLUTION AND ADVANCED SENSOR REQUIREMENTS

An
Interim Technical Report

prepared under
Contract Number NAS8-38781
"ADVANCED LIFE SUPPORT ANALYSES "

February 28, 1991

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Initial Assessments
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February 28, 1991

Prepared for

Environmental Control and Life Support Branch
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FOREWORD

This Technical Note (TN) serves as an interim documentation of the activities conducted and the results obtained through the Mid-Term Review of the "Advanced Life Support Study" (Contract NAS8-38781) for the George C. Marshall Space Flight Center (MSFC) of the National Aeronautics and Space Administration (NASA). It also contains responses to questions received from NASA on presentation of the material December 18,1990. Technical direction of SRS is given by the NASA COTR, Mr. Paul O. Wieland/ED62. Mr. Edward E. Montgomery served as the SRS Project Leader. Other SRS personnel who made key contributions to this report were Mr. Joe C. Cody, Mr. James C. Pearson, Jr., Mr. Steve Wakefield, and Mr. David Marty.

CONTENTS

LIST OF EXHIBITS

1.0 INTRODUCTION

This report provides a narrative description of the trades studies performed during the first half of the Advanced Life Support Analysis Study under contract to NASA's George C. Marshall Space Flight Center. A Mid-term Review was held at the offices of SRS Technologies in Huntsville, Alabama on December 18, 1990. Section 2 of this report describes the study results presented in the technical briefing. After review by NASA, a number of questions were raised about the material presented, primarily directed toward further explanation of the results and comparison with the results achieved by others. Section 3 of this report responds to those questions and action items. The report concludes with Section 4 which summarizes conclusions drawn from the resulting data.

1.1 Background

The Environmental Control Life Support Systems (ECLSS) testbed at NASA's Marshall Space Flight Center (MSFC) is providing opportunities to test and validate components, subsystems, and systems being developed for the Space Station Freedom Program (SSFP) /15/. To date, physical/chemical (P/C) ECLSS systems have been the primary focus of the testbed. Future space missions, especially lunar and planetary exploration like those described in the planning for the Space Exploration Initiative (SEI) could benefit from more sophisticated methods of providing life support and control /16/. Frequent resupply of critical resources in future missions may not always be practical or even possible. A bioregenerative ECLSS may be able to significantly reduce resupply requirements of these future missions /17/.

Bioregenerative systems may be achieved by combining P/C systems with biological systems to form "hybrid" systems. The biological systems will utilize the by-products of the crew to provide food, breathable air, and water purification. In order to ultimately achieve the highest level of benefits from the regenerative system, a complete transition of ECLSS technology from P/C systems to hybrid systems and finally to a Closed Ecological Life Support System (CELSS), may be required. Each phase of transition has its own peculiar challenges and benefits /18/. The best transitional pathway may be identified through studies to determine feasibility, practicality, cost, technology requirements, attributes, performance anomalies, schedule, etc.

At the Mid-term Review on December 18, 1990, an executive summary of the contract activities provided prior to the detailed discussions included: schedule/milestones, previously reported efforts, general guidelines/assumptions used in analysis, and summary conclusions for ECLSS evolution and advanced instrumentation. A schedule of tasks and milestones is given in Figure 1. The literature survey was completed in mid October and reported in the subsequent monthly report. ALS data base activity had not begun as of the midterm but has since been initiated. Computer tools have been developed and development continues. The P/C>Hybrid>CELSS Evolution task, Sensor /Monitoring Technology task, and Automation and Controls Technology task are under way.

A few of the activities performed during the first phase of the study have been presented and documented in previous reports (see Figure 2). Their inclusion here would have been unnecessarily redundant. The Literature Survey and ALS Data Base activities are addressed in the monthly progress reports SRS/STG-PR91-5738/1, 2, and 3 for August, September, and October, respectively.

SCHEDULE / MILESTONES

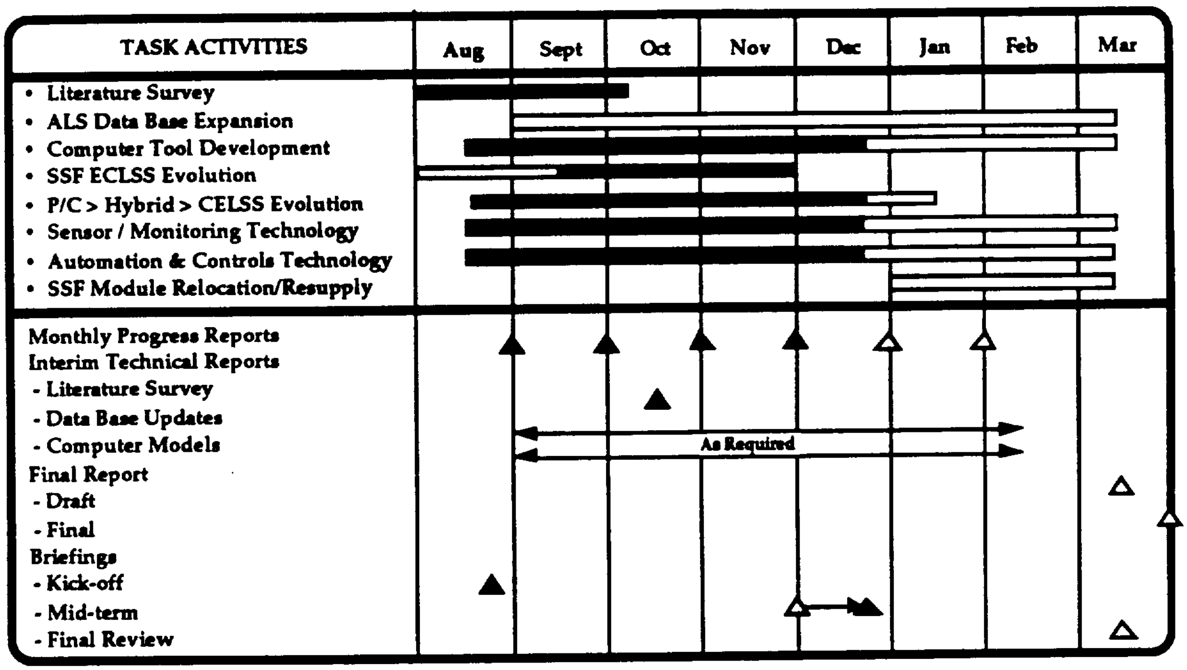

Figure 1. Schedule/Milestones

The evaluations of space station growth configurations were addressed in a draft SRS Technical Note (SRS/STG-TN91-02) entitled "An Investigation of the Growth of Intermodule Ventilation Systems and Water Distribution Systems to Accommodate the Addition of a Hab and a Lab Module with Nodes to the Assembly Complete SSF Configuration". The proceedings of the Waste Management in Space Conference was also documented in a Technical Note (SRS/STG TN91-01). Also, an effort to evaluate Clean Room-related Life Support System Technologies was reported in SRS Technical Report SRS/STG-TR91-22 entitled "MSFC Clean Room Survey and Assessment".

1.2 Guidelines/Assumptions

Bioregenerative life support technology appears to have potential for future space applications /9,10,11/. The exact level of benefits is difficult to determine due to the small knowledge base available on the technologies. A growing number of the basic processes have been demonstrated over the last ten years of closed-ecology research, but the sensitivities and interrelationships among design variables have not been explored to the degree necessary to guide designers to an optimum set of system equipment specifications /12,14/. In the absence of this technical maturity, this study was performed based on a set of pre-selected assumptions about the performance and characteristics of bioregenerative systems. Also, the analyses were performed in such a way as to minimize attempts to draw conclusions in areas where critical factors were highly uncertain. Figure 3 summarizes a set of guidelines and assumptions upon which all the life support evolution analyses were performed.

Previously Reported Efforts

- LITERATURE SURVEY
  - PRIMARY FOCUS: BIOREGENERATIVES LIFE SUPPORT AND SENSORS/ONTROL INSTRUMENTATION
  - INITIAL BIBLIOGRAPHY PUBLISHED IN 1ST MONTHLY PR. UPDATE TO BE PUBLISHED IN FIANL REPORT
- ALS DATA BASE
  - NO NEEDS HAVE BEEN IDENTIFIED
- SSF GROWTH CONFIGURATION EVALUATION
  - GROWTH BEYOND A/C TO 2 HABS & 2 LABS
  - INTERVMODULE VENTILATION STUDIES/RECOMMENDATIONS
  - A/R COMPONENT PLACEMENT RECOMMENDATIONS
  - DOCUMENTED IN TECHNICAL MEMORANDUM AND INTERIM REVIEW (10/18/90)
- "WASTE MANAGEMENT IN SPACE FOR ADVANCED LIFE SUPPORT" CONF. AT ARC.
  - ATTENDED; SYNOPSIS PREPARED AND SUBMITTED IN TECHNICAL NOTE.
- CLEAN ROOM SURVEY
  - FINAL REVIEW HELD 12/14/90.

Figure 2 Previously Reported Efforts

GENERAL GUIDELINES/ASSUMPTIONS USED IN ANALYSES

- Steady State Analyses
- Factors derived on a per person per per day basis
- Plant Chamber Model based on KSC CELSS Chamber Experiment Data
- Leakage and Airlock Losses were considered in later trades.
- Weight Trades based on Δweights, not total system weights
- Transportation penalties not considered.
- Studies address Lunar Base.
- Potable quality condensate assumed from Food Plant Chamber
- % Hybridization = Fraction of food provided from plant chamber

Figure 3 General Guidelines/Assumptions Used in Analysis

The figure of merit used to trade alternatives is comparison of mass delivered to the final destination (common) and usually is summed over a period of time representing evolutionary phases. Other factors such as safety and reliability are important, but nearly impossible to estimate without a historical data base on the technology. An estimate of life cycle cost might also be useful, but until more definitive characteristic data is available, confidence intervals on the estimates would be too large to mean anything much. Mass has long been recognized as the major factor in hardware costs. In the trade-offs between lunar life support evolution options, the total mass tracked represents only a portion of the total weight of the life support system. Only subsystem masses which changed directly as a result of considering an optional technology approach considered. For this reason, the initial mass of a radiator to reject all the heat for the lunar base was not calculated. A mass was estimated for a radiator size to reject the heat required by the ECLS option. Similarly, the mass of galley equipment, shower and toilet facilities, and enclosing module structure costs were not included in the seven initial mass calculations. These things were assumed to be essentially the same for all technology options considered. Since the volume required by a plant chamber is not insignificant, a basic structural weight penalty for it was imposed.

Several past trade studies of design options for a lunar base have included a mass penalty for transportation of the equipment along with the basic equipment weight. The results are often counted in terms of mass in lower earth orbit or launch mass. Studies have indicated for every pound of equipment placed on the lunar surface, around six or seven additional pounds of transport vehicles, propellants, and other "overhead" items is needed /8/. Transportation penalties were not calculated and applied in the following trade studies since the same transport system were assumed to make delivery to the same destination regardless of the life support option under consideration. The relative ranks of the options are not affected, but the differences between the cumulative masses between two competing options is much greater accordingly.

Initially leakage and airlock losses were not considered because it is primarily a function of enclosed volumes and airlock operations. Nothing about any of the different life support technology options considered gives it an inherently better capability to reduce leakage and losses. A possible exception could be the slight growth in total volume of the lunar base required for designs including a plant chamber. This factor was included in some of the analyses in Section 4.

There were a number of assumptions about the performance of both advanced physicochemical and bioregenerative systems which demonstrate a high leverage on the results obtained in the study. Perhaps the most profound of these is the assumption that potable quality water can be recovered from both potable and hygiene sources by a higher plant chamber /14/. It is assumed that the water transpired by the chamber and collected as heat exchanger condensate is of such quality that no significant further processing or polishing is required. It is further assumed that the same chamber and same plants that are performing this operation are also simultaneously performing gas exchange

(CO_2 consumption/O_2 generation) and providing food for the crew. While several sources in the literature point to this as a possibility, it has not yet been demonstrated on a laboratory scale. At the time of this study, the work being performed at the NASA CELSS chamber at Kennedy Space Center was perhaps the most accessible and complete on the subject /11/. Performance models used in these analyses were derived from experimental results achieved in that activity. It is noted that more information of this type will shortly be available from further research at KSC and the closed system testbed being constructed at the Ames Research Center.

The point is demonstrated early in the following study results the humans and higher plants are not a complementary ecological pairing. Other processes are needed for balance. Plants do not exchange oxygen and carbon dioxide at the same proportions as humans do. Also, the number of plants required to transpire water at exactly the rate used by a human would not likely produce enough food to support him or her. The problem of modeling the performance of a bioregenerative system is compounded because each species of higher plants performs the water processing, food production, and gas exchange at different rates and proportions.

In order to be as optimistic as possible in considering the bioregenerative technology options, it was assumed that all the daily food needs of a human could be provided by 22.73 m^3 per person of wheat. The KSC chamber was based on this value because it is equivalent to the total daily caloric needs /9,10/. These same wheat plants were used in wastewater recovery and gas exchange, i.e., plants and chamber were multifunctional.

As a final note on the approach used in the analyses, most factors are derived and used on a per person per day basis. This makes evaluation of evolution growth over time and through growth in number of people at the base possible. The major variable parameterized in the trades is called % Hybridization. It has been defined in this study as a convenient method to reflect the degree to which the crew is being supported by bioregenerative systems in a system utilizing both bioregenerative and physicochemical processors. Low values of % Hybridization indicate systems which are largely comprised on physicochemical components (or systems in which are largely comprised of physicochemical components (or systems in which only a small fraction of the total crew are supported by bioregenerative systems). High values of % Hybridization approach for biological CELSS concept.

2.0 INITIAL TRADE STUDY RESULTS

While the scope of advanced life support is definitely broad, the primary objectives and emphases of this effort may be adequately addressed through addressing these issues:

<u>Primary Issues Studied</u>

- How can the transition from a P/C to hybrid to a CELSS system be achieved,
- What sensors and monitors are needed for a P/C-CELSS hybrid system, and
- How could a CELSS be automated and what controls are needed to do so?

The first question was addressed in three parts. The first part, discussed in Section 2.1, addresses the implications of technology availability and the dates new technologies are needed in order to support an SEI-type Initiative. These schedule-type constraints limit the number of available evolution options (severely in some cases). The second evaluation, discussed in Section 2.2, addresses the evolution question from the stand-point of economics. Assuming that evolution would occur at the time in which it was profitable to do so, system mass accumulations over the duration of an initiative (25 years) were calculated and compared for a lunar base comprised of varying levels of hybridization from pure physicochemical to pure CELSS. The initial results on this topic generated a number of questions at the mid-term review. In resolution of these questions, additional studies were performed and the results were provided in Section 3.1. The third attack on the evolution question is presented (in Section 2.3) with a discussion of technical aspects of combining physicochemical and bioregenerative technologies in a single system. The study of integration issues revealed limitations and conditions which must be satisfied for the two technologies to successfully and efficiently cooperate to perform the life support function.

Two of the questions concerned advanced instrumentation technology. "What sensors and monitors are needed for a P/C-CELSS hybrid system?" was addressed through the development of sensors and control requirements. The other question was "How could a CELSS be automated and what controls are needed to do so?". Some advanced sensors and controls concepts were developed and presented in this area. A discussion of the basic advanced instrumentation presentation is contained in Section 2.4 and responses to the questions/action items in Section 3.2. This is followed by topics related to space station growth accommodations(Section 2.5) and computer tools (Section 2.6).

