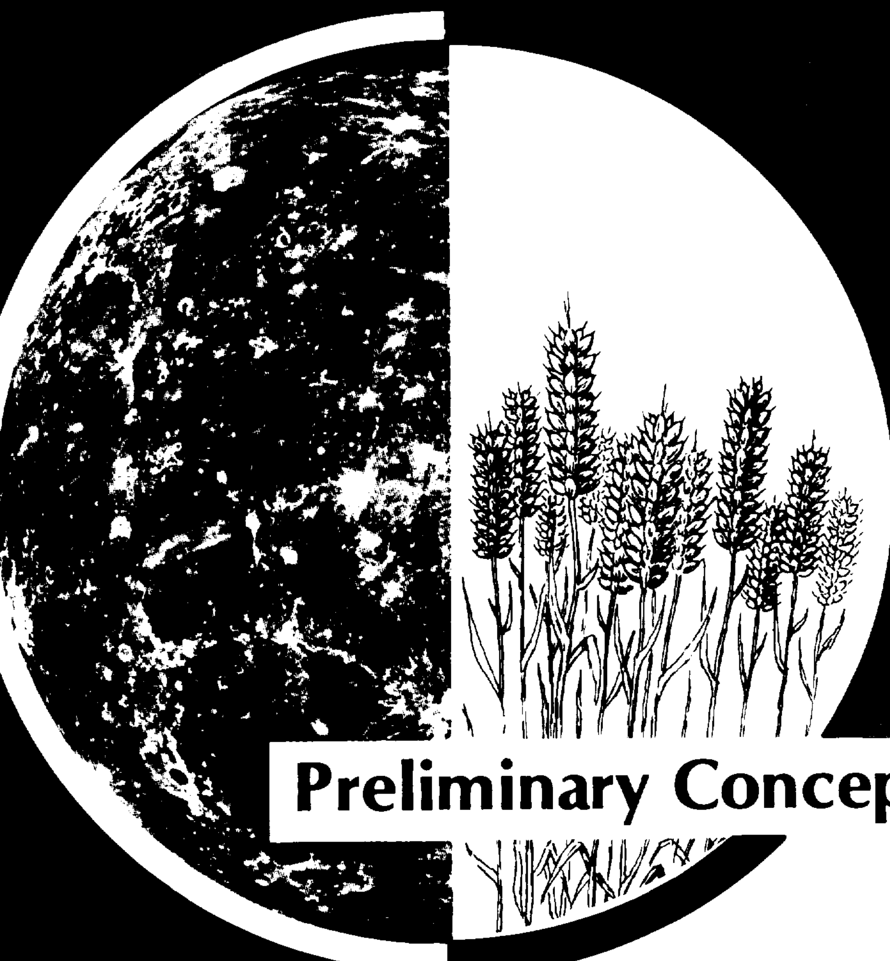
LMSC-F^80196
30 April 1991
P. 20

(NASA-CR-188479) LUNAR BASE CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEM (LCELSS): PRELIMINARY CONCEPTUAL DESIGN STUDY Final Report (Lockheed Missiles and Space Co.) 207 p

N94-18484

Unclas

G3/54 0196047



Preliminary Conceptual Design Study

FINAL REPORT

Lockheed
Missiles & Space Company, Inc.

LMSC/F280196
30 April 1991

LUNAR BASE CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEM (LCELSS)

Preliminary Conceptual Design Study
Final Report
30 April 1991

Prepared by: S. Schwartzkopf, Ph.D., O/6N-12, Technical Study Leader — Date: 4/26/1991

Approved by: J. Houle, O/6N-01, Program Manager — Date: 4/26/91

Approved by: A. Guastaferro, O/6N-01, Vice President NASA Space Flight Programs — Date: 4/26/91

Lockheed Missiles & Space Company, Inc.
Sunnyvale, California

FOREWORD

This report documents the conduct and results of a Preliminary Conceptual Design Study for a Lunar Base Controlled Ecological Life Support System (LCELSS) under provisions of Contract No. NAS9-18069 for the National Aeronautics and Space Administration at the Lyndon B. Johnson Space Center. The study was initiated in December, 1989, and reviewed in detail by NASA in April 1989, at which time Lockheed was authorized to proceed with design of the selected LCELSS concept. The draft interim report was approved by NASA after its submittal in April, 1990.

This report consists of two volumes, Volume I Final Report, and Volume II which contains the LCELSS database on computer disk. The database disks have been transmitted under separate cover.

During this study, various organizations and individuals made significant contributions to the technical content and/or conduct of this study. They are acknowledged below.

- BioServe Space Technologies (Boulder, CO), was the major subcontractor.
- Dr. Maurena Nacheff-Benedict of Allied Signal Corporation.
- Bionetics Corp. at the Kennedy Space Center.
- Dr. John Sager of NASA, Kennedy Space Center.
- Mr. James D'Andrade and Mr. Trevor Howard of ILC Dover Corporation.
- Dr. Maynard Bates of Bionetics Corp. at the Ames Research Center.
- Dr. Ray Bula and Dr. Bob Morrow of the Wisconsin Center for Space Automation and Robotics (WCSAR).
- Mr. Tom Ball and Mr. Doug McKenna of Boeing Aerospace.

Additional work will be performed under an extension to this contract, and will not be completed until after the publication of this report. An Addendum to this report (describing the results of the additional work) and a Designer's Handbook (summarizing data and relationships used in developing the design) will be issued upon completion of the contract extension. A new Executive Summary is planned also. To receive a copy of the Addendum, Designer's Handbook and the new Executive Summary, please contact:

Steven H. Schwartzkopf
Lockheed Missiles & Space Co., Inc.
P.O. Box 3504
Org. 6N-12/B-580
Sunnyvale, CA 94088-3504

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

SECTION PAGE

TABLE OF CONTENTS (Continued)

SECTION PAGE

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

DEFINITIONS

Anabolic - metabolic reactions which synthesize a product

Aquaculture - the husbandry of aquatic organisms for the purpose of providing food for people

Biomass - tissue(s) obtained from living plants or animals

Bioregenerative - a family of life support technologies in which the regeneration function is performed by living organisms

Breakeven - the mission duration at which the cumulative launch masses for two different life support systems are equal

Catabolic - metabolic reactions which degrade a substance

Controlled Ecological Life Support System (CELSS) - a life support system based entirely or partially on bioregenerative technologies

Constructible/Inflatable Habitat (CIH) - the habitat component of the proposed Lunar base concept

Extravehicular/Extrahabitat Activity (EV/HA) - surface activity involving humans in suits or in surface rovers

Foxbase+ - Apple Macintosh-based data base software used to develop LCELSS database

Habitation/Laboratory Module (HLM) - an all-purpose component of the proposed Lunar base concept

In situ resource utilization (ISRU) - use of Lunar materials (e.g., regolith) available at the base site

Interface/Resource Node (IRN) - the interface component of the proposed Lunar base concept

Lunar Base Controlled Ecological Life Support System (LCELSS) - a CELSS-based life support system applied to a Lunar base

Mass closure - the recycling of materials

Photosynthetically Active Radiation (PAR) - the intensity of visible radiation in the 400-700 nm waveband; used by plants for photosynthesis

Physicochemical - a family of life support technologies in which the regeneration function is performed by mechanical or chemical devices

Phytotron - plant growth chamber

Regolith - the outermost crust of the lunar surface; analogous to the soils of Earth

Safe haven - area(s) of maximum protection in the Lunar base to which the crew would retreat in emergencies

SSF - Space Station Freedom

TCCS - Trace Contaminant Control System

EXECUTIVE SUMMARY

> "Phase III. At home on the Moon (2005-2010)...scientific and technological capabilities allow the outpost to expand to a permanently occupied base... By 2010, up to 30 people would be productively living and working on the lunar surface for months at a time."

> "The critical technologies for this initiative...include life-support system technologies to create a habitable outpost... In the 1990s, the Phase 1 Space Station would be used as a technology and systems testbed for developing closed-loop life support systems."

These quotations from Leadership and America's Future in Space (Ride, 1987) establish the context of the Lunar Base Controlled Ecological Life Support System (LCELSS) conceptual design study. In the past, spacecraft life support systems have emphasized the use of open-loop technologies which were simple and sufficiently reliable to demonstrate the feasibility of manned spaceflight for short mission durations, small crew sizes, and limited power availability. The fundamental design problem addressed by the LCELSS study resulted from the recognition that different life support technologies will be necessary for advanced missions, especially with regard to the incorporation of bioregenerative (CELSS) technologies. This necessity is based upon advanced mission requirements to: (1) provide safe, reliable human life support which would accommodate long mission durations, (2) maximize the degree of self sufficiency of the lunar base, (3) minimize both the economic costs and the complexity of logistics associated with resupply, and (4) maintain a familiar, Earth-like living environment to promote crew productivity and psychological well-being.

The conceptual design developed by the LCELSS study is a comprehensive one, covering not only the nominal life support requirements, but also taking into consideration the requirements which might be levied on the life support system by lunar industrial and scientific research activities. The study identified and analyzed the key tradeoff issues, and has produced a conceptual design which incorporates the results of these analyses. Key outputs of the study include mass, power and volume estimates for the LCELSS conceptual design, evaluation of mass breakeven points for the design, and an identification of research and technology needs required to support the implementation of an LCELSS.

STUDY OBJECTIVE

The objective of this study was to develop a conceptual design for a self-sufficient LCELSS. The mission need is for a CELSS with a capacity to supply the life support needs for a nominal crew of 30, and a capability for accommodating a range of crew sizes from 4 to 100 people.

STUDY PHILOSOPHY

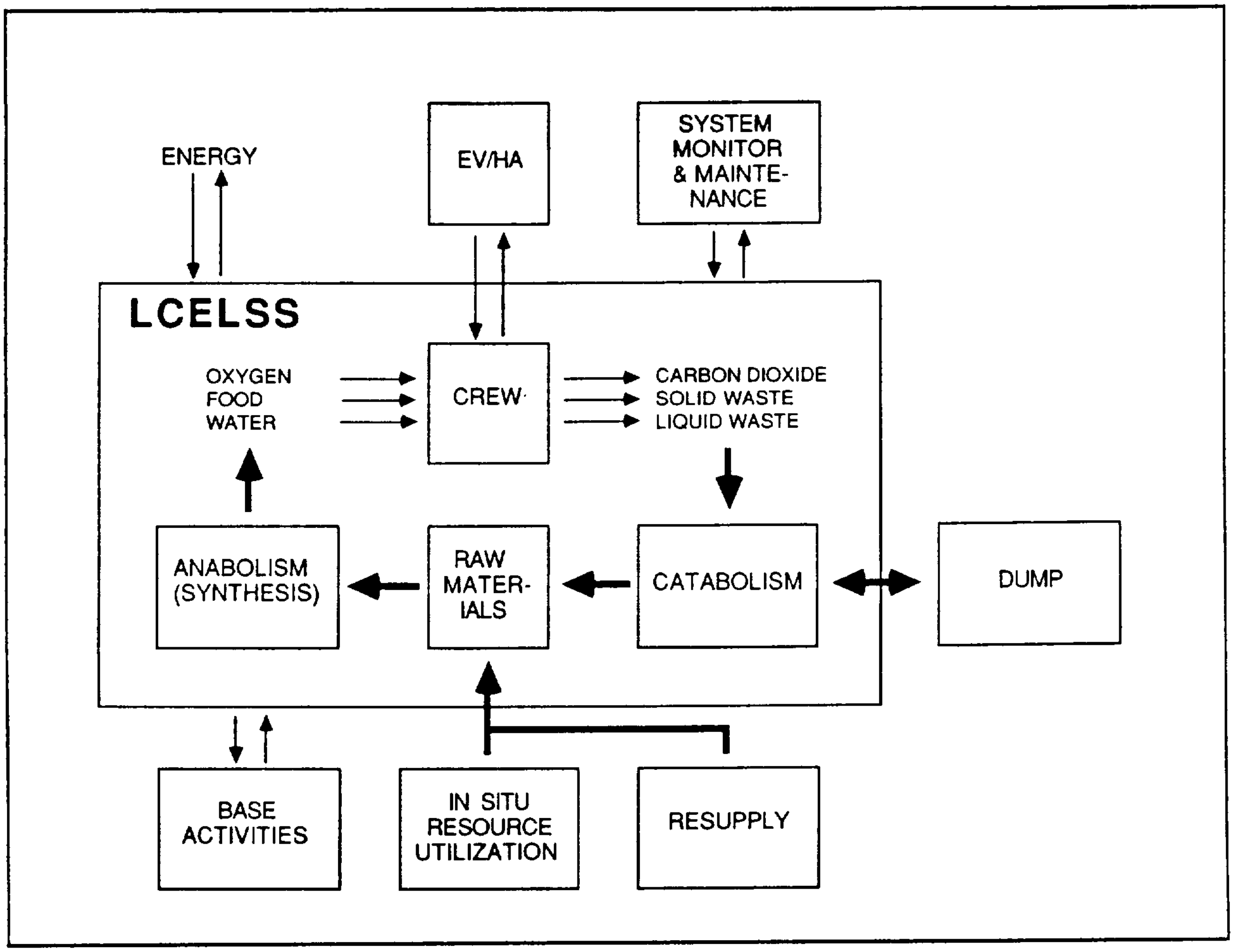
Previously, the usual view of CELSS implementation has tacitly embraced several assumptions, the most common being that: (1) higher plants would be used to produce food, recycle water and revitalize air, (2) food animals would not be included in the CELSS because of their low efficiency for converting feed into edible material, and (3) waste processing would involve physicochemical reduction of all complex organic matter to inorganic salts, CO_2, N_2 and water.

During this study, such potentially constraining assumptions were avoided by dealing with the issue of LCELSS design from a functional perspective. The basic functions of the LCELSS are to catabolize wastes to produce raw materials from which the basic materials required to support life can be synthesized (Fig. 1). This view of the system does not assume that higher plants must be the sole anabolic component. Neither does it automatically eliminate animals from consideration as LCELSS food-producing components, nor assume that organic wastes must be completely broken down to inorganic, elemental form. As a result, this philosophy provided greater leeway in completing an analysis of the LCELSS and its characteristics.

STUDY METHODOLOGY

The work performed in this study was nominally divided into two parts. In the first part, relevant literature was assembled and reviewed. This review identified LCELSS performance requirements and the constraints and advantages confronting the design. It also collected information on the environment of the lunar surface and identified candidate technologies for the life support subsystems and the systems with which the LCELSS interfaced. Information on the operation and performance of these technologies was collected, along with concepts of how they might be incorporated into the LCELSS conceptual design. The data collected on these technologies was stored for incorporation into the study database. Also during part one, the study database structure was formulated and implemented, and an overall systems engineering methodology was developed for carrying out the study .

Figure 1. LCELSS Functional Layout.



The information accumulated by the literature review was used to develop five candidate LCELSS design configurations. A preliminary analysis was then conducted to estimate mass, volume, power use, and the degree of self sufficiency (the amount of resupply mass required) for each of the candidate configurations. The results of this analysis were used to prioritize the candidates and to identify the configuration to recommend to NASA as the focal point for more detailed analysis and conceptual design development.

At the completion of part one, LMSC reviewed with NASA the overall study methodology, the database structure, and the prioritized candidate LCELSS configurations. During this review, NASA provided feedback which LMSC used to refine the study methodology. Following the review, NASA analyzed the Lockheed candidate configuration prioritization, and approved the primary candidate as the focus of subsequent detailed analysis and design work.

During part two, analyses of the approved LCELSS configuration were performed at both system and subsystem levels. The data collected on the life support and interfacing systems technologies during part one was evaluated and down-selected to produce a short list of viable technology candidates. Further data was collected on these selected candidate technologies and entered into the study database. The conceptual design of the approved configuration was then developed using the technology database and the results of the detailed analyses. Performance characteristics of the LCELSS conceptual design were estimated. Finally, an analysis of the research and technology needs for implementing the LCELSS conceptual design was performed. As part of this analysis, development schedules, manpower requirements, and rough estimates of hardware development cost were produced for each of the LCELSS subsystems.