2.1 Technology Development & Schedule Constraints

There have been a number of analyses performed to bring about a further understanding of how bioregenerative systems might be used in an advanced life support system and to estimate how well they might perform. Although much more study is needed before best solutions can be identified, there may be enough knowledge to identify the likely general characteristics. The list below is presented as a sketch of the ideal characteristics of a CELSS plant chamber system.

- High nutritional value in a small amount of food:
    - 100% of balanced needs with <800 grams/person/day of acceptably palatable food. Wheat can provide the appropriate caloric value with approximately 756 grams/person/day, however the nutritional needs are not met.
- Human complementary assimilation coefficient:
    - 0.8696 moles CO_2 consumed/moles O_2 produced.
- High efficiency biological waste treatment/recovery:
    - 100% closure through direct application of wastes to plant growth substrate.
- High quality water recovery:
    - Potable quality transpired water.
- High harvest fraction:
    - $\geq$50% of total plant mass is edible.
- Dense growth:
    - 100% of nutritional needs for one person with $\leq$25 m^3/person/day.
- Compact nutrient delivery/potting system:
    - <.05 m^3 plant growth substrate/m^3 plant volume
- Adapted to long day/night cycle:
    - 336 hours light/336 hours dark

If the specifications above are accepted as requirements for the advanced life support systems of the SEI programs, then the current readiness of bioregenerative technology as a whole to support the development of a system to the specifications above is low on the maturity scale. A maturity level of 1 requires that the basic principles of the new technology have been observed and at least reported. This can be said to be true of concepts meeting only a few of the requirements listed above. The possibility of ever meeting requirements like the adaptation to the long light cycle and human complementary assimilation coefficient, are in serious doubt. Solutions which circumvent or compensate for problems with the technology almost certainly exist, but will take time to evolve and develop. In some cases, there is not a sufficient amount of time available before the systems are needed to support the SEI program milestones as they are currently defined.

Current guidelines being used in the Space Exploration Initiative (SEI) planning call for any system, which is to be considered a candidate for use in a program, to have a Technology Readiness level of 5 at the start of Phase B development of the element in which it is to be used /19/. Level 5 maturity is assumed to be achieved when a component embodying the technology has been tested in a relevant environment /20/. In some cases, level 4 is acceptable if there is sufficient reason to believe maturity will be achieved by PDR. Today most bioregenerative concepts are at a maturity level of 1, i.e, the basic principles of the technology have been observed and reported.

SEI planning is undergoing considerable modification and will likely continue to do so for some time. However, most planning calls for initial Lunar systems to be placed in the 2000-2005 time frame with significant upgrading in the years 2007-2011. Mars initial emplacements are typically occurring between 2010 and 2015. Development (Phase C/D) usually requires 5-9 years and is preceded by a 2 year phase B Definition period. From these considerations, the timetable in Figure 4 was constructed.

Element	Maturity Level Required	Ø B Start Date	Development Time Available (from 1990)
Lunar Transfer Vehicle (LTV)	5	1993	3
Lunar Excursion Vehicle (LEV)	5	1993	3
Initial Lunar Outpost	5	1994	4
Lunar Base Upgrades	5	1999	9
Mars Transfer Vehicle (MTV)	5	2004	14
Mars Excursion Vehicle (MEV)	5	2004	14
Initial Mars Outpost	5	2005	15
Mars Base Upgrades	5	2011	21

Figure 4. Technology Development Time Available for Various SEI Elements

The initial Lunar Outpost would be a potential application for bioregenerative systems except for the lack of development/advancement time available (4 years). Some concepts in the SEI architectures include short occupation periods initially at the lunar base. Discontinuous operation of bioregenerative systems is inefficient. Therefore, initial lunar outpost systems are unlikely to include any bioregenerative concepts or even much advanced physicochemical systems due to the compactness of the schedule.

With nine years available development time before lunar base upgrades, there is some opportunity for advancement. Considering how far the ideal plant chamber (CELSS Technology) has to go, however, it seems prudent to only plan for advancements in P/C systems and , possibly, some limited function bioregenerative systems (partial food production and maybe some water recovery). These upgrades will probably define the state-of-the-art at the beginning of the Mars Outpost Phase

B and , consequently, determine the technology used there. Further upgrades and development testing on the moon could make CELSS technology available for Mars Base upgrades after 2015.

These considerations form a rationale for a phased evolution from physicochemical to hybrid to CELSS. It is generally consistent with the guidelines shown in Figure 5 as presented by R.D. MacElroy/ARC for the evolution of bioregenerative life support to fit mission expansion scenarios, reference /18/. In that evolution sequence the nature of the services provided by bioregenerative technology occurs in four phases. In the initial psychological support phase, only a few per cent of the food requirements is grown on site. The growing capability is then expanded to include a broader range of vegetables in the system enhancement phase, but still the majority of nutrition is being supplied from outside the system. In the CELSS dominant phase, wastes are recycled and grains are grown and processed into food. The bioregenerative system is providing over half the nutritional needs at this point. In the final phase, CELSS system primary, all but trace materials are produced and recycled by the system.

PHASE	ELEMENTS TECHNOLOGY	MISSION	POTABLE	HYGIENE	O2/CO2	FOOD
I	PSYCHOLOGICAL SUPPORT -Salad Vegetable Growth -Hygiene Water Polishing	SSF, MTV Early Lunar Early Mars	100	13	8	4
II	SYSTEM ENHANCEMENT -Grow Vegetables	SSF, MTV Lunar Base	100	65	40	20
III	CELSS SYSTEM DOMINANT -Grow Grains -Oxidize, Recycle Plant Wastes, Process Food	Lunar Growth Mars Base	100	100	65	65
IV	CELSS SYSTEM PRIMARY -Recycle All Wastes -Purify All Water -Grow Majority of Food, Reclaim All Air, and Reclaim Plant Wastes	Late Lunar Late Mars	100	100	90	90

[After "Evolution of Bioregenerative Life Support (CELSS) to Fit Mission Expansion Scenarios", from a briefing by R. D. MacElroy, NASA Ames Research Center, August, 1990.]

Figure 5. CELSS Evolution Goals for a Lunar Base

The evolutionary constraints imposed on the life support system development for each of the major elements (vehicles, bases, etc.) is discussed separately in the following paragraphs. Elements of like characteristics are addressed together.

2.1.1 LTV, LEV, and MEV

At first glance it appears these will be largely open loop systems since operational periods are short and system mass is a severe premium /21,22,23,24/. In a transportation vehicle, mass penalties are paid every flight rather than once on initial delivery for fixed bases. This makes it very difficult to justify anything but the bare minimum system mass approach. Since any attempt to reclaim, recover, or reuse an expendable almost always requires some additional system mass, open loop life support systems are by default the technology choice for these types of vehicles.

There may, however, be some benefit from a whole infrastructure standpoint when considerations of integrating these vehicles into the transportation nodes from which they operate (Space Station, lunar base, Mars base). For example, excursion vehicles could dump wastes into the CELSS of a base which is being visited. Also the excursion vehicle could take on base-supplied consumables (O_2, water) rather than carrying return consumables roundtrip. The mass benefits of this approach has been quantified in previous studies.

While open loop systems may be the cogent choice for atmosphere supply and control and water supply, a critical factor may be what is done with used consumables. For example, it may be better to store human metabolic and food waste rather than jettison it to reduce the vehicle's mass. The approach to air revitalization of using CO_2 recovery (e.g., mole sieve) which can collect and store CO_2 should be considered rather than LiOH cartridges as an upgrade for these systems. The CO_2 could then be reduced and reclaimed later when delivered to the more sophisticated base systems. Regeneration of LiOH cartridges may be difficult. Another alternative is solid amine beds, which could be desorbed into the systems at the vehicle's destination.

2.1.2 Lunar Outpost/Base

In four years, the state of the art for most ECLS systems will be defined by Space Station technology. Regardless of the station evolutionary path ultimately achieved, the level of maturity in a number of advanced techniques and equipment has already resulted from the program. Water electrolysis for oxygen supply, four bed molecular sieve for CO_2 recovery, and Sabatier for CO_2 reduction will likely be the atmosphere revitalization/supply technologies achieved by the eight man capability configuration. Some improvement in waste management practices will be justified by the greater transportation penalties and larger times between resupply. Supercritical water oxidation is currently at maturity Level 4 and is recommended here for processing of urine and feces at the initial human outpost. No significant food production or water recovery/polishing will be done by a plant chamber initially. Food will be supplied open loop and multifiltration (albeit very costly in resupply) will be the initial water recovery technology. These are roughly consistent with the CELSS program philosophies.

The first significant upgrade to the lunar base is scheduled to be delivered around 2007. This will allow eight or nine years for refinement of existing systems and development of new technologies. The most beneficial of these would be use of the plant chamber for water polishing (thus reducing the multifiltration load, some additional food production, and recovery of water from products of the Sabatier process). A conceptual design has been formulated (maturity Level 2) for the advanced carbon reactor. This system is based on a carbon formation reactor located downstream from a Sabatier unit. This complement to the Sabatier is an attractive alternative because it represents a smooth evolutionary transition. This minor upgrade will be consistent with the Phase II objectives stated in the CELSS program.

A dozen or so years of development time are available for the third phase which will consist largely of bringing up more plant chambers to decrease open loop food supplies and increase water polishing. It is assumed during this phase that waste will be processed and recycled to the plant chamber nutrient supply. A trade study indicated that using SCWO versus an anaerobic digester to reclaim water from waste shows no clear favorite. As plant chambers are integrated into the system, the load on water electrolysis for oxygen supply is proportionally decreasing. A problem exists in that the gas exchange coefficients of the various processes (human respiration, plant assimilation, waste oxidation, water electrolysis, and (O_2 recovery/reduction) are not balanced. The option appears to be either to operate at the required oxygen balance (CO_2 is dumped) or carbon dioxide balance CO_2 is dumped). In the latter scenario, an aerobic biological waste digester might be able to use the excess oxygen thus improving closure to this point and providing significant benefits over waste oxidation. This point is inconclusive and beyond the scope of this effort to resolve. It is assumed here that SCWO remains the preferred waste treatment technology and that processing of its ash products can recycle than to make-up plant chamber nutrients.

The final development phase, planned for emplacement around 2015, is the full function CELSS and assumes a system like the one described at the beginning of this section. Plant chambers to support the entire lunar base crew complement are delivered and the existing physicochemical systems are shut-down and/or operated only minimally for transient loads or back-up.

2.1.3 Mars Outpost/Base

The initial Mars Outpost will begin development around the time that Phase II systems are in place on the moon and Phase III systems are into the development phase. The advanced carbon reactor and a significant fraction of food supply and water recovery from a plant chamber are assumed. The Mars base upgrade will be similar to the Lunar Base Phase 4, a transition to full function CELSS with P/C components in backup roles. One possible variation in the Mars system is utilization of the CO_2 content of its atmosphere. Maturity for such techniques is low and more basic development is required before any realistic assessment can be made.

2.1.4 Mars Transfer Vehicle

The MTV provides a unique set of requirements since it is the only transportation system with relatively long continuous operations. Mission durations may be on the order of three years, and if refurbished on-orbit and reused, may have a much longer operational life. In transportation systems, the system mass penalties are so severe it is difficult to justify any growth in initial system mass to achieve resupply economies. Psychological factors may dominate the system characteristics selected. It is unlikely that any large degree of bioregenerative capability will be employed, but regenerative P/C systems, some salad machine-level food production, and possibly a small plant chamber optimized for water processing are possibilities. More basic research is needed to make a definitive recommendations for this system also.

2.2 Mass Payback Implications

Using the parametric algorithms developed in this study to estimate initial and resupply mass of bioregenerative components such as a plant growth chambers and waste recovery units, combined with current physicochemical design data available from the space station program (references /25,26/), estimates of the cumulative mass delivered to a lunar base were calculated.

The estimates should be viewed as preliminary, since they are subject to a number of highly significant variables that cannot be rigorously defined due to a lack of engineering information. The bioregenerative system design and performance characteristics are very sensitive to these parameters. These results will be compared with the results achieved by other studies and a common basis for comparison derived in the near future. Initially, the calculations were made assuming a static configuration of a facility sized to support 4 people continually for over 20 years. Cumulative mass grows at a rate of around 3.3 metric tons per year until a total of around 84 mt has been delivered at the end of 24 years. For a CELSS system which provides 100 % of the food needs of the crew, the initial mass is much higher (38 mt), but the resupply rate is slower (1 mt/yr). The two curves cross at around fourteen years. This compares with about 7.5 years given in a study by Boeing /27/. As shown in Figure 6, by reducing the power penalty, the crossover point can be reduced to 9 years. This indicates that for continuous operation of a 4-person lunar base, if mission life is less than ten to fourteen years, it is more profitable (i.e. requires the delivery of less total mass) to use a full physicochemical system, supplying food regularly rather than growing it at the base.

After the cross over time, the differences in annual resupply overcomes the additional system mass cost, so that CELSS-type systems become more economical. Also calculated and shown was a curve representing a system in which a plant chamber sized to produce half the food needs of the crew was delivered along with a smaller amount of physicochemical equipment needed to provide the correct gas exchange ratio. This traded favorably since it reduced the initial mass penalty significantly. This 50 % hybrid case using the 350 lb/kW power penalty, had a breakeven point after only 8 years as opposed to 14 years for the full CELSS. (NOTE: In our studies we designate systems by % hybridization which denotes the fraction of the crew's food needs satisfied by a plant chamber).