IDENTIFICATION OF CANDIDATE CONFIGURATIONS

The analysis performed in part one of the study focused on the identification of candidate configurations for the LCELSS. Each of the conceptual design candidates considered was based on a generic system structure consisting of six subsystems (atmosphere regeneration, water purification, waste processing, food production, food processing, and biomass production) along with three other interfacing systems (in situ resources utilization, extravehicular/extrahabitat activity and system monitoring and maintenance).

Five different design configurations were identified as potential candidates. The first configuration served as a baseline, and incorporated physicochemical air and water recycling with food resupply. Candidates 2 through 5 were specifically selected to enhance the self sufficiency of the LCELSS. Candidate 2 assumed that food carbohydrates were physicochemically synthesized from waste materials, with atmosphere and water recycled as in Candidate 1. Candidate 3 was developed on the basis of using animals to process waste materials and produce edible material for the crew, again with atmosphere and water recycled as in Candidate 1. Candidate 4 incorporated bioregenerative food production technology emphasizing the use of crop plants, while Candidate 5 added animal food production capability to the concept developed for Candidate 4. Both Candidates 4 and 5 assumed full water and atmosphere recycling by the crop plants. Figure 2 summarizes the estimated resupply mass, self sufficiency, system mass, system volume and system power requirement for each of these five candidate concepts.

Based on this initial analysis, Lockheed recommended, and NASA approved the recommendation, that Candidate 5 be selected as the design concept for further study because of its high self sufficiency score. The LCELSS conceptual design developed during the second part of this study was thus focused on a system which included both plants and animals as human food sources. A block diagram which illustrates the overall structure of the LCELSS conceptual design as well as the major mass flows in the system is presented in Fig. 3.

Figure 2. Initial Engineering Estimates Characterizing the Candidate LCELSS Design Concepts.

CANDI-DATE	LCELSS DESIGN CONFIGURATION (Crew = 30)	RESUPPLY MASS [1] (kg/day)	SELF SUFFI-CIENCY [2] (%)	SYSTEM MASS (kg)	SYSTEM VOLUME (m^3)	SYSTEM POWER [3] (kW)
1	Physicochemical with food resupply (baseline)	35	---	28,850	230	115
2	Physicochemical with carbohydrate synthesis	20	43	31,000	255	150
3	Hybrid with animal food production	30	14	93,250	1,050	165
4	Hybrid with plant food production	2	92	211,200	2,075	685
5	Hybrid with plant and animal food production	<0.1	>99	222,700	2,320	595

1. Includes mass of both dry foodstuff and food water.
2. Calculated relative to baseline, Candidate 1.
3. Plant production system assumed to be wholly artificially lighted.

The selected conceptual design reflects the requirement to provide life support for a nominal crew of 30 persons, with the capability to accommodate a range from 4 to 100. This design should not yet be considered optimal, but is intended to serve as a reference baseline. This concept incorporates full food production (both plant and animal materials) for the crew, as well as complete water and air recycling. To minimize cost and maximize reliability, many of the components illustrated in Fig. 3 are identical modules (e.g., condensing heat exchangers, trace contaminant control).

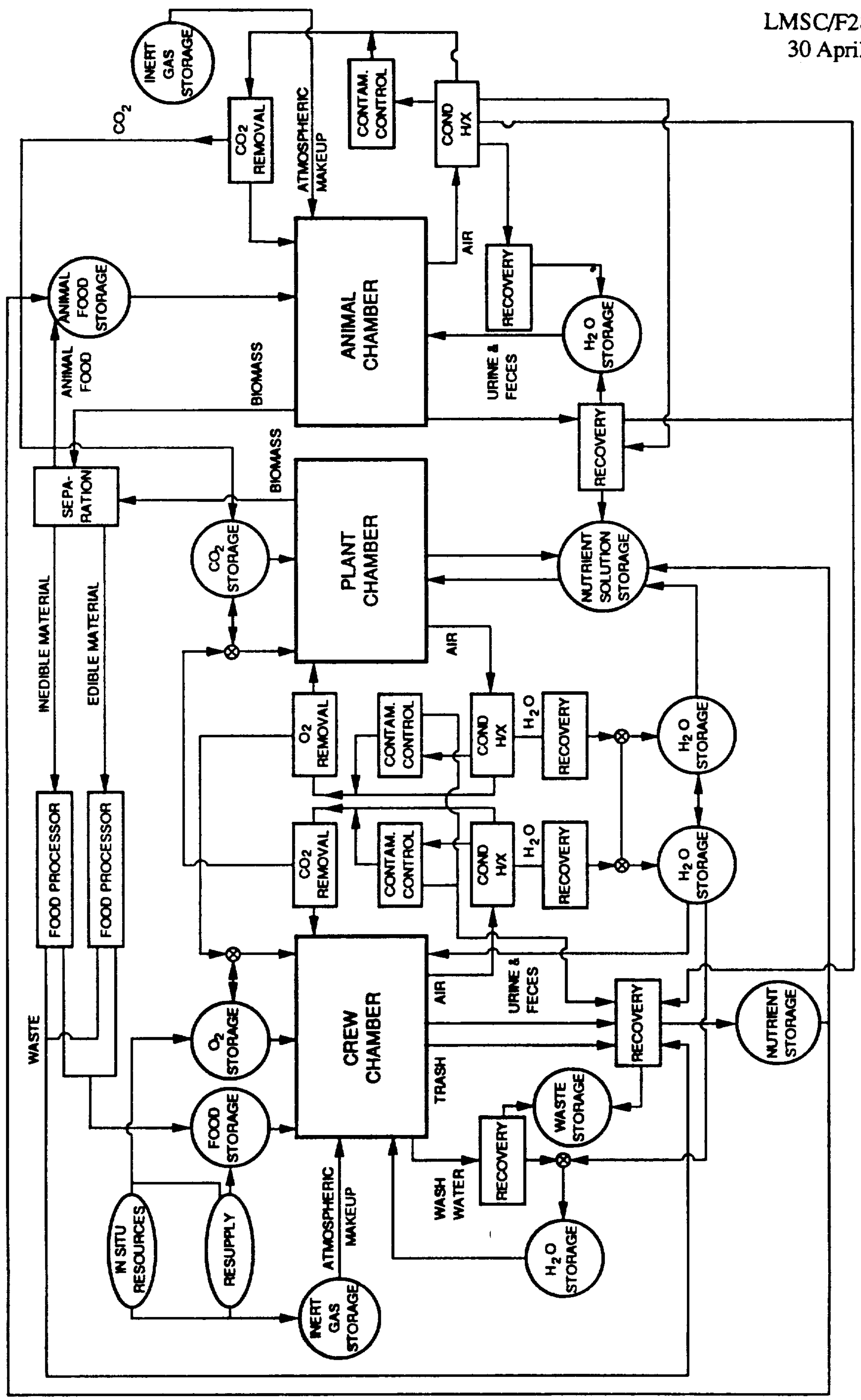


Figure 3. Block Diagram of Selected LCELSS Conceptual Design.

ANALYSES AND TRADEOFF RESULTS

Ten specific topics were identified during the study as requiring tradeoff studies and/or analyses. These topics included: 1) lighting for plant photosynthesis, 2) waste processing technology selection, 3) animals as human food in a LCELSS, 4) aquaculture system feasibility, 5) food processing technology review, 6) dietary/nutritional evaluation, 7) feasibility of using membranes for gas separation, 8) crew time requirements for LCELSS implementation, 9) cooling/heating requirements of a transparent structure on the lunar surface, and 10) in situ resource utilization. Detailed descriptions of each analysis and its results are provided in Section 4 of the final report.

DETAILED DESCRIPTION OF CONCEPTUAL DESIGN

The initial analysis indicated that the design of the plant growth unit(s) supporting food production was the strongest driver in developing the conceptual design. To meet the requirements of the 4, 30 and 100 person crew sizes, three plant growth unit concepts were developed. The first concept was based on a Space Station Freedom module, the second (Hybrid) used an aluminum backbone with an attached inflatable envelope, and the third (Inflatable) was a completely inflatable envelope. With the exception of a small amount hardware that required installation in the base habitat(s), all of the ancillary life support equipment was installed in the plant growth units.

Thus, meeting the life support requirements of four crew members requires one of the SSF Module-based units. Increasing the crew size to 30 requires the addition of a second SSF Module-based unit and three of the Hybrid units. An increase in the crew to 100 persons adds 3 Inflatable units to those previously required for the 30 person crew. An additional benefit which accrues from combining the modules in this fashion is an increase in overall system reliability.

The estimated mass of the LCELSS supporting each of the three crew sizes is summarized in Fig. 4. As this figure shows, the plant growth units constitute the largest subsystem in all three concepts. In the 4 person crew, the SSF Module-based plant growth unit accounts for about 82% of the total mass, while in the 30 and 100 person crews the plant growth subsystems account respectively for 79% and 74% of the total mass. The second largest mass item is the aquaculture system, which accounts for 9%, 10% and 12% of the total system mass for 4, 30 and 100 crew members, respectively. It should also be noted that because of the mass differences between the three plant growth unit design concepts, the total mass of the system does not increase linearly with crew size. As the crew size increases, the production of plant-based foods shifts to larger, but lighter units.

As indicated in this figure, the food and oxygen reserves were calculated for different time intervals. Food was calculated on a 90 day basis, as a problem with the food production system could take up to one full crop cycle (as high as 60-90 days from seed to harvest) to return to equilibrium. Oxygen production, on the other hand, would be adequate to support the crew approximately 30 days after starting a new crop.

Figure 4. LCELSS Mass Estimates by Crew Size.

Subsystem/Component	Estimated Mass by Crew Size (kg)		
	4	30	100
Plant Growth Unit(s)	12,322	78,641	209,081
Solid Waste Processing	63	273	808
Atmosphere Regeneration	271	1,169	3,016
Water Purification	31	233	778
Aquaculture (*Tilapia*)	1,366	10,169	33,695
Food Processing	26	52	122
Inflation Gas	N/A	1,446	12,014
90 Day Food Reserve	565	4,239	14,130
30 Day Oxygen Reserve	394	2,952	9,840
TOTALS	15,038	99,174	283,484

Estimates of the electrical power required to operate the LCELSS for each crew size are presented in Fig. 5. The maximum power listed would be required only during lunar night, when all of the artificial plant lighting was turned on. Minimum operating power during lunar day is also presented for comparison, and is based upon the assumption that all photosynthetically active radiation (PAR) is supplied by natural sunlight. It is evident from these estimates that the use of electrical power to supply PAR is an extremely strong driver of the system power use, but also that use of sunlight can significantly reduce this requirement.

Figure 5. LCELSS Power Estimates (Maximum and Minimum) by Crew Size.

Crew Size	LCELSS Power Requirement (kW)	
	Lunar Night - Max.	Lunar Day - Min.
4	72	12
30	617	94
100	1,700	226

Figure 6 summarizes the volume estimates for the LCELSS at the three crew sizes. Estimates were made for the erected volumes, which are based on the dimensions of the plant growth units. The plant growth units are sized so that they contain virtually all of the life support hardware.

Figure 6. LCELSS Volume Estimates by Crew Size.

Crew Size	LCELSS System Volume (m^3)
4	148
30	1,187
100	8,255

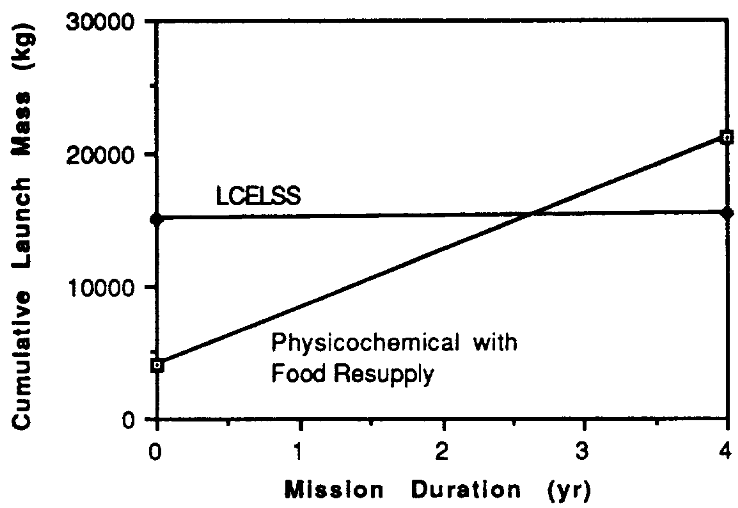
BREAKEVEN POINT ANALYSIS

A breakeven analysis was conducted to determine the mission duration at which an LCELSS design began to provide mass savings over a resupply scenario. Rather than develop new values for the resupply scenario, previously published data were used, (Gustan and Vinopal, 1982). Their closure scenario D provides data for a physicochemical system which recycles air and water, while food and replacement parts are provided by resupply. This scenario has been frequently used as a baseline for breakeven analysis of CELSS-based life support systems.

Using the physicochemical data , breakeven graphs were developed for the LCELSS crew sizes of 4, 30 and 100. The breakeven graph for a crew of 4 is shown in Fig. 7. These graphs show that the LCELSS conceptual design has breakeven times ranging from about 1.7 to 2.6 years (for 100- to 4-person crews, respectively), when compared with the physicochemical mass estimates. With regard to self sufficiency, the LCELSS conceptual design was estimated to be capable of achieving over 99% mass closure. This characteristic is illustrated by the extremely shallow slope of the

LCELSS mass lines as mission duration increases. The slight increase is due only to the need for launch of replacement parts and possible vitamin supplements for the crew.

Figure 7. Breakeven Point Graph for a Crew of 4 Persons.



TECHNOLOGY RESEARCH AND DEVELOPMENT NEEDS

A detailed evaluation of the technology research and development required to implement an LCELSS is presented in Section 7. In general, research and technology needs fall into four areas. First, performance of existing, applicable life support technologies must be more precisely characterized with respect to several basic measures, including mass flows, power requirements, potential for mass closure, and interface requirements. Second, system- and interface-definition studies must be conducted to verify operational interaction of different life support system designs. Third, although many of the required technologies are in commercial use on earth, the hardware is sized to support very large numbers of people. Accordingly, R&D efforts must also be directed at miniaturizing existing hardware for use in space. Finally, the suite of R&D efforts described in this report will require the design and construction of hardware testbeds to serve as the foundation for conducting the required definition studies and operational.

CONCLUSION

The most important conclusion reached by this study is that the implementation of bioregenerative or CELSS technologies in support of a lunar base is not only feasible, but eminently practical. On a cumulative launch mass basis, a 4-person LCELSS would pay for itself in approximately 2.6 years (when compared with a physicochemical life support system with food resupply). For crew sizes of 30 and 100 persons, the breakeven points are even lower.

Two other conclusions are particularly important with regard to the orientation of future studies, research, and development. First, this study illustrates that existing or near-term technologies can be used to implement an LCELSS; that is, there are no apparent "show-stoppers" which require the development of new technologies. There are, however, several areas in which new technologies could be used to better implement an LCELSS (i.e., by saving mass or power), and should be addressed. Second, the LCELSS mass estimates indicate that a primary design objective in implementing this kind of system must be to minimize the mass and power requirment of the plant growth unit(s), which far overshadow those of the other subsystems. As a corollary, detailed trade studies to identify the best technology options for the other subsystems should not be expected to produce dramatic reductions in either mass or power requirement of the LCELSS. It is, therefore, especially important to emphasize functional integration within the overall LCELSS as a crucial tradeoff criterion in conducting any such study.