- 4 People
- No Transportation Penalty
- No Leakage
- Food Req'd = 788 grams/person/day (in all cases)
- Spares/Maintenance at 4% of subsystem weight (excluding primary structure) per 90 days
- Only trade weights included - Total system weight not shown

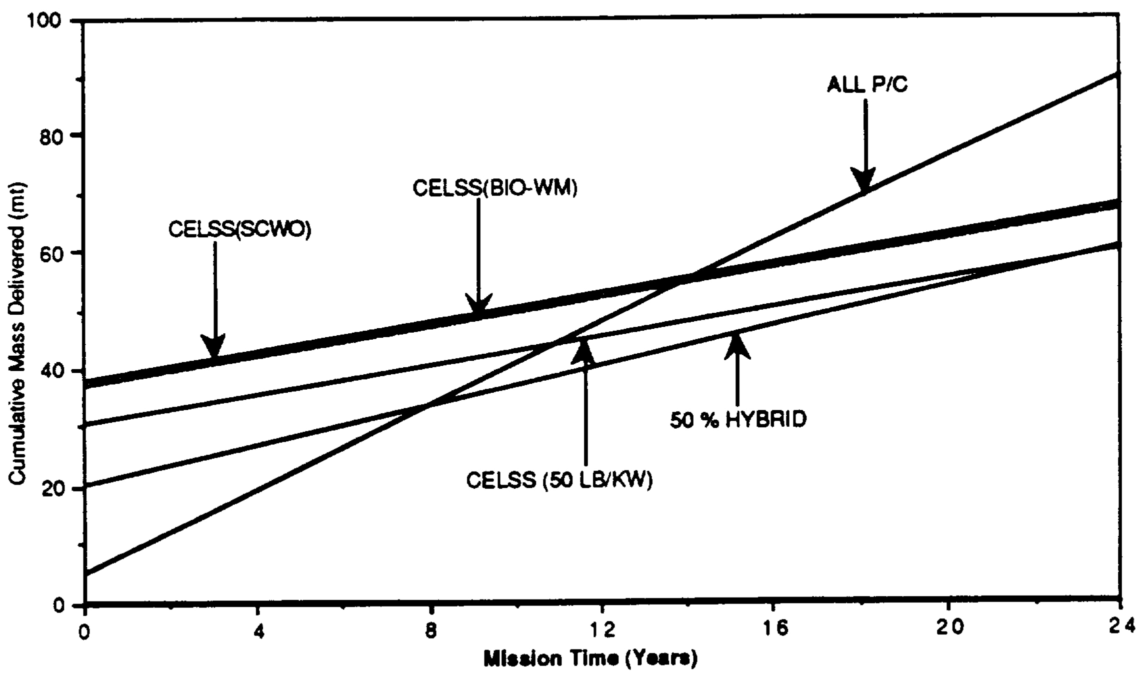

Figure 6. Preliminary Estimates of Cumulative Mass Over Time

Analyses of a CELSS concept consisting of a plant chamber and an anaerobic digester (references /28,29,30/) waste recovery system was compared with a plant chamber working in conjunction with a supercritical water oxidation (SCWO) waste management process, reference /31/. The differences in both initial and resupply mass were negligible. The major initial system mass penalty with a CELSS is the power required for growth lamps in the plant chamber. A very conservative alternate power penalty of 50 lb/kw, reference /32/, was plotted in comparison to the SEI planning value of 350 lb/kw, reference /20/. This reduced the full CELSS breakeven point from fourteen years to nine years. It is clear that the breakeven point is sensitive to power and other variables that require additional development for better definition. Atmosphere leakage was not considered in the preliminary estimates. It will be addressed in a later analyses. Transportation penalties were not included since the deliveries are to the same location, through the same nodes, and there appeared to be no significant packaging impediments.

In our resupply analysis, two factors were treated equally for the P/C versus the CELSS system. In both cases, it was assumed that 788 grams per person per day of edible food were required whether it was supplied open-loop as in the case of P/C system or whether it was grown in a plant chamber as with the CELSS system. This was value taken from the KSC CELSS plant chamber studies is consistent with one person's daily caloric needs, reference /11/. Currently, space station planning calls for food to resupplied open loop at around 2000 grams per person per day, reference /26/. If this higher resupply value were used on comparing the P/C to the CELSS, the breakeven points would occur much sooner. Also, annual resupply of maintenance and spares for the equipment was estimated at 4% of the initial mass for both the CELSS (excluding the plant chamber primary structure) and the P/C system. In an earlier study, reference /27/, by Boeing for a space station CELSS module, a value of 3 % was used. In view of the lack of experience with the reliability and operational life of these systems, it is difficult to arrive at a firm estimate of the resupply requirements. Results of a parametric analyses to investigate the sensitivity of these variables is provided in a later section of this report.

Using the same algorithms as in the breakeven analysis, the cumulative mass for a installation growing in size and evolving in technology over time were estimated. The number of crew to be served and the technology to be used throughout the mission period, these things were varied in this analysis. The growth of the lunar base was assumed at a rate of four additional people every four years starting in 2003 until a complement of 28 is achieved in 2015. This is consistent with one of the more vigorous planning architectures under study in the SEI program, the Expanding Human Presence Architecture /16/. Also, the kind of technology comprising the lunar base life support system was allowed to vary as time progressed and the base grew in size. The phases as defined by MacElroy were applied to the Expanding Human Presence Architecture. Assuming the base to be fully staffed and mature, the beginning of Phase 4 is then in 2015. Back scheduling in equal segments, the advent of phases two and three would occur in 2007 and 2011, respectively. The initial placements would be made at the phase one level in 2003. For comparison, plots of a growing, but not evolving, all physicochemical system were calculated and plotted along with a (continuously) 50 % hybrid case.

The results shown in Figure 7 have interesting implications. At the time the base becomes fully staffed (2015), the economics of the phased evolution are much worse than either the all physicochemical or the 50 % hybrid case. The latter two cases are nearly equal at that time. Because new initial masses are arriving to accommodate the added crew, the breakeven point (between phased and full P/C systems) doesn't occur for over twenty years. Furthermore the breakeven against the 50 % hybrid case doesn't occur for more than 45 years in the future, a date far beyond the expected life of the technologies themselves. Although the value of these breakeven times may vary significantly due to thermal and power penalties and other factors, the trends of the phased approach are believed to be valid. The comparison of the plots tends to indicate that it would be best to accept some inefficiencies in the resupply cost in order to reduce the initial mass penalties. Otherwise, the realization of benefits is pushed beyond a reasonable time horizon. The best approach would probably involve a full P/C system for the first complement of crew of four. When the second crew of four arrive, they bring enough plant chamber equipment to produce the requirements for four people. Because there are now eight people in residence, the system is at 50 % hybridization in food. Since this means the gas exchange and water processing needs are provided at more than 50 %, the load on the original P/C equipment would in fact be reduced. Upon the arrival of the next four crew members, they need bring only enough new plant chamber equipment for two people to maintain the 50% total hybridization level and it may not be necessary to bring any new P/C equipment for air revitalization or water recovery management. Such an analysis for a hybrid system has not been done, but could be expected to show even greater benefits. The 50 % hybrid line indicated in our plot is simply the sum of a half-size CELSS system and a half-size full P/C system and surely contains some over-accommodation. This analysis raised the issue of how best to integrate bioregenerative systems like a plant chamber into a life support system which also includes P/C subsystems for performing similar functions. That was the subject of the next topic.

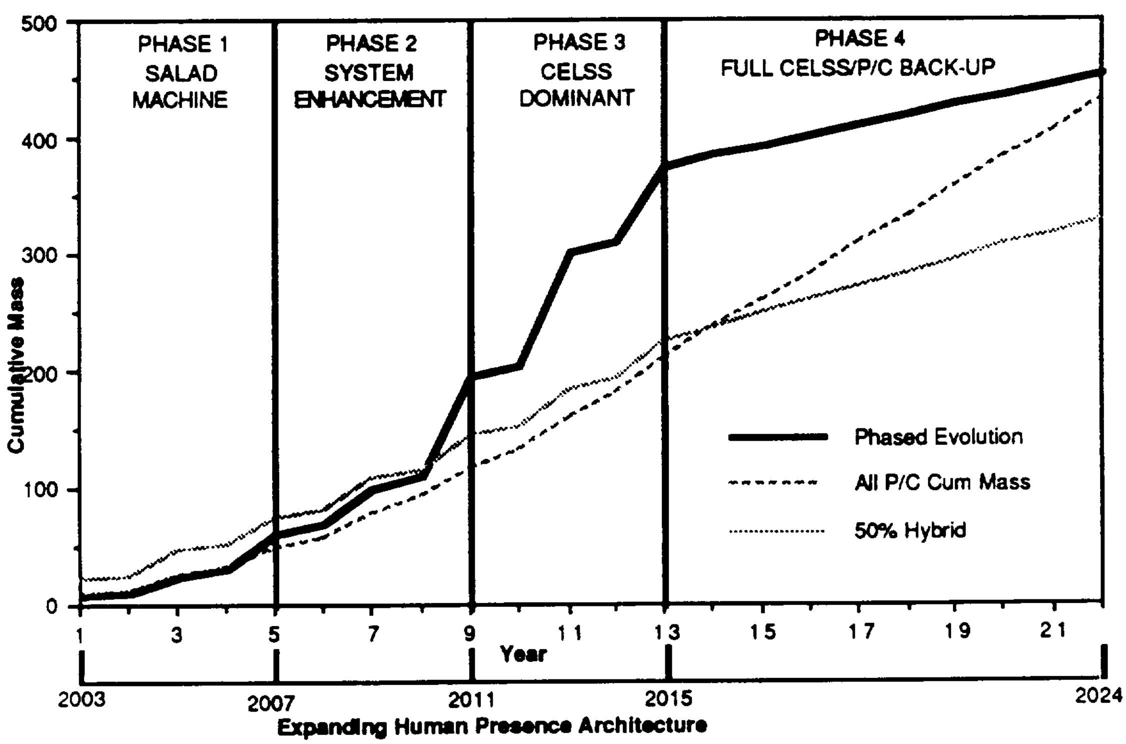

Figure 7. Preliminary Estimates of Cumulative Mass for A Growing Lunar Base

2.3 System Integration Issues

Hybridization is a term used to describe the transition and evolution from a purely physical/chemical (P/C) ECLSS to a partially regenerative ECLSS with a mixture of P/C and biological subsystems. There are many approaches to achieving ECLSS hybrids which could be considered. Reasonable minimum and maximum limits of hybridization, as well as optimum degrees of hybridization are some of the issues surrounding this new technology that need identification and understanding. The various combinations of P/C subsystems and biological subsystems which can form hybrid systems should be identified and studied in order to determine which options are the best. It was beyond our scope to accomplish such a trade. Instead , a promising hybrid ECLSS option was selected for our study which integrates a plant chamber with a molecular sieve/Sabatier carbon dioxide reduction unit, a static feed water electrolysis oxygen production system, and a water oxidation waste processor. Steady state algorithms to determine the hybrid ECLSS mass balance, to estimate power, weight, and volume, and to model subsystem and component performance were created. Computer tools were developed for each algorithm and were utilized in conducting trade studies for varying degrees of hybridization. Ultimately, these trade study results will be used to identify the controls and instrumentation requirements for this ECLSS hybrid.

The hybrid ECLSS system is defined in terms of the four subsystems/processes taking place: the plant growth chamber, the crew, the waste processor, and the P/C air revitalization subsystem. Another classification of these processes begins too illuminate the core steady state integration problem. The elements of the system are the humans, the plants, and the equipment. Humans and plants are very different kinds of processors than are the P/C systems. Each is a multiple stream processor. Which processes food, water, oxygen, and carbon dioxide. By assuming a constant processing rate, steady state analysis can be performed. More crew or more plants can be added to the system, but the same ratio of input to output will be maintained. In contrast, the equipment usually is designed to work with a single stream. However, for efficiency they also do have some interaction between streams as will be demonstrated shortly. They too have fixed processing quotients which are set by the stoichiometry of the chemical reactions upon which they are based. For example, water electrolysis produces one gram molecular weight of O2 for every two gram molecular weights of H2O input. Twice the input of water, produces twice the output of O2.

The result of integrating multiple stream processors of fixed quotient I/O is that it becomes difficult to achieve mass balance. To illustrate this principle, mass balance results will be shown beginning with the plant growth chamber and crew, then adding the waste processor (i.e. super critical water oxidation (SCWO)), and finally adding the P/C air revitalization system whose implicit function is to provide overall mass balance for the hybrid ECLSS. A draft preliminary design of a plant growth chamber was developed so that mass balance, sizing, and performance/sensitivity studies could be performed. A diagram of the chamber concept is shown in

Figure 8. The computer spreadsheet, PLTGRO, was used to determine the required growth area per person. The dimensions of the base were then determined on a per person basis assuming a square plant growth chamber. The nutrient flow stream passes just below the plants within the nutrient tray. Plant chamber atmosphere exchange ventilation ducts are located above the plants along the sides of the chamber and are part of the temperature and humidity control system. There are two complete circuits, each having an inlet duct section, an outlet duct section, a fan, and a bypass heat exchanger. The grow lamps are located below the outlet ducts and above the light filters and baffles.

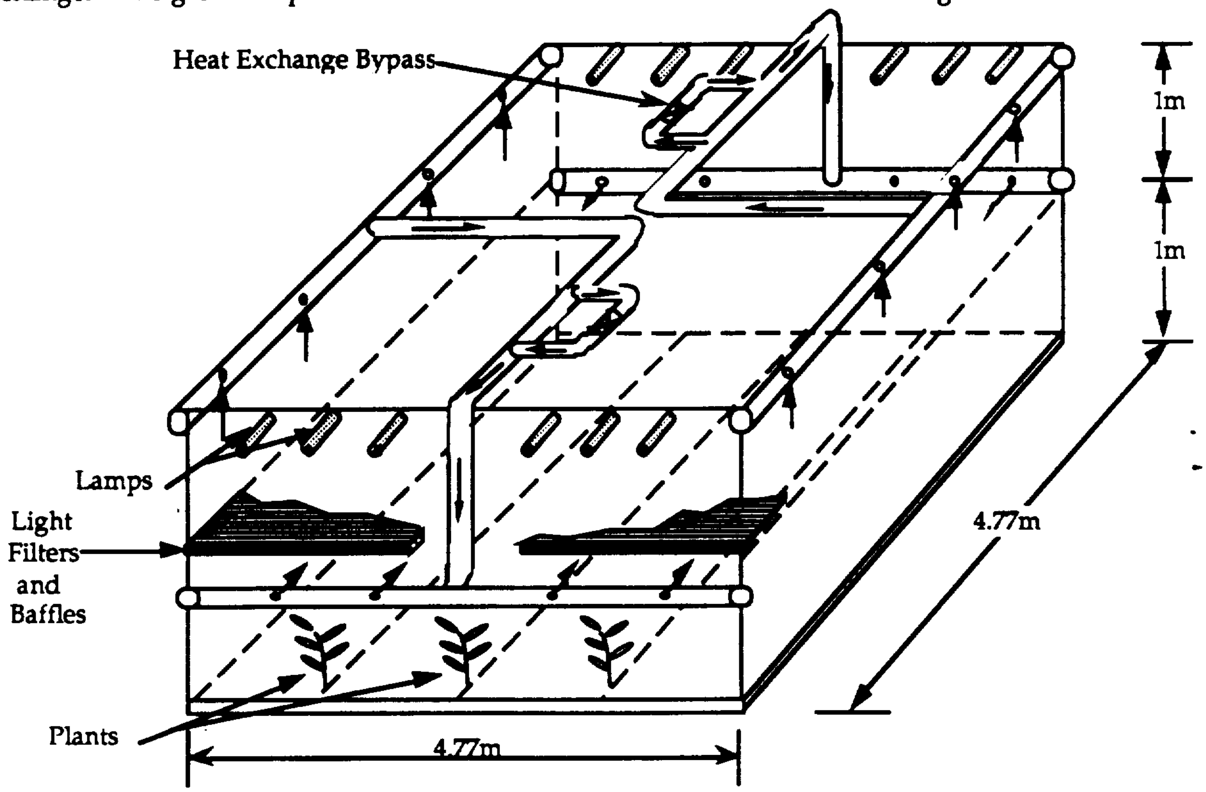

Figure 8. Plant Growth Chamber Concept

The plot in Figure 9 illustrates the results when a plant growth chamber is combined in a system with a crew without any other major processing equipment. The result is presented as the percent of the crew requirement (water purification, gas exchange, or food) that is satisfied for different size plant chambers. For larger crop areas, more of the requirements are met. At approximately 22.76 square meters per person, the plant chamber produces exactly the food needed by the crew. Smaller chambers will not produce enough food. Around 11.5 square meters will only produce half the needed food. Therefore, we say it has a % hybridization of 50%. Recall that 100% hybridization is defined as a plant growth chamber that supplies 100% of the food (caloric) requirements of the crew. From PLTGRO, a plant growth area per person of ~22.76 m^2 coincides with 100% hybridization. Meeting the crew O_2 requirement is the driver for the air revitalization system. Thus, as is demonstrated by this figure, the plant growth chamber consumes all of the CO_2 produced by the crew at ~60% hybridization but the plant growth chamber does not produce enough O_2 until ~67% hybridization. Thus a balance is not possible with only the plant growth chamber and crew; an additional subsystem/processor is required to provide balance.

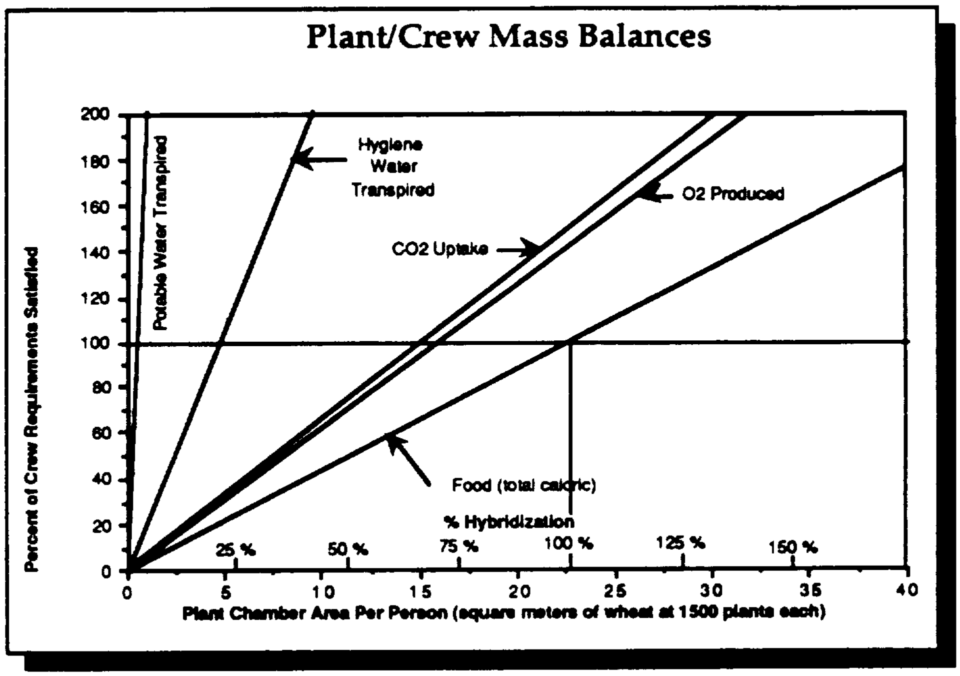

Figure 9. Plant Crew Mass Balances

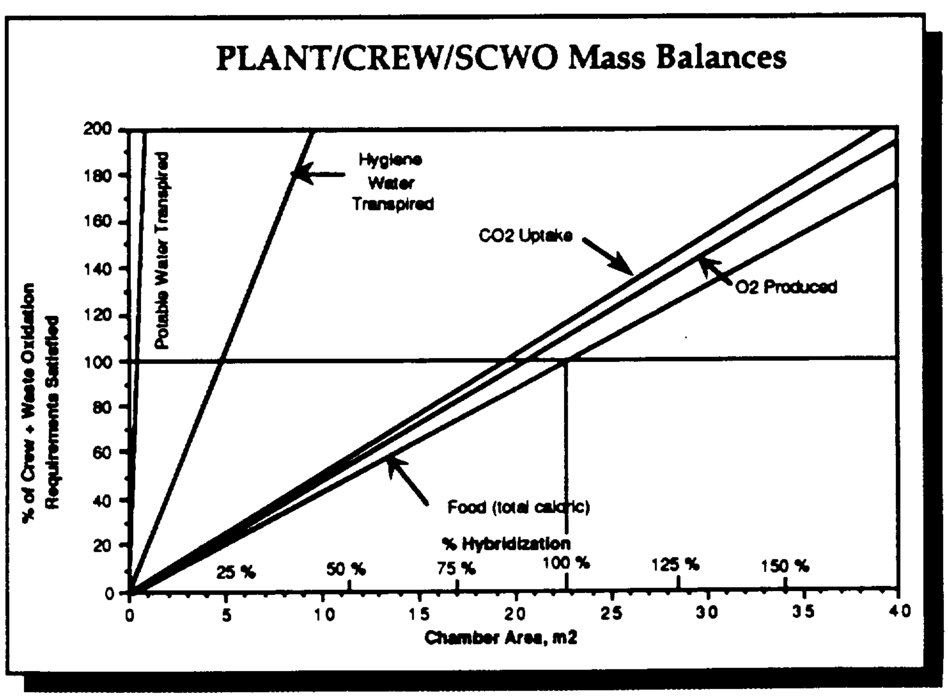

Figure 10. Plant/Crew/SCWO Mass Balances

With the introduction of a waste processor, an additional amount of CO_2 is produced via oxidation of human and plant waste as illustrated in figure. The otherwise constant O_2 requirement increases as a function of the waste processed. As illustrated in Figure 10, the addition of a waste processor improves the balance, but a purely P/C system is still required to provide balance.

Finally, the full-up P/C system is integrated with the plant chamber ,the crew, and the waste processor. It is a series combination of a 4 bed molecular sieve for CO2 concentration, a Sabatier for CO2 reduction, and a Static Feed Water Electrolyzer (SFWE) for O_2 generation. Figure 11 shows the oxygen balance required from the P/C system which graphically is the superposition of the O2 required by the crew, the O2 required by the waste processor, and the O2 produced by the plant growth chamber. Figure 12 shows the carbon dioxide balance required from the P/C system and is graphically represented by the superposition of the CO2 produced by the crew, the CO2 produced by the waste processor, and the CO2 consumed by the plants.

A pictorial representation of the four subsystems and processes which are involved in this hybrid ECLSS is shown in Figure 13. The crew requires food, water, and O2 while producing CO2 and waste. The waste processing consumes O2 and crew and plant waste and produces CO2, incineration waste, and water. The P/C system consumes CO2 and water as it produces O2, CH4, and some excess byproducts such as H2 or CO2. The beakers depict the O2 and CO2 collected/exchanged.

Figure 14 depicts the combined gas exchange needed from the P/C system. The system assumed will work for % hybrids from 0% up to 72.6%. At lower hybridization, there is not enough hydrogen produced in the electrolysis of water for oxygen, to react all the needed CO2 in the Sabatier unit. Therefore, some CO2 and methane is vented overboard. There is a point (around 72.6% hybridization) where gas exchange is exactly balanced and no venting is required. When the stoichiometrics of the process are different this value will change. For example, the Bosch or Advanced Carbon Reactor has a similar balance point around 31%. However, at slightly above that point, there is not enough CO2 for the Sabatier unit to react all the hydrogen being produced by the SFWE unit. Above a point (around 80.9 % hybridization), there is not enough carbon dioxide in the atmosphere to support the plants in the plant chamber. Above 87.6 % hybridization, the plant growth chamber produces more oxygen than is needed elsewhere in the system and the atmosphere becomes oxygen-rich.