SECTION 1
STUDY OBJECTIVE AND METHODOLOGY

The fundamental problem addressed by the lunar base Controlled Ecological Life Support System (LCELSS) study results from a recognition that bioregenerative technologies will be needed for future manned missions. This need is based on requirements to: 1) provide a safe, reliable human life support system to accommodate long mission durations, 2) maximize the degree of self sufficiency of the mission, 3) minimize the economic costs associated with the complexity of resupply and logistics, and 4) maintain a familiar, Earth-like living environment to promote crew productivity and psychological well-being.

1.1 STUDY OBJECTIVE

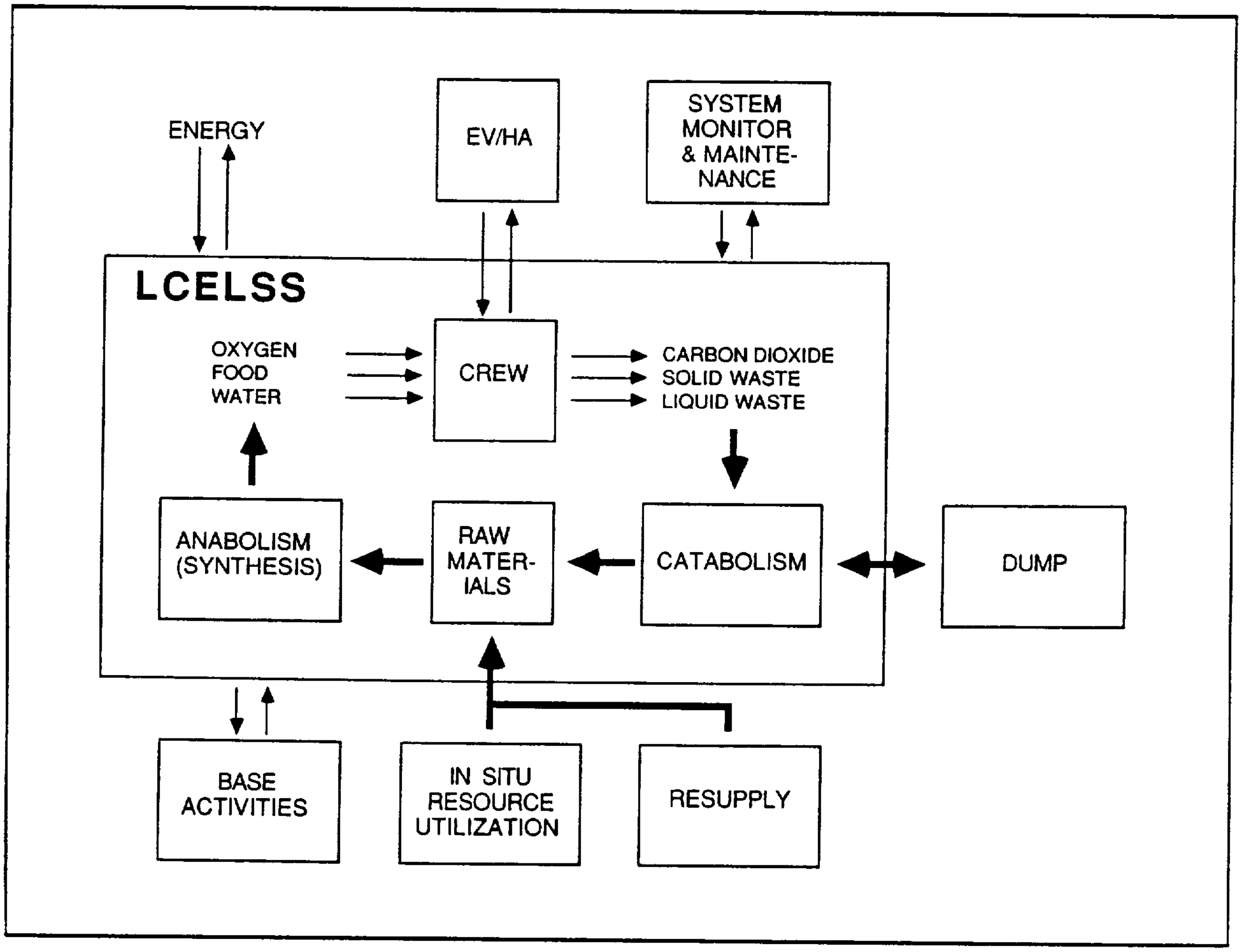
The objective of this study was to develop a conceptual design for a self-sufficient LCELSS. The mission need is for a CELSS with a capacity to supply the life support needs for a nominal crew of 30, and a capability for accommodating a range of crew sizes from 4 to 100 people.

1.2 STUDY PHILOSOPHY

In the past, the usual view of CELSS implementation has tacitly embraced several assumptions, the most common being that: 1) higher plants would be used to produce food, recycle water and revitalize air, 2) no food animals would be included in the CELSS (because of their supposed low efficiency for converting plant biomass into edible animal biomass), and 3) waste processing would be performed via a physicochemical technology which would reduce all complex organic matter to inorganic salts, CO_2, N_2 and water.

During this study, such potentially constraining assumptions were avoided by dealing with the problem of LCELSS design from a more functional perspective. Figure 1.1 provides a functional diagram of the LCELSS and its interfaces with other lunar activities. As this figure illustrates, the fundamental functions of the LCELSS are to catabolize human wastes to produce raw materials from which the basic materials required to support life can be synthesized. This view of the system does not assume that higher plants must be the sole anabolic component. Neither does it

Figure 1.1. LCELSS Functional Relationships.



automatically eliminate animals from consideration as LCELSS food-producing components, nor assume that organic wastes must be broken down to inorganic form. As a result, this philosophy provided greater leeway in completing an analysis of the LCELSS and its functional requirements.

1.3 STUDY METHODOLOGY

The work flow in this study was divided into six tasks, as shown in Fig. 1.2. Tasks 1 and 2 were performed in parallel and provided input for Task 3. Tasks 3 through 6 were performed sequentially. In Task 1, relevant literature was assembled and a review performed to identify LCELSS performance requirements, as well as the constraints and advantages confronting the design. During this review, candidate technologies were identified for LCELSS life support subsystems and the systems with which the LCELSS interfaced. Information on the operation and performance of these technologies was collected, along with concepts of how they might be incorporated into the LCELSS conceptual design. The data collected on these technologies was stored for incorporation into the study database. During the literature review, information on the environment of the lunar surface was also collected and entered into the database.

The information accumulated by the literature review was used to develop five candidate LCELSS design configurations. A preliminary analysis (using the methods developed in Task 2) was then conducted to estimate mass, volume, power use, and the degree of self sufficiency (the amount of resupply mass required) for each of the candidate configurations. The results of this analysis were used to prioritize the candidates and to identify the configuration to recommend to NASA as the focal point for more detailed analysis and conceptual design development.

In Task 2, a methodology was developed for trading candidate LCELSS configurations against requirements and constraints. System engineering methodology for conducting the study was also developed, as was a methodology for defining the conceptual design methodology. In addition, the structure of the study database was formulated and then developed during this task. A specifically-formatted summary sheet was developed and incorporated into the database to provide a standardized method of describing the characteristics and performance of each technology.

During Task 3, Lockheed reviewed with NASA the three support methodologies and the database structure developed in Task 2, along with the prioritized candidate LCELSS configurations identified in Task 1. During this review, NASA provided feedback which Lockheed used to refine the study methodologies. Following the review, NASA analyzed the Lockheed candidate configuration recommendations and approved the primary candidate as the focus of subsequent detailed analysis and design work.

In Task 4, analyses of the approved LCELSS configuration were performed at both system and subsystem levels. The data collected on the life support and interfacing systems technologies during Task 1 was evaluated and down-selected to produce a short list of viable technology candidates. Further data was collected on these selected candidate technologies and entered into the study database. The conceptual design of the approved configuration was then developed using both the technology database and the results of the detailed analyses. Finally, performance characteristics of the LCELSS conceptual design were estimated.

Task 5 included an analysis of the technologies available for implementing the LCELSS conceptual design, along with a determination of the need for specific technologies in developing this design. Development schedules and rough estimates of hardware development cost were produced for each of the LCELSS subsystems.

Finally, in Task 6, a draft of the Final Report was written and reviewed for comment by NASA and Lockheed. The comments were incorporated into the draft to produce this report.

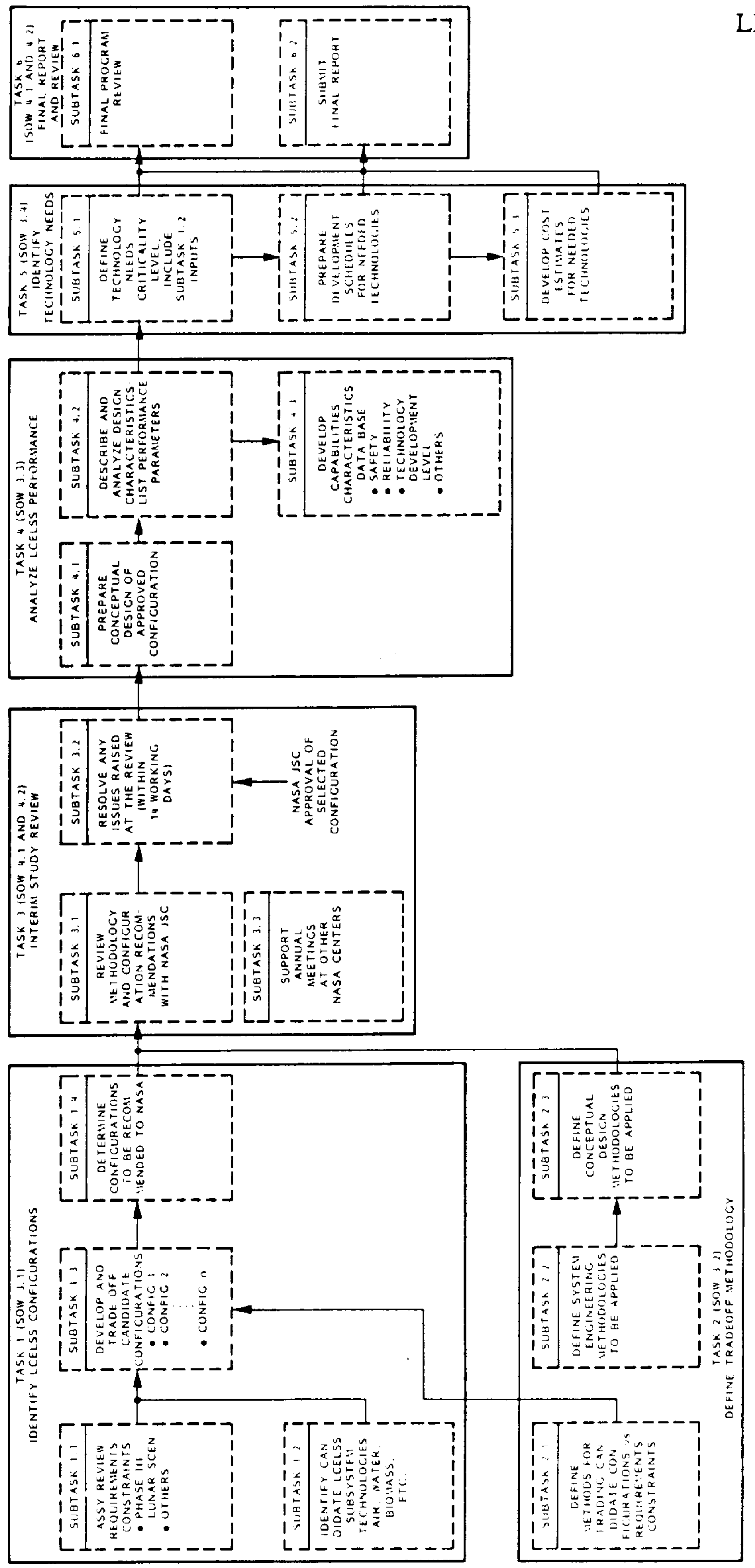


Figure 1.2. LCELSS Study Task Flow.

SECTION 2
CONCLUSIONS AND RECOMMENDATIONS

This section presents both the conclusions reached by the study, and the recommendations considered to be the most significant based upon the analyses, tradeoff studies, and the conceptual design work completed.

2.1 CELSS TECHNOLOGY APPLICATION

Based on mass breakeven data, incorporation of CELSS technology into a lunar base life support system is highly desirable. Even for a crew size of 4 persons, this technology provides a mass breakeven at a mission duration of about 2.6 years. As crew size increases, breakeven time decreases until it reaches about 1.7 years for a crew of 100.

It was estimated that an LCELSS should be able to achieve a self sufficiency of over 99% with regard to mass closure. This high degree of self sufficiency provides an extra margin of safety for the crew in the event of delayed resupply and/or some system failures.

2.2 DESIGN/CONSTRUCTION TRADEOFFS

Analysis indicates that early in base development, the modules from which the base is constructed should be self-contained units, assembled and integrated on Earth. These units will be higher mass, but will involve little or no crew time for startup. As the base evolves, light-weight structures can begin to play a more significant role because the availability of crew time to assemble them should increase. Further analysis and design work are required on the topic of light-weight pressure shells for use on the lunar surface. This work should include detailed analyses of the amounts of crew time required to erect different designs.

2.3 COMPONENT RELIABILITY

Significant attention must be addressed to increasing the reliability of pumps, fans, reactors, and other components from which the life support system will be constructed. Based on the time required for preventative maintenance in the Soviet Bios-3 experiment, significant amounts of crew time will be spent in maintenance if reliability is not increased.

2.4 ATMOSPHERE REGENERATION TECHNOLOGY

Using higher plants to provide food, regenerate the atmosphere, and recycle water and waste provides a high degree of system self sufficiency, but also requires design considerations such as the capability to isolate the crew and plant growth unit atmospheres. This capability makes it possible to provide atmospheric conditions conducive to people and plants, as well as providing a barrier to contaminants and disease organisms.

This finding supports the need for research and development into the development of interface technologies for separating oxygen and carbon dioxide from air, while preventing the passage of contaminants. It also supports the need for developing new methods of trace contaminant and disease organism monitoring and control in closed systems.

2.5 WASTE PROCESSING TECHNOLOGY

Although low pressure wet oxidation was chosen to recycle waste materials in this conceptual design, the technology analysis clearly shows that the majority of the hardware mass for waste processing is in the ancillary equipment, rather than the reactor itself. This finding leads to the conclusion that the selection of waste processing technology should be made on the basis of how the selected process fits into the overall life support system, rather than on hardware mass. Research is thus required to investigate how well different waste processing technologies accomplish the mass recycling needs of the system. Engineering development is necessary with regard to miniaturizing system components, particularly the ancillary components such as grinders, driers, and bacterial reactors.

2.6 WATER PROCESSING TECHNOLOGY

Although many of the technologies for water recovery are fairly mature, research and technology needs still exist with regard to minimizing resupply mass for some technologies (e.g., those involving filters), and in the area of trace contaminant monitoring and control. Evaluation of transpiration water collected from plants should be conducted to verify human acceptability.

2.7 FOOD PRODUCTION TECHNOLOGY

The major research and development effort that seems to be required at this time involves the miniaturization of existing hardware and the development of new support equipment. Small, automated seed planters and crop harvesters must be designed and tested in order to decrease the crew time required to support those functions. Automated monitor/control systems (e.g., nutrient solution monitor and control for hydroponics) must be developed to minimize maintenance requirements.

2.8 BIOMASS PRODUCTION TECHNOLOGY

Although biomass production may supply incidental needs of the life support system (e.g., tissues, wipes, pesticides), these needs are not now significant design drivers. A primary research and development effort required is an evaluation of the potential for growing non-food plants and extracting human nourishment from them. This area has the possibility of decreasing the amount of growing area required to support a given crew size, and thus lowering the power, mass and volume of the life support system. Alternate uses of biomass-producing plants should also receive research attention, but at a lower priority.