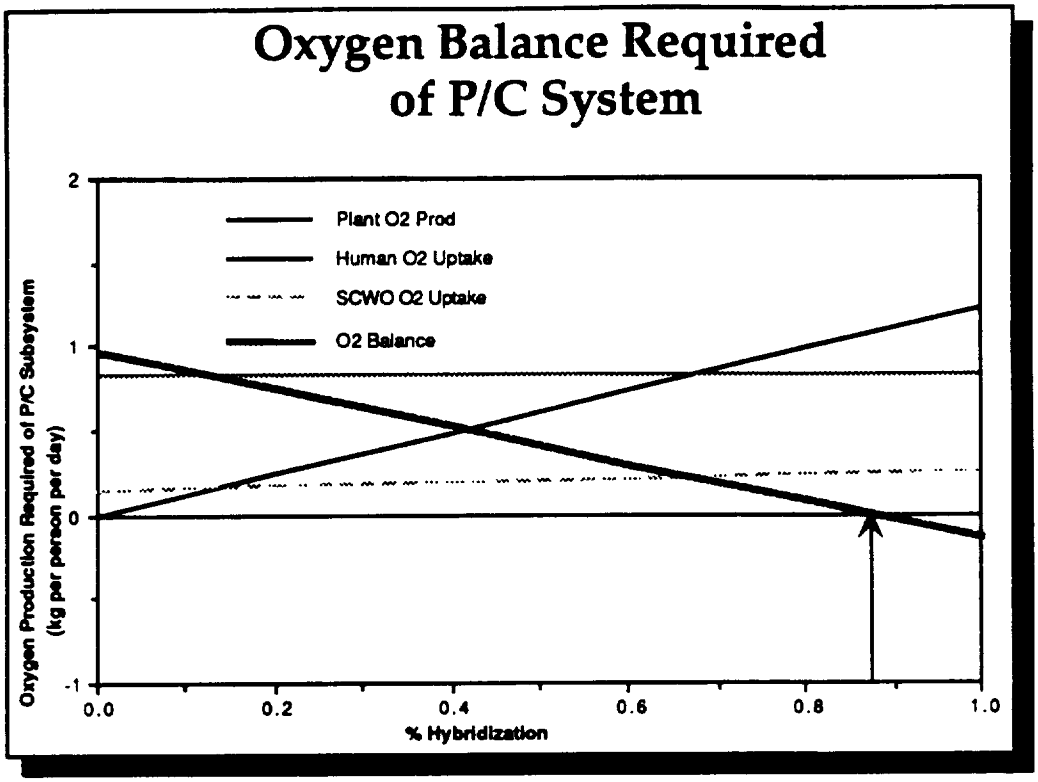

Figure 11. Oxygen Balance Required of P/C System

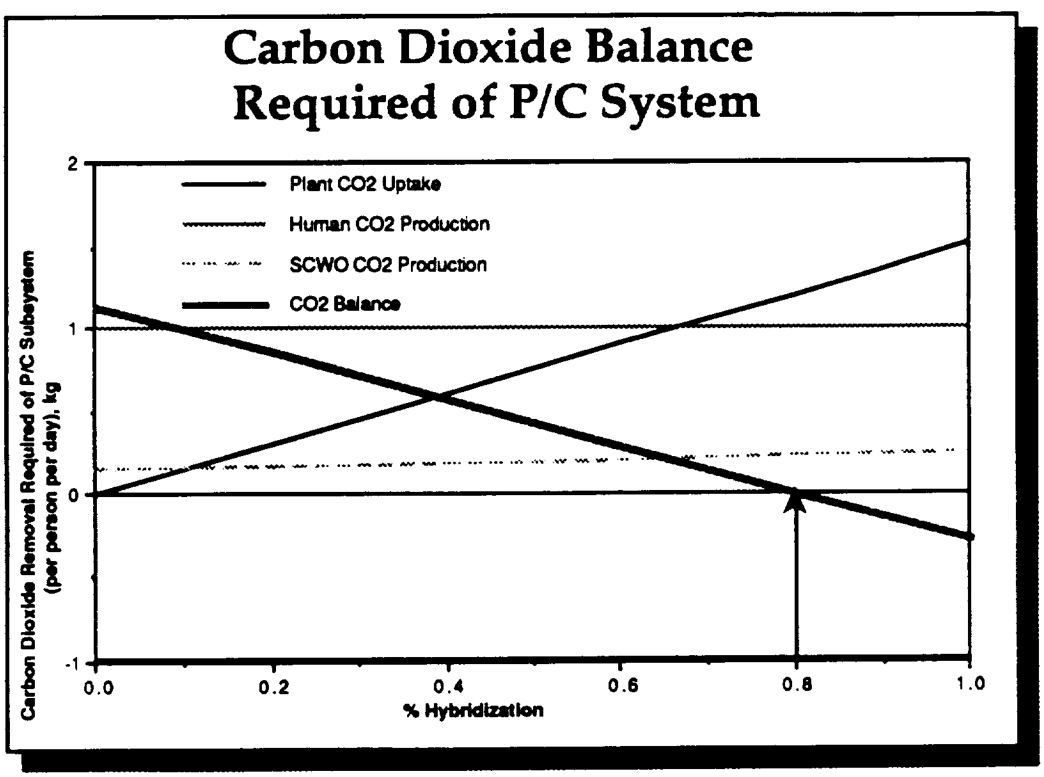

Figure 12 Carbon Dioxide Balance Required of P/C

BASIC PROCESSES MODELLED

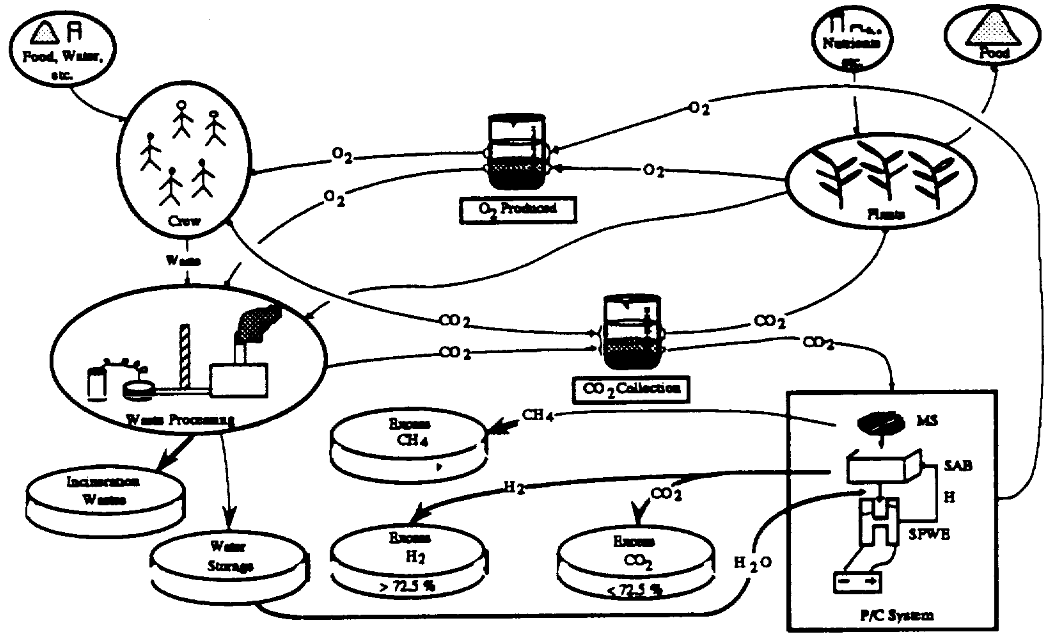

Figure 13. Basic Processes Modelled

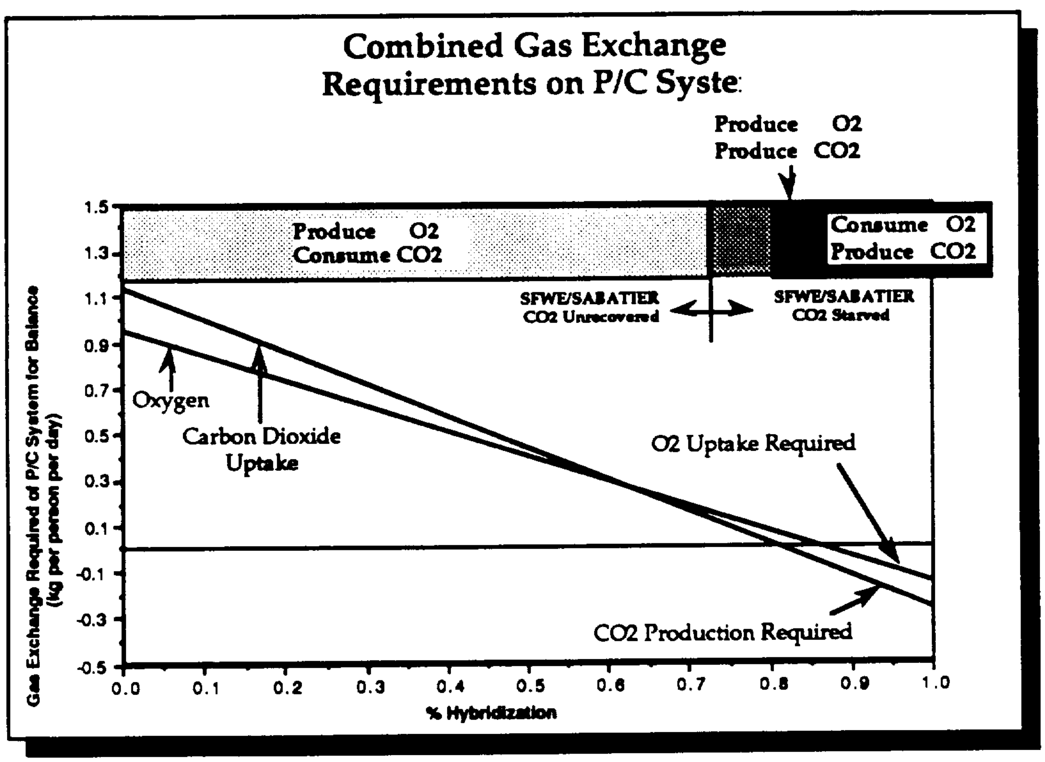

Figure 14 Combined Gas Exchange Requirements on P/C System

2.4 Advanced Instrumentation

In the area of Advanced Instrumentation, a two step process was followed during the first half of the study. An initial survey of requirements was performed drawing upon the functional definitions/missions of the systems needed and, wherever possible, the form of expected data characteristics. This survey was completed with an evaluation of the needs across-the-board and identification of high leverage sensor/monitoring needs. The second step involved a conceptual definition of some candidate sensor and control technologies which address the high leverage needs.

2.4.1 Sensor and Control Requirements

The first steps taken in deriving sensor requirements were to break the life support system into functional areas. These areas were: atmosphere management, water management, waste management, crop management, and data management. These functional areas are listed in Figure 15 along with the major components in each area. Much of the functions and monitoring requirements of these areas are similar to those of corresponding areas in a Physical/Chemical life support system. However, crop management is an area unique to a biological life support system and requires quite different monitoring and control parameters as will be discussed later in this report. Data management for a CELSS will also be similar to that for a P/C system. Both systems would benefit by using semi-autonomous data processing to remove some of the control responsibility from a central processor and place it on the specific subsystems. Although, central processing would still be needed to maintain global monitoring of the entire life support system.

- ATMOSPHERE MANAGEMENT
  - Gas Exchange / Recycle
  - HVAC
  - Trace Contaminant
- WATER MANAGEMENT
  - Potable / Hygeine
  - Nutrient Solution
- CROP MANAGEMENT
  - Lighting
  - Planting / Harvesting / Processing
  - Growth & Condition Monitoring
- DATA MANAGEMENT
  - Central Processing
  - Semi-Autonomous Processing
- WASTE MANAGEMENT
  - Biological Waste Processor
  - Incinerator
  - Nutrient Recovery

Figure 15. CELSS/Hybrid System Functions

Sensor needs for a gas exchange recycling system serving to interface the crew, plant chamber, and waste management streams were identified for CO2, O2, and N2 concentrations, temperature, pressure, and humidity, trace contaminant monitoring, and microbial monitoring as listed in Figure 16. The purpose of the gas recycling system is to control the transients in O2 and CO2 concentrations between the crew chamber and plant chamber. A schematic showing the flowstreams between crew and plant chambers using a gas recycling system is given in Figure 17. The gas recycling system controls the concentration transients by removing and storing a particular gas whose concentration is too high. The stored gas can be released at a later time to supplement a deficient flowstream. The CO2 removal can be accomplished by the same technology used in the four bed molecular sieves. The O2 removal can be performed in a similar method using beds of Salomine. The sensor needs for a gas recycling system are much the same as in a P/C system except for microbial monitoring.

- GAS EXCHANGE / RECYCLE
  - CO_2, O_2, N_2
  - Temperature, Pressure, Humidity
  - Trace Contaminants
  - Microbial / Monitoring
- PLANT CHAMBER HVAC
  - O_2, CO_2 Concentration
  - Temperature, Pressure, Humidity
  - Turbidity (Clarity)
  - Circulation Flow Rates
  - Trace Contaminants (Ethylene, Isoprene, H_2S)
  - Microbial Monitoring

Figure 16. Atmosphere Management - Sensor Requirements

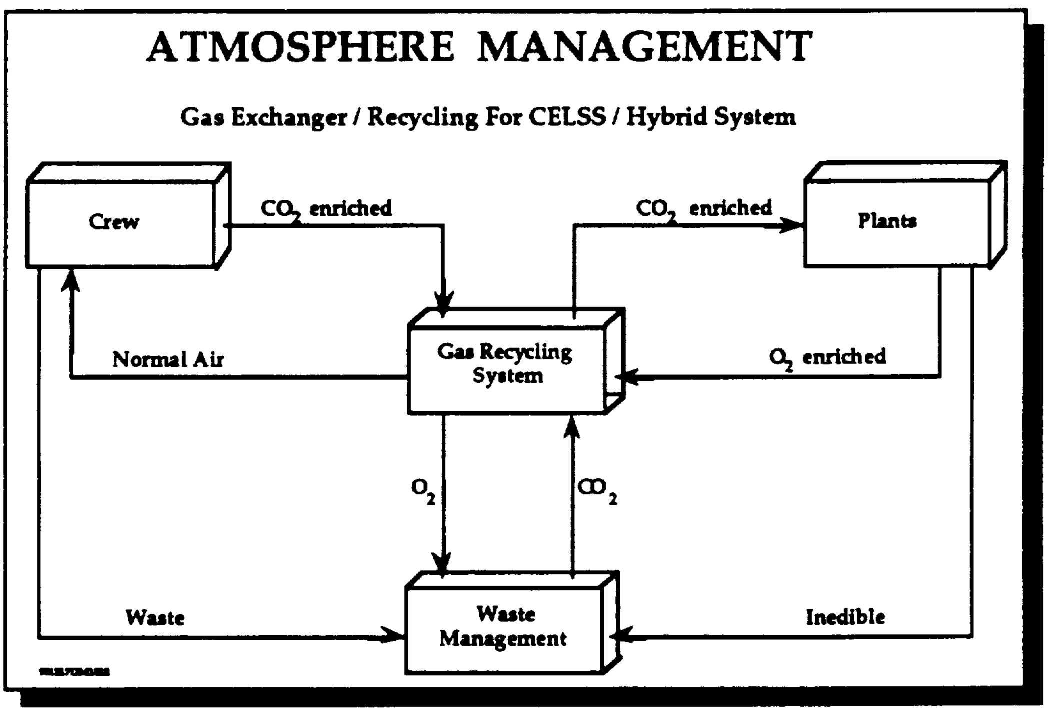

Figure 17. Atmosphere Management - Gas Exchanger/Recycling for CELSS/Hybrid System

Microbial monitoring could be considered a trace contaminant problem as in the current space station design. However, the design philosophy of the space station and all previous spacecraft, has been generally to maintain an aseptic environment through the generous application of biocides. However, when biological processors such as plants and, possibly, microbial waste treatment become residents of the system, it will become necessary to design for the maintenance of septic conditions in at least some areas of the system. The symbiotic relationship between many higher order plants and colonies of microbes living on roots and leaves is believed to be important to plant health and their removal to be an introduction of unacceptable risk. For this reason microbial monitoring is elevated to a level of its own importance in the list of sensor requirements.

Also, in the atmosphere management function is the HVAC for the plant chamber itself. Oxygen and carbon dioxide concentration measurements will be needed along with temperature, pressure, and humidity. Some measure of the clarity in the air may be needed to monitor the attenuation of photosynthetic radiation. Circulation flow rates to monitor sufficient mixing in the chamber may be needed. Trace contaminant monitoring will be needed. In this area, a few special contaminants of interest exist such as ethylene, isoprene, and H_2S. Microbial monitoring of the air within the chamber may be necessary as part of the strategy for monitoring and controlling the septic/aseptic zones of the habitat.

In the water management function, sensors are required in the potable/hygiene loops and the nutrient solution. Both will need the basic sensors for temperature, pressure, flow rates, liquid levels, dissolved oxygen and carbon dioxide concentrations, trace contaminants and microbial monitoring as listed in Figure 18. The concentrations of many of the basic nutrients in the nutrient solution will also be needed. At least,ammonium, nitrate, nitrogen, P, and S concentrations will be needed. Possibly , the list of the 16 major nutrients comprising a typical Hoaglund derivative solution recipe may be needed. A schematic showing the flowstreams in a CELSS water management system is given in Figure 19.

• POTABLE / HYGIENE	• NUTRIENT SOLUTION
- Temperature & Pressure	- Temperature & Pressure
- pH & Conductivity	- pH & Conductivity
- Dissolved O_2 & CO_2	- Dissolved O_2 & CO_2
- Trace Contaminants & Microbial Monitoring	- Flow Rates & Liquid Levels
- Flow Rates & Liquid Levels	- Trace Contaminants & Microbial Monitoring
	- Nutrient Concentrations (16 Basic)

Figure 18. Water Management - Sensor Requirements

A potentially intensive location for sensors will be in the waste management function, especially if biological waste processing is to be used. Figure 20 shows the components and flow paths for a biological waste recovery system concept /28,29,30/. A wide variety of sensor needs may exist from characteristic particle size monitoring in the effluent stream of a grinder for solid wastes to devices which measure Biological Oxygen Demand (BOD), an indicator of the treatability of the input waste stream to a biological process. If nutrients are to be recovered from the waste stream, sensors for determining constituent concentrations will be needed. Biological processes also involve living organisms and therefore have their own specific set of contaminant monitoring problems.

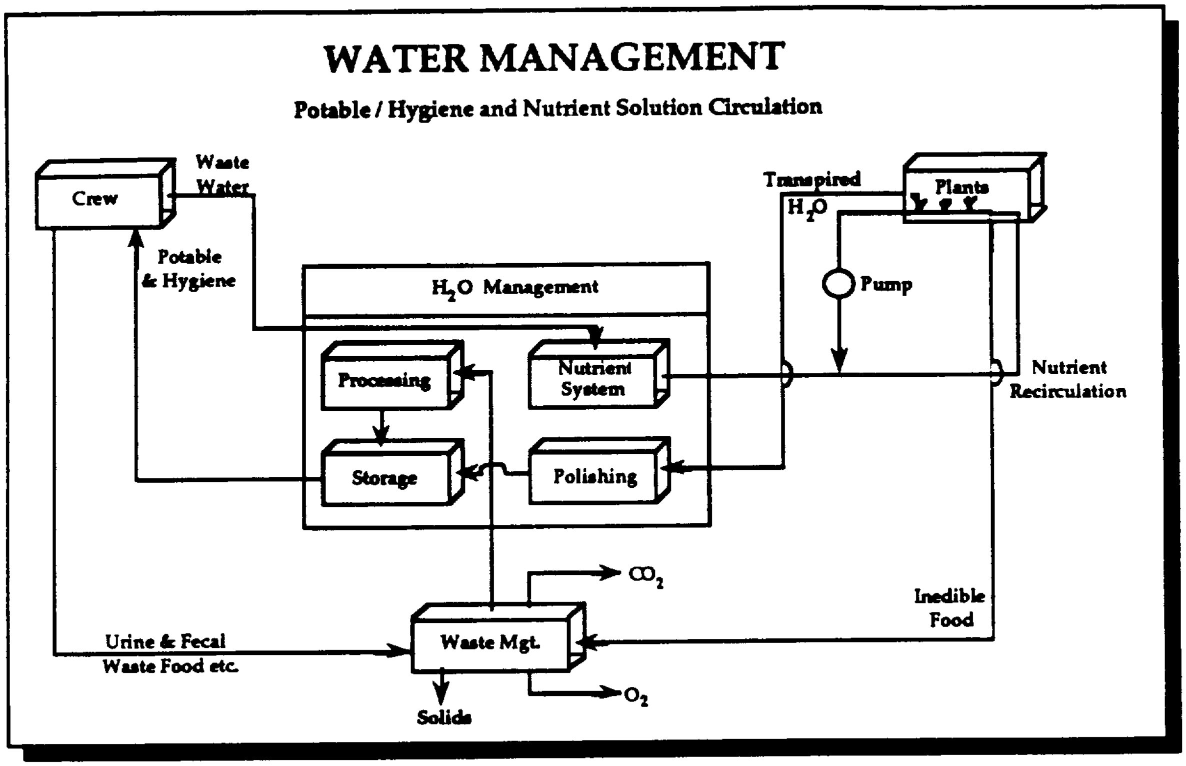

Figure 19. Water Management - Potable/Hygiene and Nutrient Solution Circulation

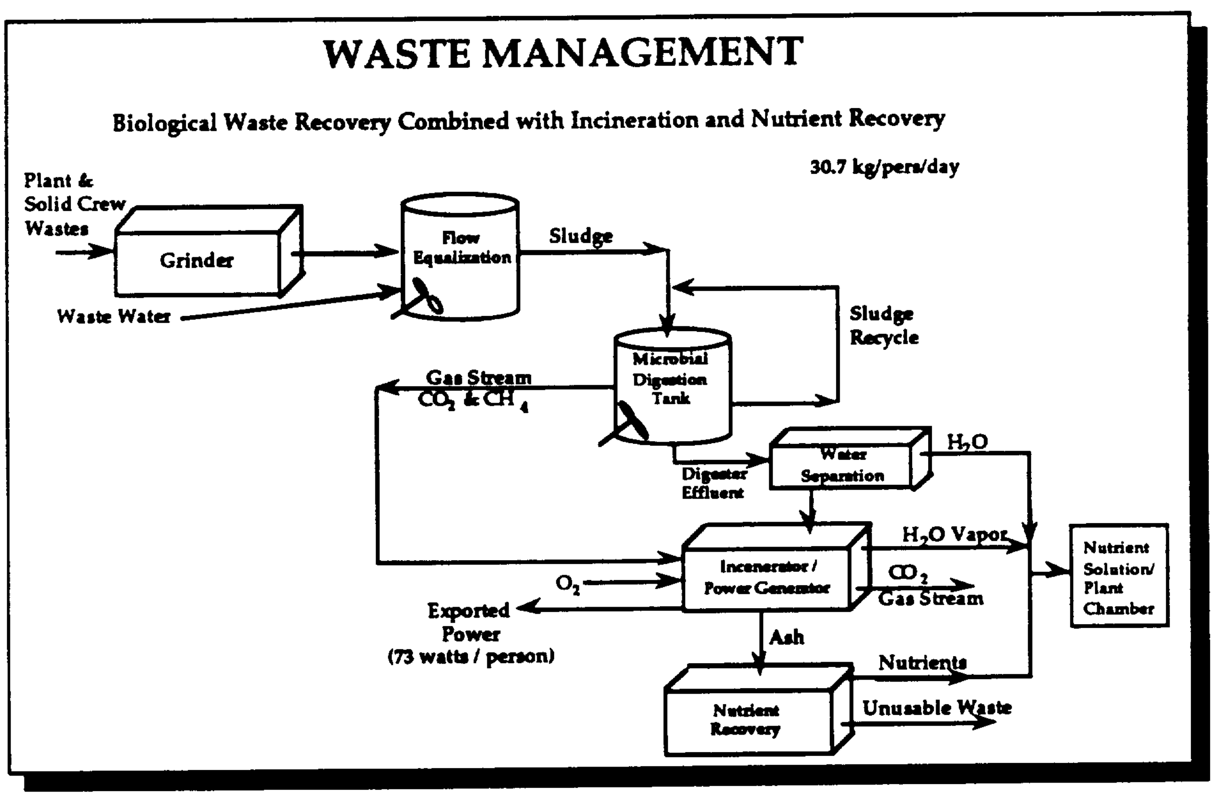

Figure 20. Waste Management - Biological Waste recovery Combined with Incineration and Nutrient Recovery

Figure 21 lists the sensor requirements for each component in a biological waste recovery system. Crop management will be a new area for space sensor technology. Three particular subfunctions are identified: lighting, planting/harvesting/processing, and growth & condition monitoring. The sensor requirements for each subfunction are listed in Figure 22. The on/off cycling is critical to both control of crop growth and minimizing power usage. Electromechanical aspects of the lamps requiring sensing will be on/off verification, power levels, and temperatures.

WASTE MANAGEMENT

BIOLOGICAL WASTE PROCESSOR SENSOR REQUIREMENTS

- GRINDER
  - Mass Flow Rate
  - Pressure (Sealed System)
  - Particle Size
  - Power
  - Microbial Monitoring
- FLOW EQUALIZATION TANK
  - Liquid Concentration
  - Temperature and Pressure
  - Total Solids
  - Microbial Monitoring
- MICROBIAL DIGESTION TANK
  - Temperature and Pressure
  - Liquid Concentration
  - Microbial Monitoring
  - pH and Conductivity
  - Biologcal Oxygen Demand (not needed for anaerobic digestion)
  - O_2 and CH_4 Concentrations
- INCINERATOR
  - Temperature and Pressure
  - H_2O Concentration
  - Flow Rate
  - Trace Contaminants (H_2S, SO_2, NH_4, etc.)
- GAS STREAM EXITING INCINERATOR
  - Temperature, Pressure, and Humidity
  - Flow Rate
  - O_2, CO_2, CH_4 Concentrations
  - Trace Contaminants (H_2S, SO_2, NH_4, etc.)
- PROCESS H_2O STREAMS
  - Turbidity
  - Conductivity and pH
  - Trace Contaminants
  - Microbial Monitoring
  - Nutrient Content (Ion detectors)
- CONCENTRATED SLUDGE STREAM
  - Total Solids
  - Moisture Content
  - Flow Rate
  - Nutrient Content
  - Trace Contaminanats
  - Microbial Monitoring
- NUTRIENT RECOVERY
  - Total Solids
  - Microbial Monitoring
  - Nutrient Concentrations
  - Trace Contaminants

Figure 21. Waste Management - Biological Waste Processor Sensor Requirements

- LIGHTING
  - On / Off Cycles
  - Power & Temperature
  - Photosynthetic Photon Flux (Intensity & wave length)
  - Radiation
- GROWTH & CONDITION MONITORING
  - Plant Surface Temperature
  - Plant Sizing
  - Plant Stress
- PLANTING / HARVESTING / PROCESSING
  - Machine Vision / Processing
  - Ripeness
  - Particles Size
  - Volume & Mass Measuring
  - Moisture Content
  - TCM & Microbial Monitoring
  - Protien & Carbohydrate Content
  - Vitamin & Mineral Content

Figure 22. Crop Management - Sensor Requirements

The critical measurement may be the Photosynthetic Photon Flux produced by the lamp. If external/alternate sources of radiation are used for growth, radiation monitoring may be required. For the quasi-steady state monitoring of crop growth and condition several types of sensors may be needed. A technique to measure plant surface temperature would be useful for plant health but may be necessary for fire prevention/control. To achieve a high degree of automation, it may be worthwhile to incorporate a device which measures the size of the plant in order to monitor its growth stage and accurately predict an optimum harvesting time. Also, research is being performed on deriving a quantitative measure of plant health called plant stress. For example, it has been demonstrated that the existence of nitrogen starvation in higher plants is indicated when veins in the stems and leaves turn red in color. A sensor to identify and quantify these types of indicators would be useful.

The labor intensive jobs of planting, harvesting, and processing the harvest yield are candidates for automation. They also require a significant amount of assessment and decision making. Ripeness sensors for determining when to harvest will be a needed. Food production is the process being accomplished by the plant chamber. The output streams include various edible and inedible plant parts. Discrimination and separation of the two streams will be needed. Several measurements are needed to monitor the quality and quantity of the process products. For the edible stream, it will be necessary to control the production of proteins, carbohydrates, fats/oils, fiber, vitamin, and mineral contents in order to maintain good nutrition for the crew.

As the operations of these functional subsystems become more defined and understood some reduction in sensor instrumentation may be possible through the use of inference. By inferring the parameter value, the monitoring instrument would be redundant and could be eliminated. This would reduce the number of instruments needed and sampling time. However, this inference technique would not be used to determine the value of critical parameters that are crucial to crew safety, plant health, or life support system operation.

2.4.2 Sensor Innovations

Two high leverage potential technologies for sensor developments were presented, the Ion Detector Array (IDA) and a neural network-based Microorganism Sensor. The IDA is a bank of specific solid state and membrane electrodes integrated with logic circuitry to filter out the effects of interference ions. It can be used in continuous on-line applications, reducing GC/MS use, with little or no reagent waste. The neural network based sensor essentially uses complex pattern recognition techniques and emerging AI processing technology to automate a process of viewing, identifying, and counting microorganisms which is currently done by humans in a microbiology laboratory. Applications of advanced computing techniques to the overall CELSS control and monitoring was also presented.

The Ion Detector Array concept utilizes ion selective electrode technology which is commercially available. Most of these electrodes measure specific ion concentrations by detecting an electrical potential across a membrane or a change in conductivity across a semi-conductor. The measurements of many of these electrodes are hindered by the presence of different ions. For example, the electrode used to detect and measure potassium ions (K+) is hampered by the presence of ammonium (NH4+). In the ion detector array, another ion selective electrode for the detection of ammonium would be used to measure the NH4+ concentration. Using the NH4+ concentration information, the effects on the potassium ion detector caused by the ammonium ions could be calculated. Thus, the true concentration of potassium ions could be determined. The calculation of interferences could be performed by control logic circuitry contained in the ion detector array. Multiple electrodes could be placed in the array and integrated into the control circuitry allowing the ion detector array to detect and measure the concentration several different ions. By knowing the ion concentration, the total concentration of the element in solution can be determined by using the equilibrium constant. The benefits of this concept would be its on-line real-time monitoring with only a minimum of reagent waste for calibration. Its use could reduce the testing load on a GC/MS or other trace contaminant monitoring devises.

2.4.2.1 Concept for a Neural Network-Based Microorganism Sensor

In proceeding toward a closed environment life-support system, several difficulties arise n the control of the biological processes of the system. These difficulties include balancing element/compound production and consumption, overcoming long control lag times due to the dependence on biological growth and slow mixing rates, and determining the actual state of the system from limited process measurements. When determining the state of a biological system, some physicochemical parameters can be measured on-line, but may provide a poor indication of actual biological activity. More direct measurements of the biological population of a process stream can be taken, but usually involve off-line analysis and additional reagents. In order to provide an improved biological system monitoring capability to address the limitations of existing measurements methods, and on-line sensor must be developed which provide a direct observation of biological activity without contaminating the sample stream. A concept for utilizing a neural network in coordination with post-processing software (e.g., analytical, knowledge-based and/or model-based techniques) is proposed as an improved sensor system offering this capability.

Solution Approach

The first requirement for achieving closed-loop control of biological systems is continuous, on-line monitoring of process parameters. On-line sensing of various physicochemical parameters such as pH and total oxygen demand (TOD) is currently performed on many biological processes. These parameters can provide an indication of the activity or health of a microorganism population, but are poor at indicating the nature or composition of that population. One primary method for studying the composition of a population is to physically view a sample under a microscope, and manually log the number of various microorganisms observed. The presence or absence of various species provide an excellent indication of the status or health of the overall population. However, the process of physically counting microorganisms is time consuming, usually conducted remotely from the process, and occurs relatively infrequently. Remote analysis of samples can allow the quality of the sample to degrade, which, at best, reduces confidence in the results, and, at worst, can lead to inaccurate test results. The lack of frequent or continuous in-situ monitoring will allow problems to be detected early, limiting the degradation of system performance.

The identification and indexing of microorganisms seen under a microscope, based on a template of typical microorganisms, is essentially a pattern matching exercise based on discriminating features of each type of organism. Excellent pattern matching capabilities have been demonstrated by a computational technology known as neural networks/1,2,3/. By training a neural network to identify the microorganisms of interest, an on-line health monitoring sensor can be developed. This sensor will periodically draw a side stream from the process line. This sample will then be fed through an on-line microscope lens connected to a specialized light sensor/camera which feeds pictures to the neural network. The neural network then identifies the microorganisms in the frame. Information is catalogued by a post-processor to the neural network and a status report is generated for each sample. The review of the status report can also be automated by processing the output of the neural network through a knowledge-based system designed to assess the health report, adjust the process, and/or notify the crew of anomalies. Figure 23 presents the general layout of such a system.

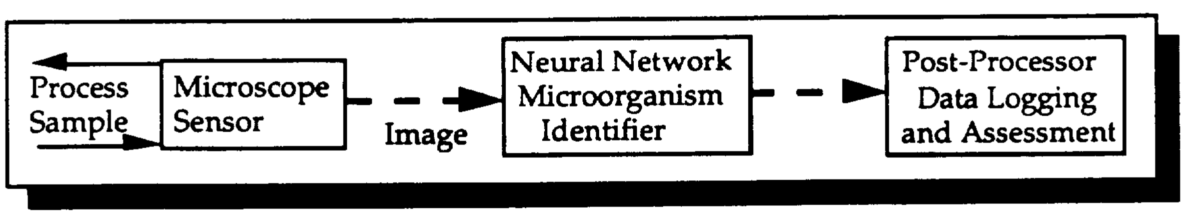

Figure 23. General Structure of Neural Network Microorganism Sensor

System Description

The proposed sensor will consist of a intermittent sampler, a microscope, a light sensor, a neural network, and a post-processor. The intermittent sampler will draw a side stream from the process and pump it through a thin, flat plate located in the microscope, providing snapshots or "frames" of the process sample. The microscope is fitted with an optical sensor containing the same element grid size as the neural network input array (see Figure 24). The neural network is "trained" to identify distinct microorganisms by placing known patterns in the input array and specifying the desired output pattern for that particular species. The neural network then adjusts its input parameters to force the desired output to be produced by the given input. A post-processor is connected to the output of the neural network to manage the resulting data. The post-processor is responsible for maintaining the counts and ratios of the various species identified over a particular interval.

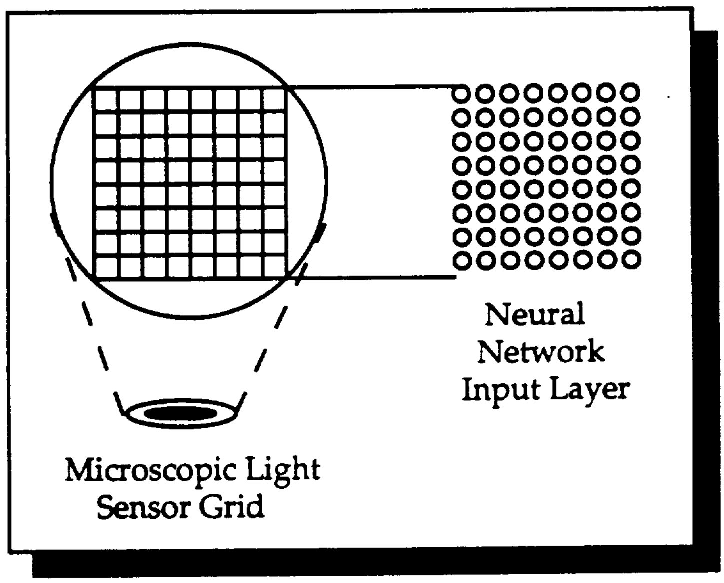

Figure 24. Sensor Grid to Neural Network Relationship

Benefits

A developed microorganism sensor can be applied to a variety of monitor points throughout a Controlled Ecological Life Support System (CELSS) (see Figure 25). The neural network can be trained to identify the primary microorganisms of interest at each monitor point, as well as be trained to identify new microorganisms, thus supporting changes from system growth. Other benefits of the microorganism sensor are reduced crew time and resupply mass requirements. Crew time is reduced since samples do not have to be taken or analyzed manually; resupply mass is reduced since no reagents are required to perform the analysis. Due to the reliance on reagents, most laboratory analysis techniques result in sample waste which must be re-introduced into the CELSS, possibly causing system imbalance or corruption of future tests. The direct observation approach of the neural network-based sensor alleviates the sample waste problem since no foreign substances are introduced into the sample stream.

Research and Development Approach

The development of an on-line microorganism sensor will require several stages of research. These stages include: 1) Developing and Demonstrating computing technologies required to identify microorganisms given two dimensional grid patterns, 2) Developing and demonstrating an on-line microscope and associated sampling system, 3) Constructing an optical sensor which will bridge the microscope and the neural network, and 4) Production of associated post-processing software to analyze the output of the neural network microorganism identification system.