2.9 FOOD PROCESSING TECHNOLOGY

Significant effort should be put into research and development of food processing systems for life support applications. This work should address the reduction of size and mass of exisiting hardware (e.g., threshing machines, mills) as well as the development of novel techniques for extracting consumable nutrients from normally inedible materials. To the highest degree possible, this research and development should focus on automation and robotics, and on regenerative extraction and/or conversion techniques to sustain system closure and self sufficiency.

2.10 MONITORING AND CONTROL SYSTEMS

Research and development work is required on computerized monitor and control systems, sensor technologies, and automation and robotics. These topics must be addressed with regard to monitoring and maintaining life support systems which incorporate both physicochemical and bioregenerative technologies. Ideally, prototype monitor/control systems should be developed and tested on mass-closed full scale models of an LCELSS.

2.11 EV/HA SYSTEM INTEGRATION

EV/HA systems operating on the lunar surface will either be physically self-contained or linked via umbilical to the habitat life support. Self-contained systems will interface with LCELSS during pre-mission charging and post-mission servicing and/replenishment. In either case, the EV/HA system is effectively an LCELSS subsystem, and the nature of the EV/HA-LCELSS interface will impact the LCELSS design. It is recommended that increased research and development attention be directed at defining EV/HA technologies and nominal activities for potential lunar surface missions. The results of this attention must be combined with LCELSS conceptual design refinement to ensure optimization of each system with respect to self sufficiency, cost and mission effectiveness.

2.12 IN SITU RESOURCE UTILIZATION

Although the contribution of ISRU to the establishment and maintenance of an LCELSS does not appear to be a significant design driver, it is essential that developments in ISRU for industrialization be considered in refining the design of an LCELSS. For instance, small amounts of material removed from ISRU rocket fuel production (i.e., oxygen) would have little effect on the sizing of that system, yet could make a substantial contribution to the establishment of a self-sufficient LCELSS. Incorporation of ISRU considerations into refinement of LCELSS design also requires site-specific evaluation of the available resources, thus leading to a need for precursor flights.

More importantly, significant research and development should be directed toward production of easily recycled, organic materials for packaging or other "throw-away" materials. Such materials, if synthesized to include high concentrations of oxygen, carbon, nitrogen and hydrogen, could contribute significantly and very efficiently to filling the LCELSS' buffers and accelerating the processes leading to self sufficiency.

2.13 SURFACE MISSION MODELING AND DEFINITION

Lunar surface activities will be significant users of base power and LCELSS products, as well as potentially important (if not critical) suppliers of LCELSS-required materials, such as oxygen. Thus, more mature definitions of the scope and nature of lunar surface activities is required for the refinement of the LCELSS conceptual design. It is recommended that refinement of LCELSS conceptual designs be conducted in parallel to, and on an iterative basis with, expanded studies of lunar surface activities, including science activities, ISRU system requirements, and definition of surface system (EV/HA) activities.

2.14 POWER AND THERMAL CONTROL SYSTEMS

The use of higher plants to provide food, regenerate the atmosphere, and recycle water and waste requires substantial amounts of power if only artificial lighting is used. This finding supports the need for research and development on both power and thermal control systems for planetary/lunar base applications, as well as the need for research and development of efficient, low-mass mechanisms for capturing and transmitting sunlight.

SECTION 3
DEVELOPMENT OF CANDIDATE CONCEPTS

This section describes the performance requirements, design constraints, design advantages and assumptions made in conducting the study and in developing a spectrum of conceptual designs. Descriptions of the generic LCELSS structure and the five candidate concepts developed in Task 1 are also presented.

3.1 PERFORMANCE REQUIREMENTS

During the initial literature review, six performance requirements crucial to the development of the LCELSS conceptual design were identified. These included:

- Maximize safety and reliability. To be useful for life support, the system and its component subsystems must be as safe and reliable as possible. These factors have been incorporated into the LCELSS database as characteristics of each subsystem technology.

- Maximize self sufficiency. For this study, self sufficiency was defined as the completeness with which elements are recycled by the LCELSS, thus measuring the degree of mass closure achieved by the system. In absolute terms, self sufficiency is measured as the total mass of all chemical elements which must be added to the system to maintain nominal operation. This total mass is a function of several factors, including replacement of precipitates, replacement of losses due to leakage, etc. By this definition, the more mass that must be added to the LCELSS, the lower its performance with respect to self sufficiency. By defining self sufficiency in this fashion, LCELSS performance can be evaluated independently of the source of the added mass (e.g., from Earth versus from in situ lunar resources).

- Minimize resupply. One of the key concerns addressed by the use of CELSS and other closed-loop technologies is minimizing the need for logistical support. By making maximum use of all materials transported to the lunar surface and in situ resources, it will be possible to dramatically decrease the complexity and cost of logistical support. This reduction is extremely desirable for long duration missions such as lunar or Mars bases, not only because of the obvious savings in mission cost , but also because of the clear problem that would be presented by any interruption of launch schedules.

- Accommodate base evolution. It was assumed that the base life support system would be developed in an evolutionary fashion. This, in turn implies that the life support hardware would include scars for later addition of new subsystems or technologies, and that the computer control systems would include software hooks to enable easy addition or replacement of software subroutines. Implementing this requirement in the conceptual design dictated that particular consideration be focused on factors such as modularity and subsystem interfacing.

- Minimize residual waste. The philosophy of maximum self sufficiency implies minimizing the generation and discharge of non-recoverable waste materials. Ideally, all wastes should be reprocessed and recycled by the system. In some instances, however, discharge of materials to a storage dump may be necessary to maintain crew or system health. One such situation exists for metals such as chromium, aluminum and nickel, where it is essential to prevent these materials from entering the food production cycle where they can be bioconcentrated to unacceptable levels.

- Acceptable human lifestyle. The need to maintain a healthy crew dictates that the life support system inputs be of suitable quality and reliability to provide a reasonable analog to life on earth. In general, this means that the diet must supply all the necessary human nutritional requirements, that the water must be suitable for drinking, that trace contaminants are removed from both water and air, and that LCELSS living provide nominal levels of emotional satisfaction for the crew.

- Maximize use of lunar resources and activities. It is assumed that some of the capabilities normally associated with an advanced operation would be present, and that some lunar industrial activities such as mining or extraction of oxygen from regolith (for rocket fuel use) would be potential contributors to LCELSS needs.

3.2 DESIGN CONSTRAINTS/ADVANTAGES

The study identified both potential constraints and potential advantages imposed on the LCELSS conceptual design by the physical and operational environments. The design constraints included:

- Lunar physical environment. Four factors in the lunar environment which constrain the LCELSS design are radiation, thermal control requirements, the two-week long lunar day/night cycle, and in situ resource availability.

- LCELSS operation and maintenance demands. Very little data exist on the amount of crew time required to operate and maintain an LCELSS. Clearly, if the LCELSS design requires too much time to operate or maintain, it will detract from other crew activities and thus be undesirable.

- Bioregenerative and physicochemical subsystem compatibility. Because a subsystem technology may produce compounds which are not compatible with another technology to which it is connected, compatibility is a particularly important issue. As a result, the performance of the second subsystem may not be acceptable in that design. One example of this kind of compatibility issue is the production of trace volatiles by amine-based CO_2 absorption systems, which are especially toxic to higher plants in a food production system.

- Power Economy. Since electrical power will be at a premium on the lunar surface, it is imperative that the LCELSS conceptual design minimize overall system power utilization.

- Launch mass and volume. To reduce mission cost both the launch mass and launch volume of the system must be minimized. Ideally, the mass of the overall LCELSS plus its makeup must be lower than the mass of the alternative life support system plus the total mass required to replenish its life support for the mission duration.

The design advantages identified by the study included:

- Lunar environment. The four potential advantages offered to LCELSS by the lunar surface physical environment include: 1) 1/6 Earth gravity, 2) use of the lunar surface as a thermal sink, 3) availability of sunlight, and 4) availability of in situ resources.

- In situ radiation protection. The lunar surface provides a capability for shielding the LCELSS from radiation by locating the lunar base or portions of the LCELSS in the shadow of lunar geographical features such as mountains or crater walls, or by using lunar regolith directly as a shielding agent.

- Construction/operations area. Unlike free space, the lunar surface provides an area in which to conduct construction operations. As a result, it may be possible to use construction techniques quite similar to those used on Earth.

3.3 DESIGN ASSUMPTIONS

Several assumptions were made in developing the LCELSS conceptual design. These included:

- Base is an advanced concept. Since a primary study assumption is that the lunar base was to be considered an advanced concept, capabilities for in situ resource utilization and accompanying industrialization, as well as for scientific research and experimentation are considered in the analyses.

- Emphasize implementation of bioregenerative technologies. Life support system design was focused on the use of bioregenerative technologies, although the approach was to evaluate both bioregenerative and physicochemical technologies and select the most appropriate.

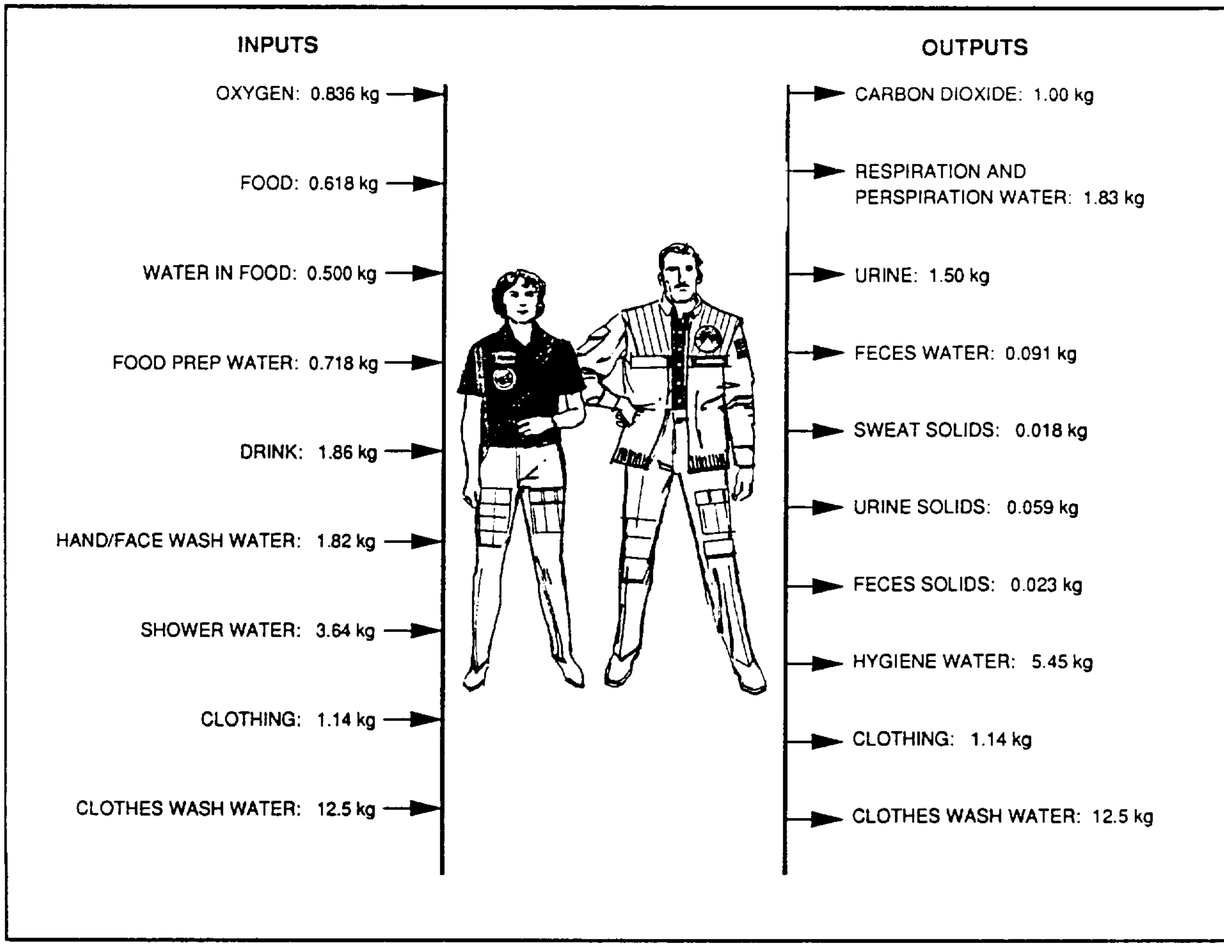
- Utilize only existing or near-horizon technologies. Although the base was considered an advanced design for study purposes, the conceptual design includes only those technologies which exist currently or which are expected to be realizable in the near-term time horizon. This assumption ensured as realistic and accurate a system conceptual design as possible.

- Values of Life Support Mass Inputs/Outputs. The life support mass inputs and outputs used in this study were identified during the initial literature review. Figure 3.1 shows these mass flow rates on a per person per day basis.

- Disregard power and thermal control penalties. Because NASA has made no selections for power supply and thermal control technologies, the study assessed no mass or volume penalties in developing the conceptual design. Both power and thermal requirements were calculated, however to support such assessment in future studies which might utilize such data.

- Separation of life support system and industrial/scientific reservoirs. In order to protect the life support reservoirs, and because all of the lunar base industrial/science activities could not be anticipated at this time, the assumption was made that materials reservoirs would not be shared between the life support system and the other activities (except for atmosphere). This assumption eliminates the necessity of designing systems to remove and recycle unknown waste materials produced by base scientific or industrial activities. The common atmosphere assumption implies that: 1) the crew is supplied with breathable atmosphere in the science/industrial areas by the base life support technology, and 2) trace contaminants are removed from the science/industrial area atmosphere before returning it to the LCELSS.

Figure 3.1. Life Support Mass Inputs/Outputs (kg per person per day).



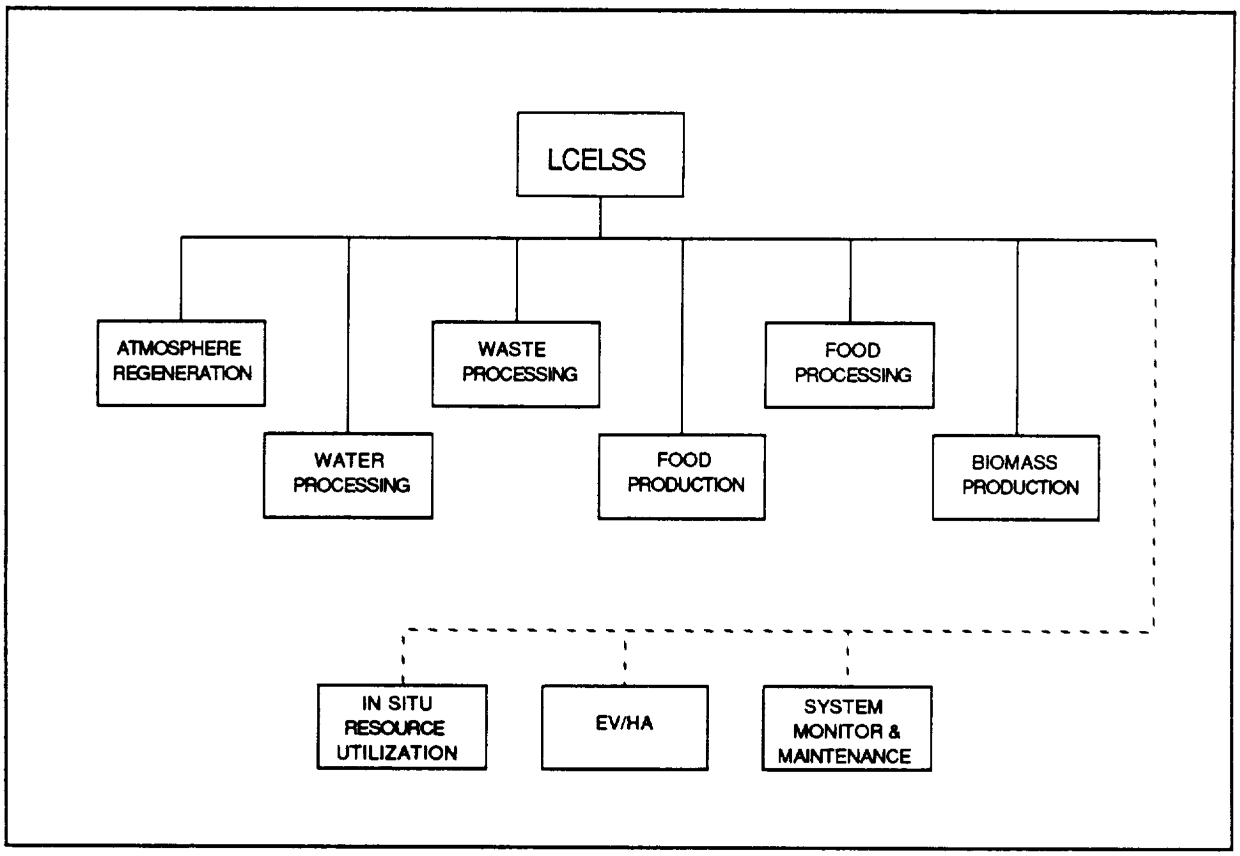
- <u>Isolation of water purification, waste processing and industrial/scientific systems.</u> It was assumed that water and waste processing systems for life support were separate from those for industrial/scientific water and wastes to prevent contamination of the life support subsystems.