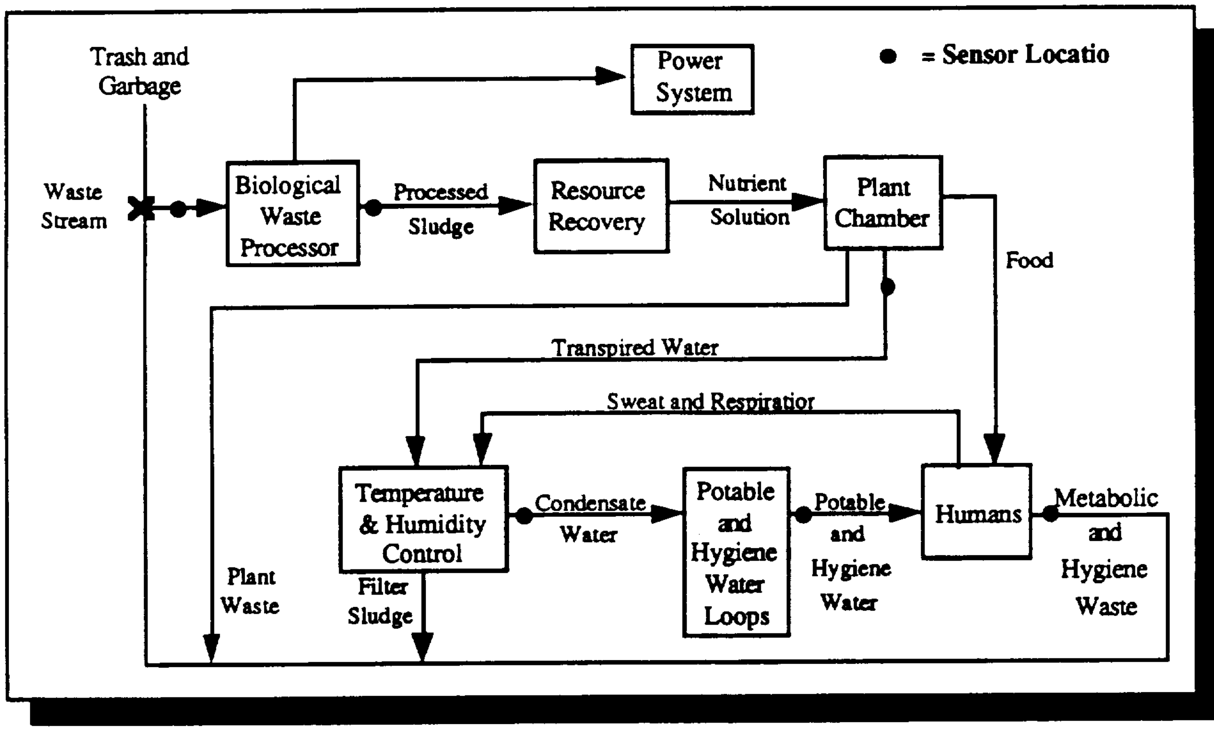

Figure 25. Applicability of an On-Line Microorganism Sensor in a CELSS

An initial major milestone would be the demonstration of the ability to train a neural network to identify a small subset of pertinent microorganisms. This first research phase should focus on pattern recognition technologies. Neural network research has produced a set of software networks and training algorithms which can be used for the initial microorganism recognition demonstration Fast Fourier Transform (FFT) algorithms have been incorporated into neural network software to address translational and rotational variance in input patterns. The research required to demonstrate the feasibility of neural network technology applied to microorganism identification could probably be performed over a period of six months utilizing two persons full time.

2.4.2.2 Concept for Applying Intelligent Computing Technologies to CELSS Control

The control of a closed life support system presents several major challenges. Several of the problems with controlling systems involving biological processes have already been discussed. In order to address some of these issues, NASA has recognized the need for "computer-compatible monitoring systems... for real-time analysis of trace quantities of organic, inorganic, and biological components" /4/. The need for predicting problems based on the results of the real-time analysis has also been identified /4/. Several elements of the area of computer science termed "Artificial Intelligence (AI)" can be applied to these problems. The two areas presented are neural networks for pattern recognition and knowledge-based systems for analysis and prediction.

Solution Approach

Two types of control system development strategies have been proposed /5/. The first requires human management of the various processes within the ecological system, known as exogenous control. The second type, endogenous, utilizes only the inherent control mechanisms of the biological processes within the system. Exogenous control relies on monitoring the gaseous, liquid and solid components of the various processes within the system, and introducing needed, or expelling excess, elements in order to maintain a stable environment. Added and expelled substances violate the goal, of obtaining a closed-loop system and are known as "cheating vectors." Initially, for the exogenous control system, humans will monitor the health and status of the CELSS via physicochemical attributes. This requires the use of mass spectrometer and gas chromatograph fingerprints. The process of identifying healthy fingerprints and subsequent system monitoring can be supported directly by knowledge-based and neural network techniques. Neural networks can be trained to identify healthy patterns, and a knowledge-based system can support the neural network pattern matching by analyzing patterns representing unhealthy systems. Thacker and Mayhew describe a neural network which modifies its own structure to identify and classify new patterns /6/. The knowledge-based system can be developed to identify possible causes of the unhealthy systems and suggest corrective actions. The eventual goal of exogenous control is to minimize the degree of human control required and to minimize the disturbance of the system by monitoring techniques. The computer based mechanisms presented will allow iterative development toward each of these goals and will allow the effect of removing "cheating vectors" to be studied and implemented within the control scheme.

System Description

The pattern classification capabilities of neural networks can provide real-time automated analysis of gas chromatograph (GC) and mass spectrometer (MS) fingerprints to discriminate healthy and unhealthy system conditions. The neural network is trained by using known fingerprints as inputs and specifying as outputs the health of the system associated with those fingerprints. During operation, the neural network will produce the output health status pattern which most nearly matches the input fingerprints, based on its previous training.

Neural Network output results can be further analyzed by a knowledge-based system to provide diagnostics and control response. When an unhealthy condition is identified by the neural network, the knowledge-based system can request additional tests from the crew, retrieve supporting data from other on-line sensor systems, and inspect the strength and type of the neural network output pattern in order to determine the source of the problem and the remediation procedure required. If the process correction can be performed on-line, then appropriate control commands are issued; otherwise, the crew is notified of the problem and its most likely cause, along with the suggested correction procedure.

Benefits

The use of a combination of neural network and knowledge-based technology can result in significantly improved control of the ecological system. By training the neural network to assess GC and MS results, the analysis time required of the crew is reduced. Utilizing a knowledge-based system to automatically examine the neural network analysis results, to compare the results to other analysis, and to decide what responses, if any, are required to further free the crew's time for other tasks. By designing the knowledge-based evaluation to include a model of the overall system to develop macro-level relationships, the required number of sensors can be reduced to the minimum required to fully define the system. Continued growth of the system is also supported by retraining the neural network to recognize new composition patterns or even using the neural network to identify new patterns /6/. The structure of knowledge-based systems also provides relatively easy expansion since the knowledge about system design or operation can be modified without requiring any modification to the knowledge processing software (i.e. inference engine).

2.5 SSF Growth Trades

Some space station growth trades were performed during the first half of the study. They are documented in Interim Technical Report SRS/STG-TN91-03 . Since no actions or questions concerning them arose at the mid-term, that information is not repeated here.

2.6 Computer Tools

To date, four electronic spreadsheet models have been developed. Three of them (PLTGRO, PG-PWV, and % CELSS) host the parametric algorithms for sizing life support systems. The other spreadsheet, MOLSIEV, calculates the carbon dioxide removal rate for a given concentration in the cabin atmosphere. To document and describe the operation of these models, a set of flow charts for them was developed and documented in appendices to the December, 1990 progress report. These charts describe the relationships between inputs and calculations internal to the spreadsheets and the passing of calculated values between spreadsheets. CASE/A modelling activities were also reviewed briefly in the mid-term review.

3.0 RESPONSE TO QUESTIONS/ACTION ITEMS

The presentation of the material in the previous sections of the Mid-Term Review elicited a number of questions and requests for clarifications. Many of the requests for clarifications have been accomplished in the narrative discussions provided in the preceding sections. The following paragraphs contain the response to those action items needing additional research and evaluations. Section 3.1 addresses issues related to ECLS Evolution and Section 3.2 responds to Advanced Instrumentation topics.

3.1 Mass Payback Implications

Trades addressing CELSS and physical/chemical systems have been conducted to determine at what time in the mission the CELSS system gains the advantage based on cumulative system mass on orbit. These trades typically known as breakeven analyses, are subject to a broad range of assumptions and estimates that can significantly affect the results. These assumptions and estimates are necessary because the life support technology is still in the early stages of development of closed ecology life support systems (CELSS). Addressing all parameters, selecting a reasonable range of variations, and determining the sensitivity of the trades to these variations, is beyond the scope of this investigation. The sensitivity of these trades to resupply estimates, power penalties, and leakage assumptions was investigated. There are many other factors such as crop yield, redundancy philosophy, and transient operation that will influence estimates of breakeven times.

The addition of a plant chamber implies that the additional volume and the resulting leakage must be considered. We are particularly interested in the impact on the breakeven time. It is assumed that the leakage may be attributed to the additional structure to house the plant chamber. However, this may not be exactly the case depending on the excess food and metabolic water available. The available metabolic water will be electrolyzed to provide make up oxygen in scenarios where food containing water is resupplied. The leakage was assumed to be 0.5 lbs/day/element. When the CELSS plant chamber volume requirement exceeded the volume of a space station module, it was assumed that another element was needed. The resupply food mass used in this analysis is as follows:

Solid	0.616
Water Content	1.7666
Package	0.453
TOTAL	2.2196 Kg/person-day

The nitrogen leakage make up was provided via supercritical cryogenic storage.

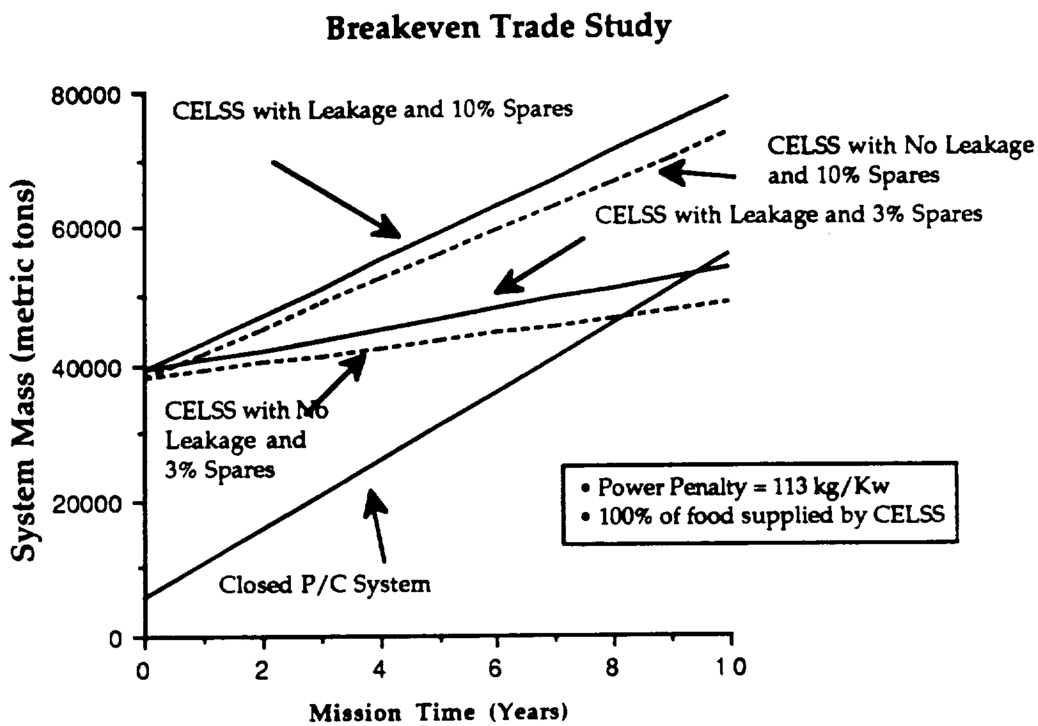

Figure 26. Breakeven Trade Study

Results of these investigations are shown in Figure 26. The breakeven times for different sparing and leakage scenarios are shown. There is an extremely wide variation in breakeven times. Assuming no leakage and 3% spares (a highly optimistic case) the breakeven time is about eight years. This compares with about 7.5 years estimated by Boeing, for a crew of four in low Earth orbit /7/. Mason gives a range of 7.7 to 12.4 years /13/. The worst case scenario shown in Figure 26 is leakage and 10% spares. The breakeven time for this case is about 31 years. A variation of resupply weights for the P/C system was not done because the resupply estimates for this system were taken from Space Station values which are much more defined than those for CELSS. The CELSS values were estimated by taking a percentage of the estimated weight of equipment, such as ventilation, coolant loops, lamps, etc. that will require maintenance. This excludes structural and radiator weights. The leakage penalty is small (slightly more than one year) compared to the effects of spares resupply.

The effect of power penalty (PP) is shown in Figure 27. Power penalty ranges from 28 to 113 kg/kw and produce breakeven times from 8 to about 9.5 years. A hybrid system that provides 50% of the food from wheat, and relies on resupply for the other 50%, was investigated and compared with a 100% bioregenerative system (i..e, CELSS) and a closed P/C system. Typical results are shown in Figure 28. In this optimistic scenario the plants provided complete water reclamation. No P/C systems, not even polishing filters, are used for water recovery or purification. The 50% system has a breakeven time of about 5 years when compared with the P/C system and breaks even with the CELSS in about 17 years. Obviously, increasing the spares resupply will significantly increase these breakeven times.

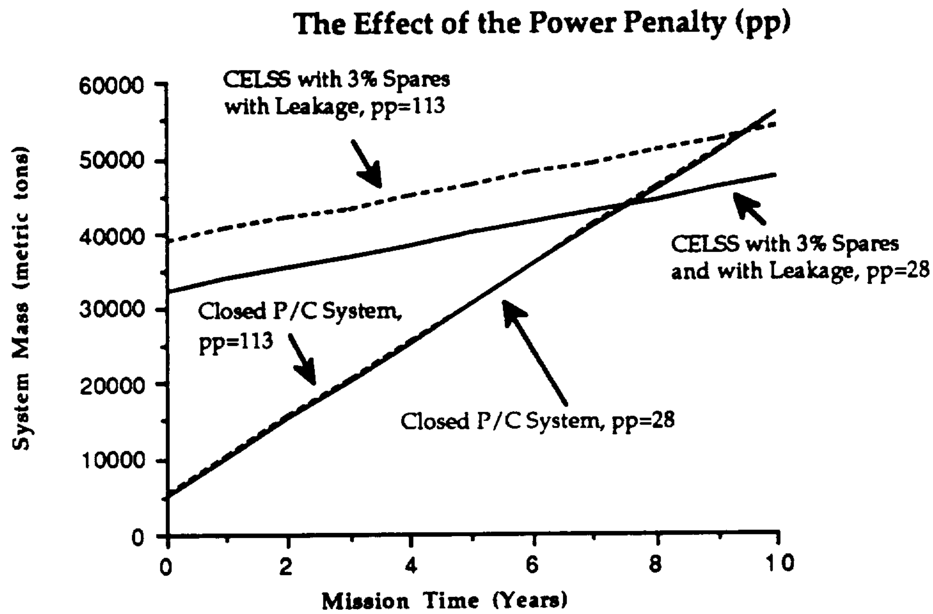

Figure 27. The Effect of Power Penalty

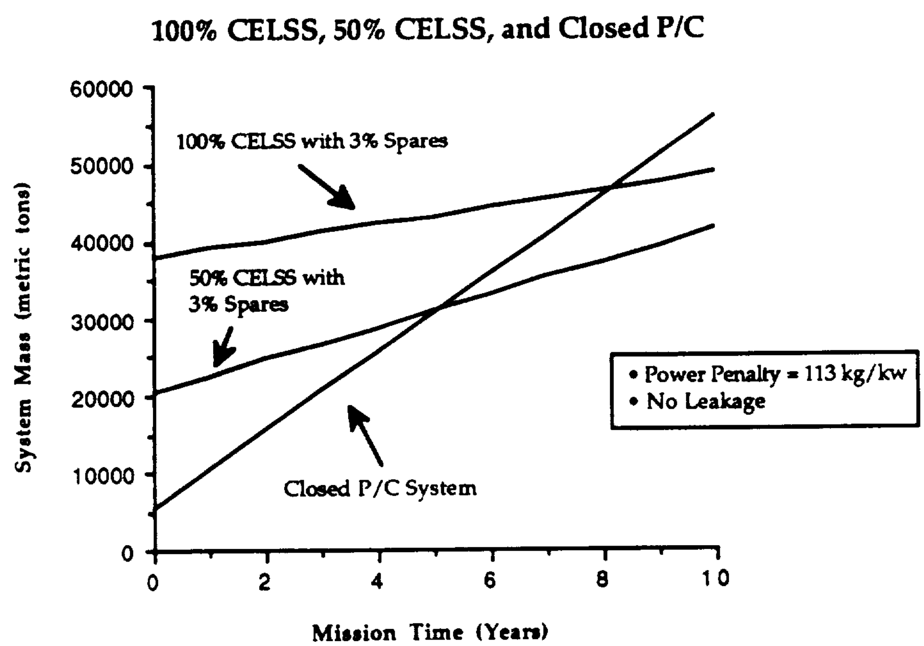

Figure 28 . 100% CELSS, 50% CELSS, and Closed P/C

Even though the 50% hybrid provides an earlier breakeven time with the P/C system, than the CELSS (based on a mass comparison), it may not be the best choice from a cost standpoint. For example, the 50% scenario should require about the same level of research and development as the CELSS.