- <u>Early assembly and filling of LCELSS buffer reservoirs.</u> It was assumed that LCELSS buffer reservoirs be assembled as early as possible during the evolutionary construction of the advanced base, so that waste materials could either be stored directly for subsequent use, or be converted into more useful compounds/elements and then stored for later use.

3.4 SUBSYSTEM IDENTIFICATION AND DESCRIPTION

All of the conceptual design candidates considered were based on a generic system organization (Fig. 3.2) consisting of six constituent subsystems, along with three other interfacing systems (in situ resources utilization, extra-vehicular habitat activity and system monitoring and maintenance). Brief descriptions of each subsystem/system, their respective functions, and the technologies identified by the literature review as being potentially applicable are presented below.

Figure 3.2. Generic LCELSS Organization.



3.4.1 Atmosphere Control and Regeneration Subsystem

The atmosphere control and regeneration subsystem includes technologies to remove and reduce carbon dioxide, supply oxygen, and control temperature, relative humidity, atmospheric pressure and trace contaminant load. The results of the initial review of technologies available to accomplish these functions are summarized in Fig. 3.3.

Figure 3.3. Candidate Atmosphere Control and Regeneration Technologies (Not Prioritized).

A. Carbon Dioxide Removal
1. Metal Hydroxide (e.g., LiOH, Ca(OH)2)
2. Metal Carbonate (e.g., K_2CO_3)
3. Electrochemical Depolarized CO_2 Concentrator (EDC)
4. Solid Amine Water Desorbed (SAWD)
5. Solid Amine Vacuum Desorbed (HSC)
6. Molecular Sieve
7. Carbon Molecular Sieve
8. Metal Oxides
9. Semipermeable Membrane
10. Higher Plants
11. Algae
12. CO_2 Electrolysis
13. Liquid Amine

B. Oxygen Supply
1. High Pressure Gas Storage
2. Cryogenic Storage
3. Potassium Superoxide
4. Electrolyzer (e.g., Static Feed, Solid Polymer)
5. Gas Concentrator (e.g., Semipermeable Membrane, Molecular Sieve)
6. Higher Plants
7. Algae
8. Lunar Soil Processing
9. Water Electrolysis (Liquid or Vapor)

C. Carbon Dioxide Reduction & Oxygen Supply
1. Sabatier
2. Bosch
3. Sabatier/Carbon Formation Reactor
4. Solid Electrolyte

D. Humidity Control
1. Condensing Heat Exchanger
2. Dessicant
3. Hydrophilic/Hydrophobic Membrane Separator

E. Temperature Control
1. Heat Exchanger
2. Heat Pipe
3. Thermoelectric Unit

F. Trace Contaminant Control
1. Filter
2. Activated Carbon
3. Catalytic Oxidizer
4. Cold Trap
5. UV Irradiation
6. Chemical Absorption

G. Atmospheric Pressure Control
1. High Pressure Gas Storage
2. Hydrazine Decomposition to N_2
3. Cryogenic Storage

3.4.2 Water Processing Subsystem

The LCELSS water processing system must collect, purify, store, and redistribute both potable and hygiene water. The waste water types available for recycling range from relatively pure to moderately contaminated to highly contaminated. Sources of relatively pure water include humidity condensate, fuel cells, and carbon dioxide reduction. Moderately contaminated, or grey, water includes that from personal hygiene sources (hand and face wash, shower, etc.), food preparation, and dish washing. The highly contaminated, or black, water includes urine, feces water, and commode flush water. Technologies identified in the initial review as available for recycling water are summarized in Fig. 3.4. (Note that the recycling of relatively pure water can generally be achieved by using the polishing technologies listed under Water Polishing, Storage & Distribution).

Figure 3.4. Candidate Water Processing Technologies (Not Prioritized).

A. Grey Water
1. Reverse Osmosis
2. Multifiltration
3. High Temperature Distillation
4. Vacuum Distillation
5. Higher Plants
6. UV Irradiation
7. Air Evaporation
8. Bacterial Filter
9. Enzymatic Processing

B. Black Water
1. Vapor Compression Distillation (VCD)
2. Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES)
3. High Temperature Distillation
4. Vacuum Distillation
5. UV Irradiation
6. Higher Plants (e.g., Halophytes)
7. Air Evaporation
8. Bacterial Filter
9. Electrolytic Processing
10. Enzymatic Processing

C. Water Polishing, Storage & Distribution
1. UV Irradiation
2. Ozone
3. Hypochlorite
4. Iodine
5. Thermal Processing
6. Submicronic Filtration
7. Iodinated Resin Filtration

3.4.3 Solid Waste Processing Subsystem

The processing of solid wastes, of both biological and non-biological origin, is instrumental in achieving full self sufficiency of the LCELSS. These waste materials provide sources of carbon, nitrogen, hydrogen and oxygen, all of which play critical roles in operation of the life support system. Figure 3.5 summarizes the solid waste processing technologies identified in the initial review.

Figure 3.5. Candidate Solid Waste Processing Technologies (Not Prioritized).

A. Incineration
B. Low Temperature Wet Oxidation
C. Wet Oxidation
D. Super Critical Wet Oxidation
E. Bacterial Filter (Bed or Reactor)
  1. Aerobic
  2. Anaerobic
F. Higher Plants
G. Algae
H. Ultrasonic Processing
I. UV Irradiation
J. Electrostatic Processing
K. Plasma
L. Goats with Aerobic Bacterial Digester
M. Enzymatic Processing

3.4.4 Food Production Subsystem

Historically, astronauts have eaten foods which were stored aboard their spacecraft at launch. For LCELSS, reaching full self sufficiency will require the incorporation of a food production system which will convert waste materials into edible foodstuffs. A summary of the food production technologies identified by the initial review is presented in Fig. 3.6.

Figure 3.6. Candidate Food Production Technologies (Not Prioritized).

A. Higher Plants
  1. Vegetables
  2. Grains
  3. Legumes
  4. Root/Tuber Crops
B. Algae
C. Vertebrate Animals
  1. Terrestrial
  2. Aquaculture
D. Invertebrate Animals
  1. Terrestrial
  2. Aquaculture
E. Bacteria
  1. Photosynthetic
  2. Non-photosynthetic
F. Yeast
G. Fungus
H. Physicochemical
  1. Carbohydrate
  2. Protein
  3. Fat
I. Enzymatic Processing
  1. Synthetic Enzymes
  2. Biophysicochemical Processes

3.4.5 Food Processing Subsystem

Food processing ranges from relatively simple manual tasks (e.g., cleaning vegetables), to very elaborate technologies (e.g., conversion of cellulose to glucose, extraction of fats or proteins). Specific technologies were not identified for food processing during the initial literature review. Food processing techniques are heavily influenced by the raw materials being processed. As a consequence, the study involved a detailed analysis of this subsystem during Task 4, after the desired diet and associated foodstuffs had been identified.

3.4.6 Biomass Production Subsystem

Virtually all of the previous CELSS-related plant research has been directed at satisfying food production or atmospheric regeneration requirements. As a consequence, little attention has been directed at identifying non-food uses of plants (or, for that matter, animals). There are however, a number of such potential uses, including the production of lubricating oils, rubber, pharmaceuticals, resins, or fuels (e.g., ethanol, methanol). The technologies identified for this subsystem involve living organisms (by definition), and a summary of those identified in the literature review is presented in Fig. 3.7.

Figure 3.7. Candidate Biomass Production Technologies (Not Prioritized).

A. Higher Plants
1. Woody Plants (e.g., Scrub Pine)
2. Forage Plants (e.g., Alfalfa)
3. Fiber Plants (e.g., Cotton, Flax)
4. Crop Plants (as a secondary or by-product)
5. Oil/Rubber Plants

B. Algae
C. Vertebrate Animals
D. Invertebrate Animals
E. Bacteria
F. Yeast
G. Fungus
H. Physicochemical Methods

3.4.7 In Situ Resource Utilization (ISRU)

A wide range of technologies was identified for ISRU during the literature review. These ranged from the direct use of lunar regolith as a radiation shield to sophisticated technologies for the mining of regolith and extraction of raw materials. Figure 3.8 summarizes ISRU technologies.

Figure 3.8. Candidate In Situ Resource Utilization Technologies (Not Prioritized).

A. Regolith Bags
B. Thermal Release (Gases)
C. Carbonyl Processing
D. Electrolysis (e.g, Molten Silicates)
E. Ilmenite Reduction
F. Destructive Distillation
G. Lunar Concrete
H. Lunar Glass
I. Bacterial Mining
J. High Temperature Processing (e.g., Glass Fiber)

3.4.8 Extravehicular/Extrahabitat Activity (EV/HA)

Activity on the lunar surface external to the base is likely to be performed using both rovers and space-suited crew. As a result, the LCELSS must accommodate interfaces with both suit and rover life support systems. Technology candidates identified for this application are listed in Fig. 3.9.

Figure 3.9. Candidate EV/HA Technologies (Not Prioritized).

A. Carbon Dioxide Removal
  1. Metal Hydroxide (e.g., LiOH, $Ca(OH)_2$)
  2. Metal Carbonate (e.g., K_2CO_3)
  3. Metal Oxide (e.g., Ag_2O)
  4. Electrochemically Regenerable Carbon Dioxide Absorber (ERCA)
  5. Solid Amine Vacuum Desorbed (HCCS)
  6. Freeze Out
  7. Carbon Molecular Sieve
  8. Algae

B. Oxygen Supply
  1. High Pressure Storage
  2. Cryogenic Storage
  3. Algae

C. Humidity Control
  1. Condensing Heat Exchanger
  2. Dessicant

D. Temperature Contol
  1. RNTS (Thermoelectric Cooler, Wax Capacitor & Radiator)
  2. Metal Hydride
  3. Sublimation

E. Interfacing
  1. Liquid Exchange
  2. Atmospheric Exchange

3.4.9 LCELSS Monitoring and Maintenance

In the past, life support systems have been designed to meet specific requirements for each environmental variable (usually a nominal value plus tolerance limits). These requirements have been derived from a basic understanding of the physiological needs of living organisms, and from observations of the effects of exceeding the tolerance limits. Life support systems have not been designed, however, with low stress or health maintenance in mind. For lunar base application, the ultimate goal of an LCELSS must not be to simply sustain existence, but to supply an environment which maximizes the productivity and health of the crew. As a result, the computerized process control system that monitors and maintains the functions of the LCELSS is of vital importance. In addition, because the LCELSS will include living organisms other than humans, it is imperative that the monitoring and maintenance system address the issues involved in monitoring their performance. Figure 3.10 summarizes the technologies identified by the literature review.

Figure 3.10. Candidate LCELSS Monitoring and Maintenance Technologies (Not Prioritized).

A. Crew
  1. Telemetry (Temperature, Heart Rate)
  2. Metabolic Rate (Direct measurement, medical checkups)
  3. Physical Exams

B. Higher Plants
  1. Remote Spectral Sensing
  2. Nutrient Uptake
  3. Water Throughput
  4. Nutrient Solution Bacterial/Fungal Load

C. Algae
  1. Spectral Sensing (Cell Density)
  2. Metabolic Measurement
  3. Nutrient Uptake
  4. Media Bacterial/Fungal Load

D. Vertebrate Animals
  1. Telemetry Implants (Temperature, Heart Rate)
  2. Metabolic Rate

E. Invertebrate Animals
  1. Metabolic Rate
  2. Nutrient Uptake

F. Bacteria
  1. Spectral Sensing (Cell Density)
  2. Metabolic Measurement
  3. Nutrient Uptake

G. Fire Monitoring
  1. Thermal Sensor
  2. Particulate Sensor
  3. Atmospheric Optical Density

H. Toxic/Contaminant Monitoring
  1. Gas Chromatograph/Mass Spectrometer
  2. Specific Gas Contaminant Sensor
  3. Ion Chromatograph/HPLC
  4. Specific Contaminant Sensors
  5. Bacterial Enumeration (CFUs)
  6. Bacterial Taxonomy
  7. Biological Sensor

I. Radiation Monitoring
  1. Dosimeter
  2. Charged Particle Detector

3.5 CANDIDATE CONCEPT DESCRIPTIONS

Initial analysis focused on identifying candidate configurations for the LCELSS. Five different design concepts were identified as potential candidates. Each of these candidates is discussed in detail below.

3.5.1 Physicochemical System With Food Resupply (Candidate 1)

The first configuration we identified was essentially the same as Gustan and Vinopal's (1982) closure scenario D, which involved physicochemical air and water recycling with food resupply. It incorporates current, available technology for air and water recycling, all of which are at a high level of technical maturity. A block diagram of this configuration is provided in Fig. 3.11. Candidate 1 was intended to serve as a reference point for the succeeding analysis.

In this option, food is provided through resupply, and waste materials are stored. As a first step in LCELSS evolutionary development, this candidate provides a safe haven as well as an in-place backup system. It also supports the establishment and filling of LCELSS buffers early in the base development sequence. It provides the minimum initial launch cost, power consumption, crew time requirement and system complexity, but it has the highest logistics costs and the lowest self sufficiency. In summary, although this candidate makes sense as the first step in LCELSS development, it is an interim option only, as the base must develop a capability for self sufficiency as quickly as practical.

3.5.2 Physicochemical System With Carbohydrate Synthesis (Candidate 2)

This candidate incorporates the same air and water recycling technologies as those used in Candidate 1, but adds the capability for producing carbohydrates for human consumption. Over 90% of a human's energy needs come from carbohydrates, and thus their importance for life support. By adding this capability, the resupply mass requirement for the base is significantly reduced, and self sufficiency is increased.

A number of methods for chemically synthesizing carbohydrates were reviewed, and a generic scheme for inclusion in this option was developed (Fig. 3.12). One of the primary problems in carbohydrate synthesis involves the need for relatively pure raw materials. The yield of the

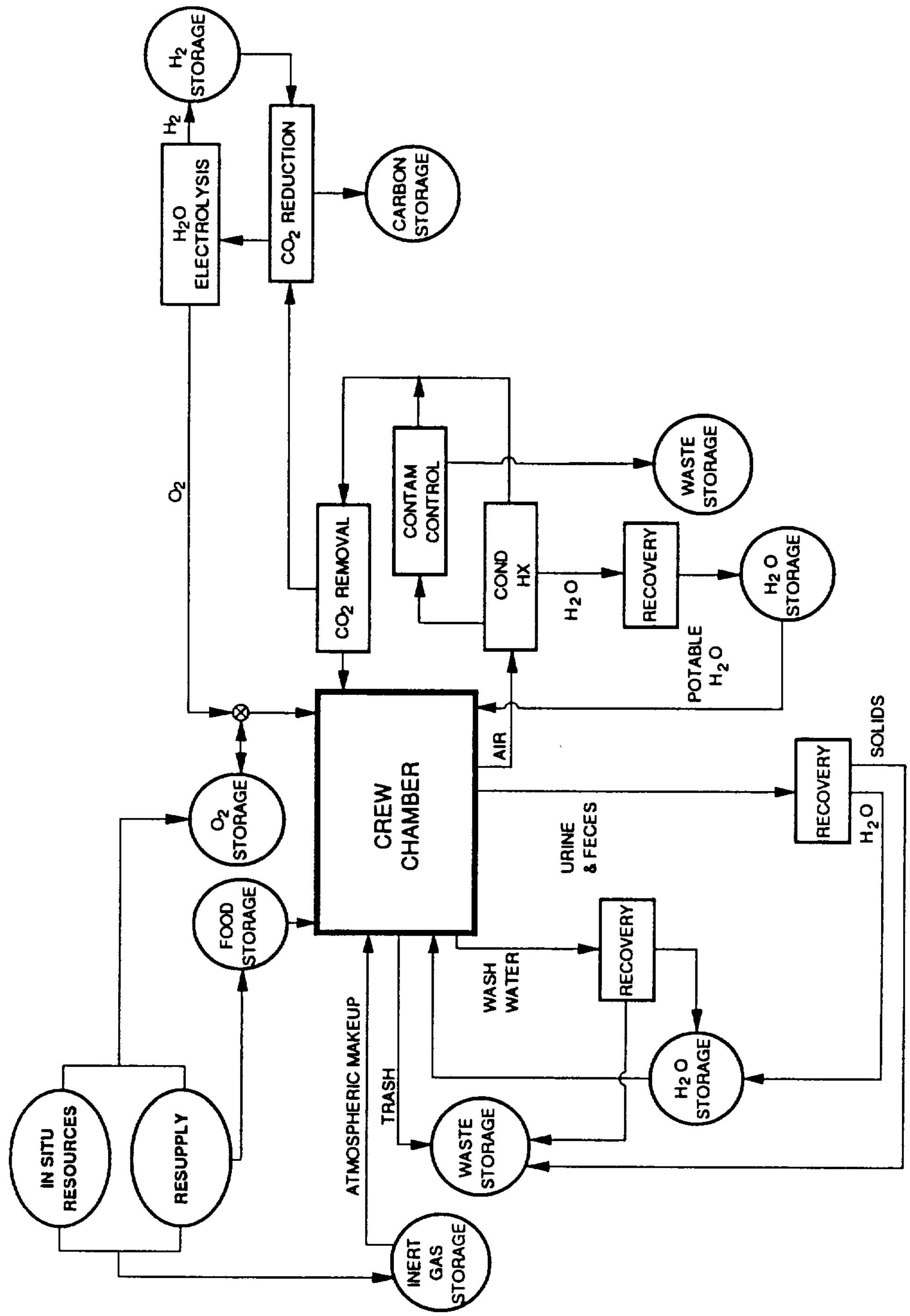


Figure 3.11. Physicochemical System With Food Resupply (Candidate 1).

synthesis process is strongly related to the purity of the raw materials, and high degrees of purity are not easy to achieve using waste materials as feedstocks for the synthesis process. In addition, the process produces equal amounts of d- and l-isomers, so that only 50% of the carbohydrate produced can be digested by humans. This decrease in overall system efficiency is partially alleviated by recycling the non-digested isomers along with the other waste materials.

In general, synthesized foods of this sort are not assimilated well by humans. Since they frequently cause intestinal disorders or other adverse symptoms, synthesized materials are usually considered appropriate only for short-term human consumption. Also, since these recent technologies have never been tested in the space environment, they are therefore considered unattractive. There are also concerns about potential increases in the Trace Contaminant Control System (TCCS) capabilities which might be required due to side products being produced (such as formaldehyde) by the synthesis reactions.

3.5.3 Hybrid System With Animal Food Production (Candidate 3)

This candidate was considered as another potential means for closing the food loop by using a wide variety of animal species as potential food sources (Fig. 3.13). The most critical selection criteria were that the selected species had to be capable of eating very low grade human waste materials (possibly supplemented with high grade stored animal food) and producing a high-quality human food. Although we found no animal species clearly capable of meeting these criteria, we were able to calculate overall physical characteristics of the life support system based on some optimistic assumptions regarding input/output ratios and production efficiencies.

It was found that the system complexity increased substantially, along with a small increase in system self sufficiency (relative to Candidate 1). The methods and technologies which could be employed for implementing this design are extremely uncertain, however. In addition, the system mass increased significantly, and the power requirements increased by about 45%.

3.5.4 Hybrid System With Plant Food Production (Candidate 4)

This is the usually discussed CELSS concept (Ref. Fig. 3.14). This candidate provides an extremely high degree of self sufficiency by almost totally closing the food loop. It also provides a number of potential psychological benefits, many of which have been described by Soviet cosmonauts during long stays in space.

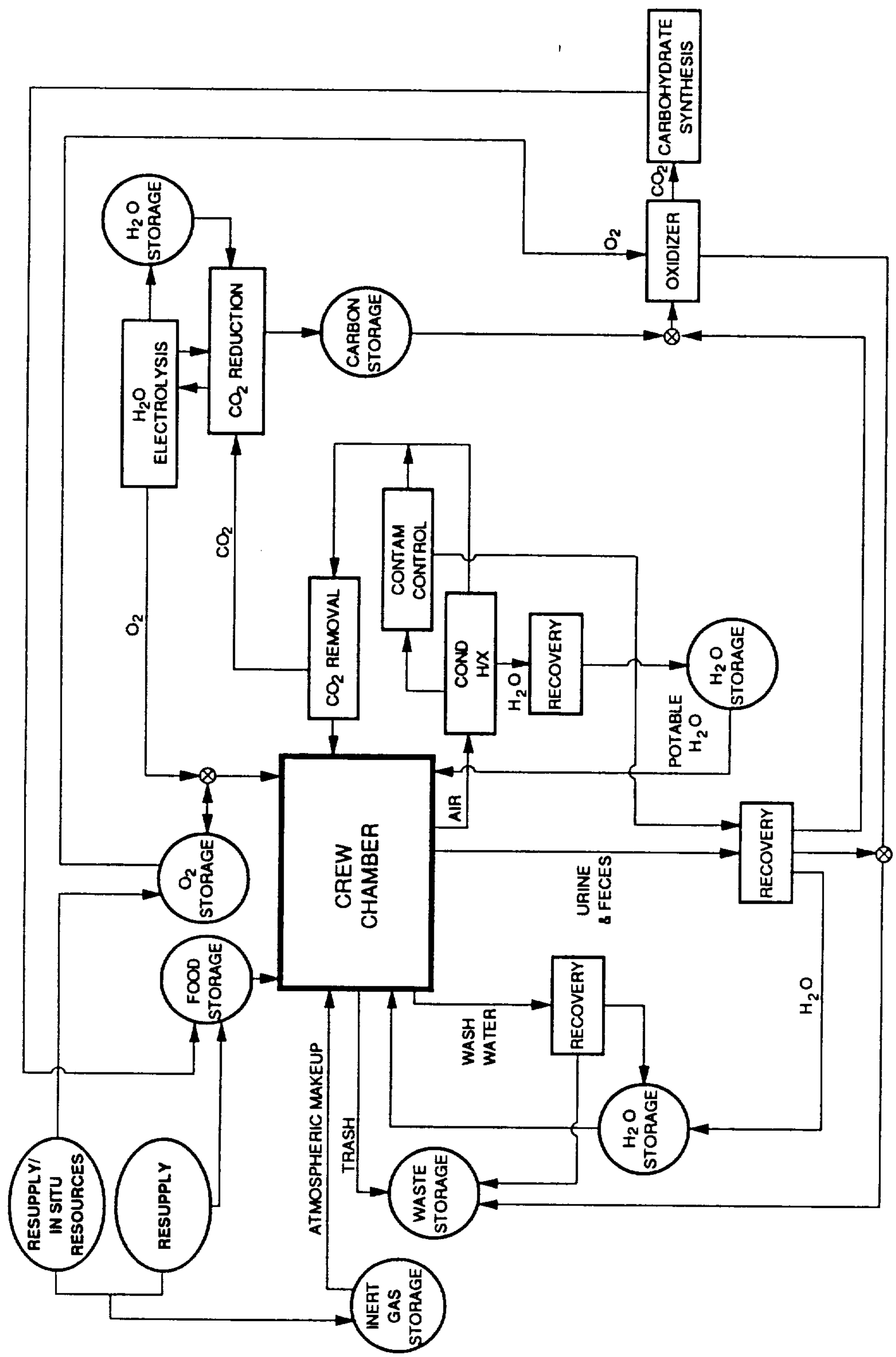


Figure 3.12. Physicochemical System With Carbohydrate Production (Candidate 2).

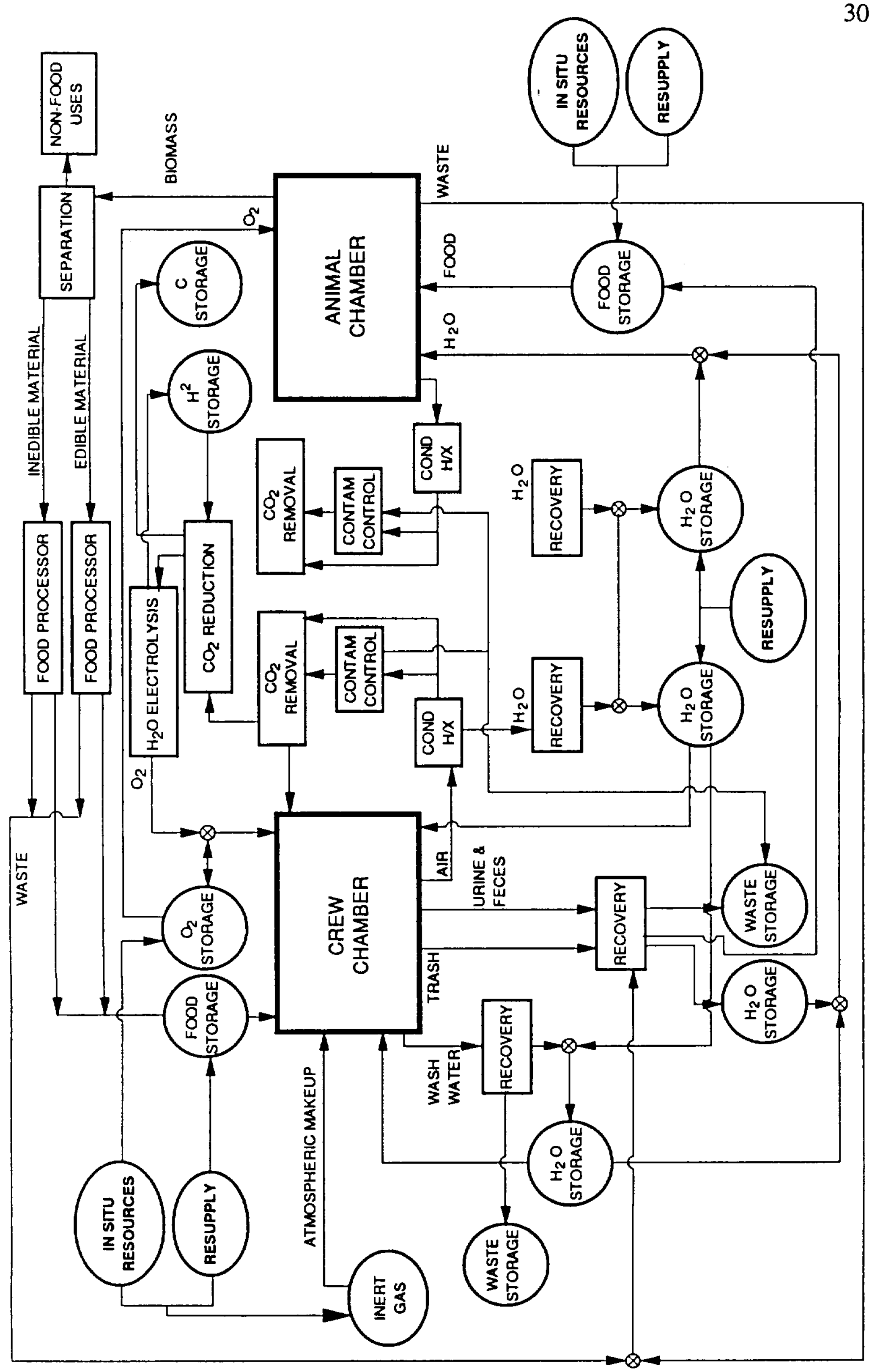


Figure 3.13. Hybrid System With Animal Food Production (Candidate 3).

The primary drawbacks to implementation of this concept are the extremely high requirement for power, and the substantial increase in system mass needed for the plant growing system. One additional problem is the difficulty of meeting all of a human's dietary requirements and/or dietary needs with a completely vegetarian diet. In this last case, it may be possible to achieve a nutritionally complete diet by providing vitamins or protein supplements to the crew through resupply.

3.5.5 Hybrid System With Plant and Animal Food Production (Candidate 5)

The block diagram for this candidate is pictured in Fig. 3.15. The central focus of this option is to close the food loop by providing a diet which completely meets the human's dietary requirements and/or dietary needs. In the past this option has generally been dismissed because of the perceived inefficiency of animals in converting food into biomass suitable for human consumption. Our initial analysis indicated that this perception was not true of all animal species.

This candidate promised the maximum nutritional quality and the maximum crew acceptance. It also had the largest mass, the highest design complexity and appeared to require the largest amount of attention by the crew. Because of its dietary diversity, however, it potentially provided the highest level of self sufficiency.

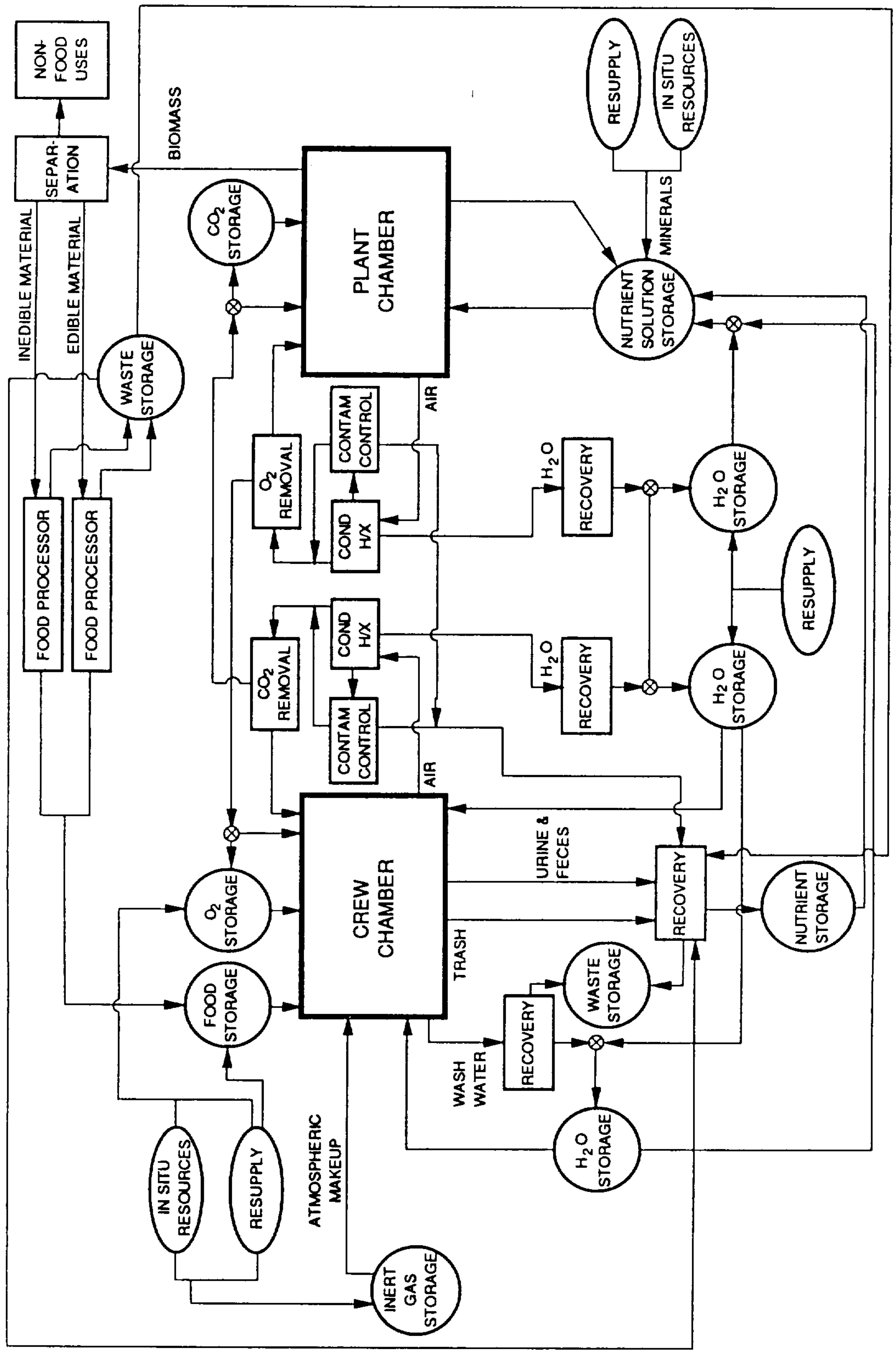


Figure 3.14. Hybrid System With Plant Food Production (Candidate 4).