Further analyses are needed to investigate the sensitivity of other significant variables such as crop growth rates, harvest yields, alternate means of providing photosynthesis energy (solar vs. electrical), redundancy issues, transient requirements, etc. Cost trades are needed to understand the cost/benefits of increased reliance on CELSS to provide the crew habitat functions.

3.2 Advanced Instrumentation

The sensor data base which has been developed using Foxbase+ has been installed and is operational at SRS on a Macintosh computer. The data is currently being reviewed for completeness. SRS will update the data base by providing available information on the sensors in the data base that are presently shown to have incomplete data. References for updated information will also be provided in the appropriate location in the data base. References found for existing information in the data base that do not have a listed reference will be provided.

Through identification of the parameters that require monitoring for the functional subsystems of a CELSS, the appropriate sensor instrumentation can be determined. Because the majority of the subsystems in a biological life support system would operate at moderate temperatures and pressures and most of the process streams would be carrying materials that are not expected to be extraordinarily corrosive, current state-of-the-art instrument technology should be acceptable for most of the monitoring requirements. Many of the monitoring parameters identified are analogous to parameters in a Physical/Chemical life support system. Therefore, needs of the technology developed for the P/C instrumentation would be directly applicable to a CELSS or hybrid system. However, some parameters such as nutrient solution and microbial monitoring in a CELSS would require time and labor intensive operations using current technology. Initial indications are that these two areas in CELSS monitoring and control operations could benefit most from innovative instruments that reduce crew labor and sampling time.

4.0 REVISED RESULTS/CONCLUSIONS

Figure 29 summarizes the conclusions drawn from the first phase of this effort on the topic of life support technology evolution. Figure 31 summarizes the conclusions on instrumentation, sensors, and monitor needs to support SEI advanced Programs.

4.1 P/C -> Hybrid -> CELSS Evolution

The study of the achieving gas exchange balance in a system containing humans and higher plants through the action of P/C technologies revealed the existence of a number of constraints of importance on the kind of P/C technologies needed and degree of hybridization to incorporate in a lunar base design. The approach wherein the lunar base life support system evolves in a continuous process from predominantly physicochemical AR processes to predominantly bioregenerative processes may not be viable. This results because the basic character of the P/C processes needed to balance a human dominated system is significantly different than for a system dominated by the plant chamber. In fact, there are at least four different conditions. For purposes of this discussion they will be called regions and are summarized below.

Region I:	<20 %	Full complement of P/C systems needed for balance - plant analogous processes.
Region I:	20-70 %	No P/C WRM needed - plant analogous processes.
Region I:	70-85 %	Carbon dioxide production rather than removal/reduction needed from P/C.
Region I:	>85 %	Oxygen consumption rather than production needed from P/C - human analogous processes.

In the first region, which relates to systems in which only a small sized plant chamber exists, the plants do not have the capability to completely perform any of the life support functions of oxygen generation, carbon dioxide removal, water recovery, or food production. Therefore, a full complement of physicochemical systems will be needed to achieve overall life support system stability. The plant chamber will only serve to relieve some of the load on the hardware. In this region less than 20% of the food needs are provided. For this system, the humans dominate the gas exchange. Oxidation of plant and human wastes consumes oxygen and produces carbon dioxide, but contributes insignificantly to the balance in proportion to the plants and humans. There is a net lack of oxygen and excess of carbon dioxide for which AR equipment must compensate. The solution could be a typical space station-type SFWE, 4BMS, and Sabatier unit. Note that since this combination of equipment has the net effect of producing oxygen and consuming carbon dioxide, it has respiratory characteristics analogous to those of a higher plant.

Above 20% hybridization, the plant chamber is large enough to recover the daily potable and hygiene water needs of the crew. But up around 70%, P/C hardware for air revitalization and supplementary food from other sources will be needed. At the lower end of this second region, the Sabatier unit is having to dump to space a portion of the carbon dioxide removed by the 4BMS unit because there will be an insufficient supply of hydrogen from the SFWE production of oxygen to feed the Sabatier reaction. This assumes that the system would be designed to match oxygen production needs. Alternatively it could be operated to match carbon dioxide removal needs. In which case, there would be an excess of oxygen produced. At the top end of the second region, there is a point where the plant chamber, no relatively larger in size is performing just enough of the carbon dioxide removal job so that the amount left for the Sabatier removed is exactly the amount possible from the hydrogen supplies it gets. This should occur around 70% for a process with the stoichiometrics of the Sabatier and most higher plants and represents a candidate point of optimality to keep in mind in designing the system. Rather than slowly stepping up the % hybridization evolutionary path a few percent at a time, it would be more reasonable to evolve in a few large steps. If the stoichiometrics of the recovery process are improved to that available by Bosch (or an upgrade of the Sabatier to an Advanced Carbon Reactor), then the carbon dioxide balance point is much lower (around 35 % hybridization). At either of these points, three of the four major process streams (oxygen, carbon dioxide, and water) are balanced. Only food production will require supplementation.

It is quite possible that it will not be beneficial to evolve beyond these two points for some time. One of the problems that must first be overcome is development of a nutritionally complete and balanced diet of operationally efficient higher plants and acceptance of the diet by the crew. Some significant supplementation of the food supply in the form of meat and dairy products may be desirable. But the major reason that evolution to the next higher hybridization may be delayed is because the processes required of the P/C to balance a plant-dominated environment are very much different than previously required.

Above 70 % hybridization, the carbon dioxide exhaled by the humans is insufficient to support the respiratory needs of the plant chamber. In order to achieve balance, the P/C system must now produce carbon dioxide rather than removal and recovery. The 4BMS and Sabatier units previously placed in the system are useless except maybe as a back-up for crop failure contingencies or as controlling elements. Up until around 85%, the P/C system needs to be able to produce both oxygen and carbon dioxide. An SFWE could still resolve the oxygen generation, but the hydrogen byproduct is no longer needed. A simple combustion-type process could produce the needed carbon dioxide, but a source of carbon is needed and the oxygen production demand is increased.

Around 85% hybridization marks the transition to the last region. The plant chamber is large enough here to provide most, if not all, of the nutritional needs of the crew and the plants have thoroughly overpowered the human population in every aspect except food production/consumption.

The plant chamber produces and excess of oxygen and requires more carbon dioxide than is available from the summary of human respiration and the oxidation of human and plant wastes. The P/C system required to achieve balance now must make reactions move in the opposite direction from any life support system ever designed for space. The very highly hybridized system includes an AR unit that emulates the human process rather than the plant, i.e., it consumes oxygen and produces carbon dioxide. Many of the lunar base mission concepts developed over the past ten years have included an in-situ processing activity at the base. One of the most common products is oxygen derived from lunar soil and developed for , among other uses, life support at the base. The results here indicate that a mature technology base, dominated by bioregenerative life support is more likely to export rather than import oxygen.

- Regardless of the degree of hybridization, P/C components are neededto balance biological processes in a space life support system for humans.
- Very different P/C processes are needed depending on the degree of hybridization.
- The CO2 reduction reaction determines the optimum degree of hybridization for gas exchange:
  - incomplete reduction (e.g., Sebatier) ~ 30 %
  - complete reduction (e.g., Bosch/ACR) ~ 75 %
- For fast rapid build-ups like adding 4 lunar base crew every 2 years:
  - system mass growth has stronger affect on payback than resupply.
  - breakeven points are pushed out beyond reasonable planning horizons.
- In-situ manufactured oxygen not needed for Lunar Base life support:
  - for mostly bioregenerative systems (above 85% hybridization).
  - except for leakage/airlock loss make-up.
- Factors critical to early breakeven points in hybrid versus P/C ECLSs:
  - power penalty for plant chamber lamps.
  - spares/maintenance resupply mass for plant chamber subsystem.
  - Assumption on required daily food mass per crew (4.5 vs. 1.84 lb).
- Plant transpiration as a method of water recovery has significant benefits if:
  - Condensate quality meets contamination standards.
  - Contamination of plant chamber with biocides can be avoided.
  - Same plants canprovide food, gas exchange, and water recovery.

Figure 29. Summary Conclusions - P/C>Hybrid>CELSS Evolution

The studies on accumulation of system mass over time for different options, sometimes referred to as breakeven analyses, also revealed a few conditions that may not be normally apparent. The mass accumulation curve is a function of the initial system mass (the y-intercept point) and the resupply mass (the slope of the curve). Open loop systems tend to have higher resupply mass per year than closed loop systems. But closed loop systems have higher initial masses. This results in a crossover point which indicates the number of years until the day when it would have been better (i.e., would have required less total mass) to have gone with the partially closed loop system. When applying these types of curves in cases like a lunar base, the build-up rate of crew being served by the system can have a great affect on the breakeven time. For example, consider a system with a breakeven point of six years. When build-up of the lunar base starts, such a system could be put in place along with the first four people. If this system operates for six years or more, it is desirable to partially closed bioregenerative technologies. If the mission duration is less, open loop P/C design options are preferable. Now consider that two years later the base is expanded to house a crew of eight. The breakeven for the added four crew is six years from that date or eight years from the overall start of the lunar base deployment. The breakeven point of the overall lunar base system is somewhere between six and eight years from the start. The effect of this delaying mechanism is more pronounced when the number of crew increases rapidly over a short period of time. For fast growing system loads, (adding 4 lunar base crew every two years), system mass growth has a stronger affect on payback than resupply, and breakeven points are pushed out beyond reasonable planning horizons. .

Conclusions drawn in the comparison of bioregenerative with physicochemical dominated system options are highly dependant on certain design and performance assumptions. In reviewing the algorithms used, three parameters of high sensitivity in determining system mass are grow light power, spares, and the daily weight of food required for a person. The single largest contributor to the initial mass of the system is the power penalty for the grow lamps. Together with the weight of the lamps and equipment, it comprises almost 30% of the total initial mass. Due to the absence of an attenuating atmosphere, direct solar incidence on the lunar surface is around 1380 watts per square meter. Optimum plant growth flux has been demonstrated to be around only 200 watts/square meter. Unfortunately, the day/night cycle on the moon lasts a lunar month (28 days) which is a considerably longer period than that to which most higher plants are accustomed. If direct sunlight could be harnessed (without adding significantly to system mass), the bioregenerative options presented here would be much more attractive. But the impediments were deemed to severe to support using it even as an optimistic option. An exterior consideration which could also alleviate this drawback to plant chambers would be the availability of "cheaper" power . Large variations in the value for a power penalty factor have been suggested. The default value used in this study (350 lb/kw) was established as a ground rule for SEI studies by the Office of Aeronautics, Exploration, and Technology. Other values as low as 50 lb/kw have been suggested.

The weight of food comprising different types of diets is important when comparing P/C versus bioregenerative system options. A diet of over 2000 grams per day per person of earth-supplied meals may be significantly preferred by the astronauts over a 688 gram diet composed primarily of wheat products. Some normalizing of the data presented in this study to adjust comparisons so that they reflect the same degree of palatability is needed. A compromise between earth supplied and fresh grown food stuffs is probably the most palatable preference.

Also, annual resupply of maintenance and spares for the equipment was estimated at 4% of the initial mass for both the CELSS (excluding the plant chamber primary structure) and the P/C system. In an earlier study, reference /27/, by Boeing for a space station CELSS module, a value of 3 % was used. In view of the lack of experience with the reliability and operational life of these systems it is difficult to arrive at a firm estimate of the resupply requirements. A parametric analyses demonstrating the sensitivity of this variable is shown below.

4.2 Advanced Instrumentation

Earlier studies have indicated the sensor needs identified for physicochemical systems also address the needs of bioregenerative system. However, CELSS-type systems are likely to have some sensor requirements not found in P/C systems. Also, they have a need for more robust monitoring of particular parameters than P/C systems. The presence of a plant chamber in a CELSS system brings about a whole new range of fundamental differences in the approach to design and controlling life support. Because of the symbiotic relationship between higher order plants and microbial life, it is believed that aseptic conditions would be disastrous to the health of the plants. The current space station method of dealing with microbes is to control them by destruction. Although humans normally coexist with microbes on earth, their presence was both hard to detect and of no known value. As a result the systems planned for the space station will seek to control microbial populations through the use of biocides. The existence and identification of types of microbes will not be done onboard the space station. Instead, surrogate measurements will be used to infer their presence and the application of biocides used to assure their control. With the advent of plant chambers, it will be necessary to actually provide life support (rather than denying it) to microbes in selected areas.

The mission of providing life support to humans, higher order plants, and microbial life is a broad expansion to the number and kind of processes, environmental conditions, and substances/materials requiring sensing and control. For example, harvest from a plant chamber represents a kind of process stream never before monitored in a space application. A measurement list might include items such as ripeness, harvest fraction, and sensors to determine the concentrations of many if not all the recommended daily amounts of vitamins and minerals, proteins, fats, and carbohydrates. Another example could be the identification of the kind and amount of a particular microbe or class of microbes present. Potential bioregenerative waste processing techniques include aerobic and anaerobic digestion with the object in either case to promote and control growth of one type and reduction of the other.

- Sensor requirements exist for bioregenerative systems beyond those of P/C systems:
  - plant chamber harvest is new process stream for a space system.
  - higher plants may require life support to symbiuotic microbial life.
  - current microbial monitoring technology unlikely to be sufficient.
- Available technology development time is short for bioregenerative systems:
  - current technology maturity levels are low.
  - early deployment of bioregenerative systems in most SEI plans.
  - increased emphasis in technology development programs needed .
- Hybrid and CELSS involve significant new control challenges:
  - evolution requires highly adaptive systems and controllers.
  - compensation for human and plant metabolic dynamics.
  - more complex interactions with new processor types and streams.
  - "Man System Integration"-type standards needed for higher plants.
- Potential automation benefits likely for farming and food preparation:
  - Value difficult to assess until system concepts mature.
  - benefits from reduction in crew labor rather than safety or lack of human ability.

Figure 30 Summary Conclusions - Advanced Instrumentation

Potential applications for automation in the lunar base exist, but the availability of hard data makes it difficult to assess their cost/benefit aspects. The three main applications for automation have traditionally been to reduce menial work loads on humans, perform dangerous tasks, or serve in cases in which a significant improvement in performance is possible and valuable. In this case, the former type appears to be the most applicable.

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