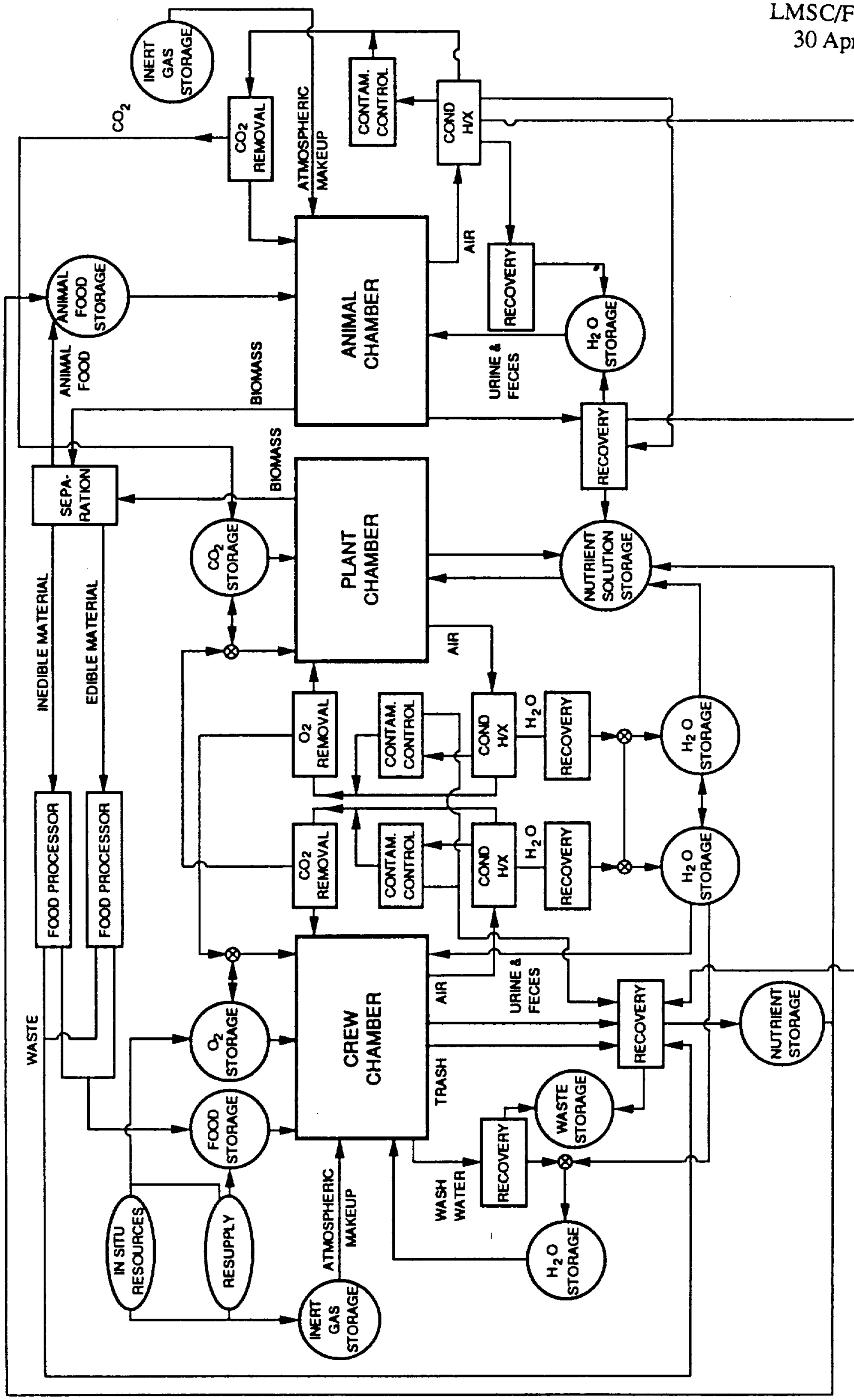


Figure 3.15. Hybrid System With Plant and Animal Food Production (Candidate 5).

3.6 CANDIDATE CONFIGURATION ANALYSIS

Figure 3.16 summarizes the initial engineering estimates of the fundamental physical characteristics for each of the five candidate configurations. The results reflect an analysis for an LCELSS with an assumed crew size of 30. The analysis includes only the characteristics directly associated with the design candidates described above, and does not include living quarters, power supply, or heat rejection systems.

Figure 3.16. Initial Mass, Volume and Power Estimates for Candidate LCELSS Design Concepts.

CANDI-DATE	LCELSS DESIGN CONFIGURATION	RESUPPLY MASS 1 (kg/day)	SELF SUFFI-CIENCY 2 (%)	SYSTEM MASS (kg)	SYSTEM VOLUME (m^3)	SYSTEM POWER 3 (kW)
1	Physicochemical with food resupply (baseline)	35	---	28,850	230	115
2	Physicochemical with carbohydrate synthesis	20	43	31,000	255	150
3	Hybrid with animal food production	30	14	93,250	1,050	165
4	Hybrid with plant food production	2	92	211,200	2,075	685
5	Hybrid with plant and animal food production	<0.1	>99	222,700	2,320	595

1. Includes mass of both dry foodstuff and food water.
2. Calculated relative to baseline, Candidate 1.
3. Plant production system assumed to be wholly artificially lighted.

Based on this initial analysis, Lockheed recommended and NASA approved the recommendation that Candidate 5 be selected as the design concept for further study because of its high self sufficiency score. The LCELSS conceptual design developed during this study was thus focused on a system which included both plants and animals as potential human food sources.

SECTION 4
TRADEOFFS AND ANALYSES

This section summarizes the results of the detailed tradeoff studies and systems analyses performed in support of the conceptual design process. Ten specific topics which required tradeoff studies and/or analyses were identified during the initial part of the study: 1) lighting for plant photosynthesis, 2) waste processing technology selection, 3) animals as human food in a LCELSS, 4) aquaculture system feasibility, 5) food processing technology review, 6) dietary/nutritional evaluation, 7) feasibility of using membranes for gas separation, 8) crew time requirements for LCELSS implementation, 9) cooling/heating requirements of a transparent structure on the lunar surface, and 10) in situ resource utilization. Each of these topics is discussed in the following sections.

4.1 LIGHTING ANALYSIS FOR PLANT PHOTOSYNTHESIS

One of the most significant drivers in the design of an LCELSS is the means by which light is supplied to photosynthetic organisms. In this study, three methods of supplying Photosynthetically Active Radiation (PAR) to plants or photosynthetic bacteria were analyzed: 1) natural sunlight during lunar day, followed by a refrigerated, dark cycle during lunar night, 2) natural sunlight during lunar day, followed by artificial light (at lower intensity) during lunar night, and 3) completely artificial light, regardless of lunar diurnal cycle.

The use of natural sunlight during lunar day, followed by a refrigerated, dark cycle during lunar night was evaluated by Gitelson, et al. (1989). This research tested a variety of food plants under continuous light at 24°C for 15 days, followed by continuous dark at 2.5 - 3°C for 15 days. When exposed to these conditions, several plant species (tomatoes, cucumbers and sedge-nut) did not survive. Other plant species (wheat, barley, peas, turnip, dill, carrot, beet, radish) tolerated the environmental shift, but suffered visible tissue damage and produced edible yields 30-50% lower than control plants. As a result, this option seems viable if growing areas are increased to make up for the yield losses. However, it was not considered desirable for the purposes of this study.

The use of natural sunlight during lunar day, followed by artificial light during lunar night maximizes the efficiency of electrical power usage. During lunar day, the plants could be supplied with PAR as high as 2400 $\mu mol/m^2/sec$. During lunar night, the plants would be illuminated at

PAR levels of 10-15% of full Earth surface sun (200-300 μmol/m²/s). By providing an elevated atmospheric CO_2 concentration during this interval, the plants can be kept growing, albeit at a slower pace than with full sunlight intensity.

The exclusive use of artificial lighting provides the most straightforward method of supplying PAR. By not using sunlight, however, this method substantially increases the amount of electrical power required to support the plants.

4.1.1 Artificial Lighting

Table 4.1 summarizes the power allocations of different types of electrical lamps. Although the highest efficiency (27%) for conversion of electrical power to PAR (400-700 nm) is provided by low pressure sodium lamps, these lamps provide an essentially monochromatic light which may not be suitable for all varieties of higher plants. A number of other lamp types have conversion efficiencies in the 20-25% range and provide emission spectra which are more acceptable to a diversity of higher plants.

Data for the most efficient, wholly artificially-lighted plant growth system known, (Phytofarm, DeKalb, Ill) was used in calculating the amount of power required for artificial lighting of a plant growth unit. The Phytofarm system utilizes optimally-designed 1000 W high pressure sodium (HPS) lighting with custom designed reflectors and cooling water jackets for each lamp. The system was designed to provide a nominal PAR of 300 μmol/m²/s, and achieves near that value with new lamps (M. Bates, personal communication). After about three years, the output of these lamps is significantly reduced, however, and the PAR values are more typically around 150 μmol/m²/s (R. Bula, personal communication). The lighting system installed at Phytofarm averages approximately 255 W/m² of growing area (based on bulb wattage).

Based on the data in Fig. 4.1, only four lamp types were determined to be efficient enough to merit consideration for LCELSS use. These were HPS, LPS, metal halide (MH), and cool white fluorescent (CWF). In analyzing the power requirements for an artificially-lighted LCELSS, the Phytofarm installed HPS wattage was used as a baseline. Using the data in Fig. 4.1, the PAR output of the other three lamps was evaluated relative to that of the HPS. Figure 4.2 shows the installed lamp wattage required per square meter of growing area to produce 300 μmol/m²/s PAR.

Figure 4.1. Power Allocation of Light Sources.*

Lamp Type	Total Input Power (Watts)	Visible Radiation (400-700nm) (%)	Nonvisible Radiation (%)	Conduction and Convection (%)	Ballast Loss (%)
Incandescent:					
60A	60	6	84	10	0
100A	100	7	83	10	0
200A	200	8	83	09	0
Fluorescent:					
Cool White (FCW)	46	20	32	35	13
Cool White (FCW)	225	20	37	39	4
Warm White (FWW)	46	20	32	35	13
Plant Growth A (PGA)	46	13	35	39	13
Plant Growth B (PGB)	46	15	35	37	13
Clear Mercury (HG)	440	12	63	16	9
Mercury Deluxe (HG/DX)	440	13	62	16	9
Metal Halide A (MHA)	460	20	54	13	13
Metal Halide B (MHB)	460	22	52	13	13
High-Pressure Sodium (HPS)	470	25	47	13	15
Low Pressure Sodium (LPS)	230	27	25	26	22

*Source: Cathey and Campbell, 1974.

The mass per square meter of growing area for several artificial lighting systems as a function of lamp type and lamp wattage was estimated from the information presented in Fig. 4.2. These mass estimates are summarized in Fig. 4.3. As these values indicate, the most effective lighting systems from a mass perspective are the 1000 W HPS and MH systems. Only slightly less mass-effective are the 175 W MH and 150 W HPS lamps. The least effective illumination systems are the CWF and LPS lamps, which require approximately 3-6 times more mass for equivalent PAR.

The potential effectiveness of high-intensity light-emitting diodes or LED's was also analyzed in evaluating artificial light sources. Like the LPS lamp, these devices are essentially monochromatic light sources. Unlike LPS lamps, their light emission characteristics can be altered by judicious choice of the impurities used to dope the electrode. The most common high-intensity LED's emit in the red portion of the visible spectrum. There are also some silicon carbide based LED's which emit in the blue portion of the visible spectrum,. but their intensity is much lower than that typical of high-intensity red LED's. Work in progress at the Wisconsin Center for Space Automation and Robotics (WCSAR) has indicated that it may be possible to provide an acceptable source of PAR with high-intensity red LED's supplemented by about 30 $\mu mol/m^2/s$ of light from blue LED's. (R. Bula, personal communication.)

Figure 4.2. Installed Lamp Wattage Required to Produce 300 $\mu mol/m^2/s$ of Photosynthetically Active Radiation (PAR).

Lamp Type	Installed Lamp Wattage Required
High Pressure Sodium (HPS)	255
Metal Halide (MH)	319
Cool White Fluorescent (CWF)	319
Low Pressure Sodium (LPS)	237

Figure 4.3. Lighting System Mass Estimates.

Lamp Type	Lamp Wattage	Mass/m^2 (kg)
High Pressure Sodium (HPS)	150	7.7
	250	8.4
	400	11.2
	1000	6.1
Metal Halide (MH)	175	6.6
	250	8.7
	400	10.9
	1000	6.2
Cool White Fluorescent (CWF)	110	34.3
	215	20.9
Low Pressure Sodium (LPS)	90	31.8
	180	23.5

Two particular advantages of LED technology are that: 1) it does not present a problem of mercury contamination if the device is broken, unlike conventional lamps, and 2) LED lifetimes are significantly longer that conventional lamps, providing as much as 100,000 hours of illumination with only a 20% decrease in output. Most conventional lamp types have lifetime figures of

10,000-20,000 hours, and some lamp types can loose as much as 40-50% of their initial output intensity over their lifetime.

Assuming that LED's could provide an acceptable source of illumination for LCELSS use, the mass and power associated with use of an LED lighting system were evaluated. WCSAR has estimated that a printed circuit board for illumination of 1 m^2 area would have a mass of about 4 kg (including LED's), and would require about 400 W to produce a PAR of at least 300-400 $\mu mol/m^2/s$ (R. Morrow and R. Bula, personal communication). One of the main problems in estimating LED power use is the extreme variability in PAR output of high intensity LED's. If more uniform LED's could be fabricated, or if a screening process was developed to enable selection of more uniform devices, it is probable that this power requirement would be reduced while maintaining PAR at the desired value. Thus, based on current technology estimates, an LED-based illumination system would be about 2/3 the mass of the 1000 W HPS and MH systems described above, but would use about 50% more power.

4.1.2 Natural Sunlight

In space, the 400-700 nm wavelength band of the solar spectrum is approximately 516 W/m^2, or 2375 $\mu mol/m^2/s$ (CRC Handbook of Physics and Chemistry, 1980). For comparison, the 400-700 nm band on the Earth's surface is about 435 W/m^2, or about 2000 $\mu mol/m^2/s$, at sea level at midday on a cloudless summer day. Thus, each square meter of collection surface exposed to solar radiation in space or on the lunar surface can provide about 8 m^2 of area with a PAR of 300 $\mu mol/m^2/s$.

Three methods of using solar radiation directly for illumination of plants were identified. The first utilizes a fiber optic system called the Himiwari designed by Dr. K. Mori. (See Fig. 4.4). The unit is a matrix of fresnel lenses, each of which is focused on a fiber optic bundle. The spectrum of the light transmitted by each bundle is determined by the distance between the lens and the end of the bundle. Descriptive and performance data provided by Dr. Mori were used to specify the physical characteristics of a series of Himiwari collectors (Fig. 4.5). This table also presents physical data on a fiber optic solar collection system (Oleson, et.al., 1987) specifically designed for use in micro-gravity on Space Station Freedom.

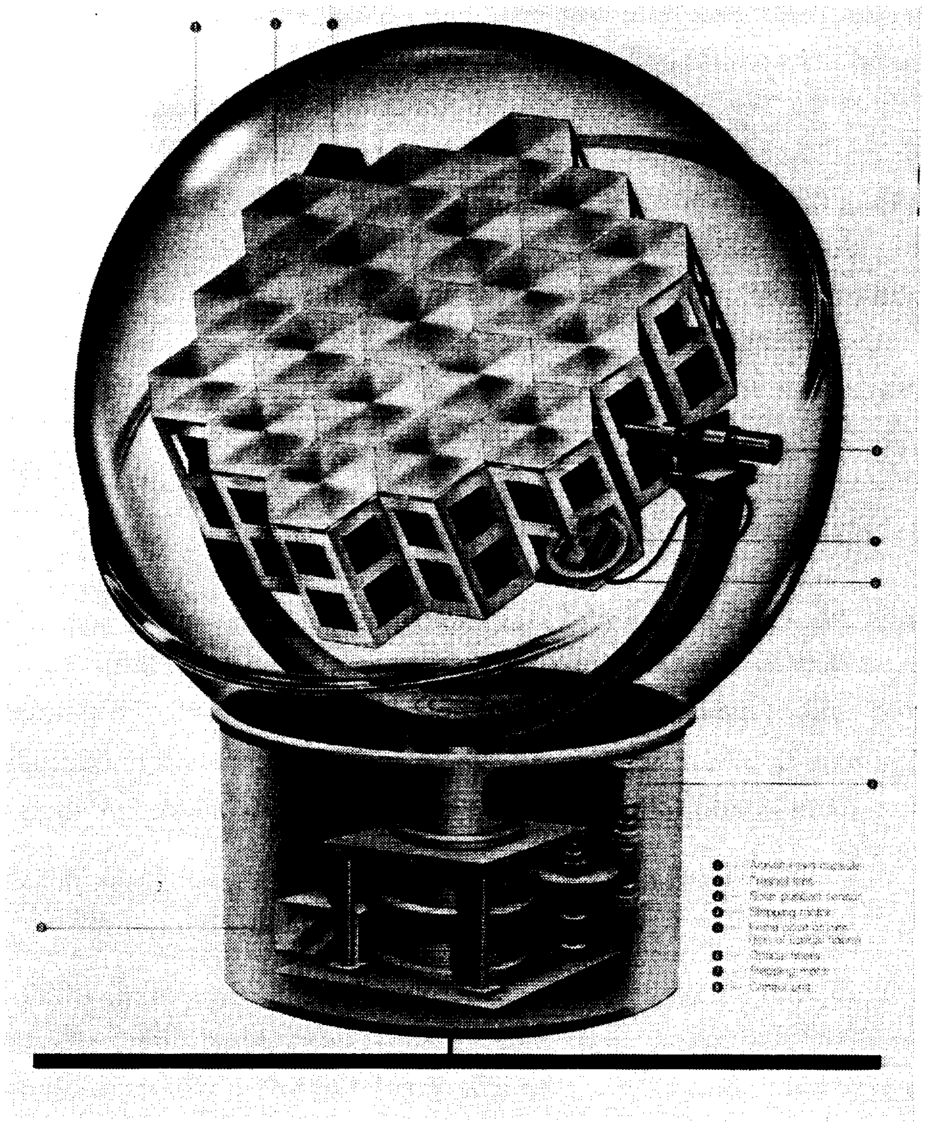


Figure 4.4. Himiwari Fiber Optic Light Collection System.

Two scenarios were developed to analyze the use of Himiwari-based systems. Scenario 1 assumes usage of three Himawari units, each with a collector area of 8.87 m^2. The use of these collectors was postulated because they are 4 meters in diameter, and could be launched in the NSTS cargo bay without disassembly. Scenario 2 assumes that one of the SSF units (Oleson, et. al., 1987) would be used as the collector. The mass breakdowns for the components used in these two scenarios are specified in Fig. 4.6.

The data supplied by Mori indicated that the maximum sunlight transmittance achieved with his design was about 50%. This transmittance was determined by measuring the intensity of the transmitted solar radiation compared with the incident radiation. Using a 50% transmittance value, the amount of collector area each of the two scenarios could supply with a target PAR value of 300 $\mu mol/m^2/s$ was calculated. The area that could be illuminated if the transmittance could be increased to 100% was also calculated. These calculations indicate that even at 100% transmittance, the lowest mass per m^2 of illuminated area is 27.5 kg. (See Figure 4.7) A more realistic value is 54.9 kg/m^2, using the 50% transmittance value. These values are between 4.5 and 9 times greater than the mass per unit area for artificial lighting with HP or MH lamps, and about 7-14 times greater than the mass per unit area for LED lighting.

Thus, it appears that the use of fiber optic-based sunlight transmission systems is not worth considering for a lunar base application, unless the power penalty for supplying electric power to artificial lamps exceeds about 200 kg/kW. Even if a fiber optic system were installed, an artificial lighting system will be required to provide PAR during the lunar night.

Figure 4.5. Physical Data for Fiber Optic Solar Radiation Collectors.

Lens Quantity	Collector Area (m^2)	Mass (kg)	Tracking Motor Power (W)
7	0.56	300	150
19	1.37	600	180
37	2.59	1012 [1]	221 [1]
61	4.26 [1]	1579 [1]	278 [1]
127	8.87	3129 [1]	433 [1]
~900	62.92 [2]	5503 [2]	373 [2]

1. Calculated from data supplied by K. Mori.
2. Data from Oleson, et. al., 1987.

Figure 4.6. Summary of Fiber Optic Lighting Systems Mass Characteristics.

Scenario	Collection Area (m^2)	Collector(s) Mass (kg)	Fiber Optic Cable Mass (kg)	Diffuser Mass (kg)	Total Mass (kg)
3 Himiwari Collectors	8.87	9,387	1,542	737	11,666
SSF-type Collector	62.9	5,503	6,283	1,893	13,679

Figure 4.7. Summary of Fiber Optic Lighting Systems Performance Characteristics.

Scenario	Transmittance (%)	Area Illuminated* (m^2)	Mass/Illuminated Area (kg/m^2)
3 Himiwari Collectors	50 100	105.3 210.6	110.8 55.4
SSF-type Collector	50 100	249.1 498.2	54.9 27.5

* At a PAR of 300 $\mu mol/m^2/s$.

4.1.3 Alternative Designs Using Natural Sunlight

Two other methods for supplying natural sunlight to plants were considered. The lowest mass alternative is a transparent-walled greenhouse structure on the lunar surface which would have artificial lamps to provide PAR during the lunar night. The major problems with this alternative are: 1) the heating/cooling that a transparent structure would experience on the lunar surface (see para. 4.9), 2) the selection of a transparent wall material which would be low in mass, yet tolerant of the solar ultraviolet radiation load, and 3) exposure to hard radiation (cosmic and solar flares).

Two potential solutions to these problems were envisioned. One is to utilize lunar glass, fabricated in situ for the greenhouse walls. This option is attractive for a number of reasons, but requires an analysis of the mass of machinery required to manufacture the glass, an analysis of the capability of the glass to withstand the temperature and humidity conditions it would be exposed to, and an analysis of the mechanisms that could be used to mount glass panes with minimum leakage. It is recommended that these analyses, which are beyond the scope of the present study, be completed in conjunction with future LCELSS investigations.

The second solution utilizes light plastic films, coated to prevent or retard degradation by ultraviolet radiation. Southwall Technologies (Palo Alto, CA) has produced plastic films which are metal sputter-coated to reflect UV radiation at the film surface. It is also recommended that these materials be analyzed both for resistance to lunar surface environmental conditions and for structural/mechanical characteristics which would typify the wall of a greenhouse structure.

The potential use of light, inflatable reflectors and light guides as sunlight collection mechanisms was also reviewed. These devices hold a great deal of potential for enabling direct use of sunlight at a very low mass, without using transparent-walled structures. The mass of 100 m^2 of reflector surface was calculated to range from about 20 kg for Mylar to 130 kg for specular aluminum. Space Station Freedom windows could be used as ports for transmitting the light into the plant growth module. The SSF triple-glazed windows have a mass of 37.5 kg each. With 4 windows, 4 light pipes, and 100 m^2 of reflector surface, the total mass of the illumination system would be approximately 430 kg (using specular aluminum). This concept would also provide full- or near full Earth-surface PAR values. Although use of this concept would not eliminate the need for artificial lighting during lunar night, it is preferable to the Himiwari option. In addition, it provides a means of protecting the plants from radiation by covering the plant growth unit with regolith, while still using natural sunlight; an advantage over a greenhouse design.

4.2 WASTE PROCESSING TECHNOLOGY SELECTION

Four physicochemical processes for oxidation of solid waste materials were compared at scales appropriate for 4, 30, and 100-person lunar based systems. These included: 1) low pressure wet oxidation, 2) high pressure wet oxidation, 3) supercritical wet oxidation, and 4) incineration. It was assumed that these processes were operated in an environment which included the growing of food plants, that the liquor from the incomplete wet oxidation processes could be used as a plant nutrient solution, and that the organics could be incorporated by the plants.

Waste material was assumed to include hygiene and urine brines, human feces, packaging material and food plant wastes. The waste model was derived from one produced by Hightower (1989). The oxygen demand of the treatment processes was calculated from an elemental analysis of the waste material and extent of expected oxidation of the processes under study.

Schematics for each of the systems were developed to analyze the commonality of system components. When evaluated in this fashion, it was apparent that the major portion of subsystem mass consisted of energy recovery, waste collection, grinding, and storage components. The actual mass associated with the central oxidation component was a small part of the total. This result indicates that the selection of a waste processing technology is dependent upon considerations other than mass, such as corrosion resistance, maintainability, operating pressure and interaction with other physicochemical or bioregenerative technologies.

The schematic analysis showed that preparation and storage equipment, (which includes collection, storage, grinding, energy recovery, heat addition, reactors, and other minor equipment) comprised about 70 percent of the system mass; a percentage that is common to all of the processes studied. Energy recovery, heat addition, and minor components account for about 10 percent. The remainder is process unique. Summary comparisons of alternative waste models and processes are presented below.

4.2.1 Low Pressure Wet Oxidation

The wet oxidation process breaks down organic material through hydrolysis and oxidation. Since low molecular weight compounds such as acetic acid tend to be refractory to the process, hydrolysis in low temperature wet oxidation processes leads to lower oxidation efficiency. The result is a breakdown of solids, reduced oxidation demand and a product liquor rich in those soluble organics which are refractory to the process.

The low pressure process typically is carried out at conditions below 230°C and below 3460 kPa (500 psi). Process analysis shows that the heat of oxidation is not significant in wet oxidation. Further, the energy recovery equipment is constant and independent of the process efficiency. Thus, even though contact times are higher (e.g., 1 hour) in the low pressure process, the larger reactor penalty is offset by the reduced wall thicknesses. The estimated mass of an LP wet oxidation system as a function of crew size is shown in Figure 4.8.

4.2.2 High Pressure Wet Oxidation

This process is carried out at over 6920 kPa (1000 psi) and about 290°C. Under these conditions, oxidation efficiency is higher and reactor contact time can be reduced to approximately 30 minutes. This process has a higher mass penalty as the pressure effects on construction are greater than the reduced reactor volume.

Figure 4.8. Estimated Mass Values for Low Pressure Wet Oxidation Waste Processing System.

Component	Mass By Crew Size (kg)		
	4	30	100
Collection	4.55	9.09	27.27
Storage/dry	17.27	129.09	429.55
Grinding	13.64	36.82	68.18
Transfer Pump	10.91	29.55	65.91
Energy Rec	0.48	3.64	12.00
Heat Add'n	0.97	7.27	24.00
Reactor Heat	4.77	35.77	119.09
Gas Purify	4.55	5.45	11.36
L/G Separator	1.82	2.27	4.55
TOTAL MASS	58.95	258.95	761.91

The key to employing this process is a system requirement for high oxidation efficiency. This degree of efficiency may not be required for the hybrid processes which include live plants, however. The estimated mass of a HP wet oxidation system as a function of crew size is shown in Fig. 4.9.

Figure 4.9. Estimated Mass Values for High Pressure Wet Oxidation Waste Processing System.

Component	Mass By Crew Size (kg)		
	4	30	100
Collection	4.55	9.09	27.27
Storage/dry	17.27	129.09	429.55
Grinding	13.64	36.82	68.18
Transfer Pump	10.91	29.55	65.91
Energy Rec	0.99	7.45	24.82
Heat Add'n	1.49	11.18	37.23
Reactor Heat	5.32	39.86	132.73
Gas Purify	6.82	8.18	17.05
L/G Separator	1.82	2.27	4.55
TOTAL MASS	62.80	273.50	807.27

4.2.3 Supercritical Oxidation

The supercritical oxidation process occurs at temperatures above the critical point of water. Typical operations pressures are over 27,670 kPa (4000 psi) and temperatures over 370°C. At these conditions, essentially 100 percent oxidation efficiency can be achieved with a reactor residence time of 2 minutes. This process carries both corrosion and high pressure burdens, however. The energy recovery equipment has a high weight penalty due to the pressure requirements, which offsets the advantage of small reactor size. Sludging of the reactor is a potential development problem.

This process takes the organic material to carbon dioxide, water, and other trace materials. Since it is an end process, it does not require an organic uptake capability of live plants to contribute to waste processing. The estimated mass of a supercritical oxidation type solid waste disposal system by crew size is shown in Figure 4.10.

Figure 4.10. Estimated Mass Values for Supercritical Wet Oxidation Waste Processing System.

Component	Mass By Crew Size (kg)		
	4	30	100
Collection	4.55	9.09	27.27
Storage/dry	17.27	129.09	429.55
Grinding	13.64	36.82	68.18
Transfer Pump	21.86	59.09	132.27
Energy Rec	3.45	25.95	86.36
Heat Add'n	4.31	32.45	107.73
Reactor Heat	1.45	10.91	36.36
Gas Purify	4.55	5.45	11.36
L/G Separator	3.64	4.55	9.09
TOTAL MASS	74.72	313.41	908.18

4.2.4 Incineration

In this process wastes are nearly dried, then fed into an ambient pressure, high temperature oxidizer. Oxidation efficiency in this process is near 100 percent. Contact times are low, making reactor penalties low even with the necessary insulation burden. The additional mass associated with energy recovery and dehydration equipment is the major system penalty. The estimated mass of an incineration system as a function of crew size is shown in Fig. 4.11.

Figure 4.11. Estimated Mass Values for Incineration Waste Processing System.

Component	Mass By Crew Size (kg)		
	4	30	100
Collection	4.55	9.09	27.27
Storage/dry	17.27	129.09	429.55
Grinding	13.64	36.82	68.18
Transfer Pump	5.05	13.64	30.55
Energy Rec	4.55	13.64	45.41
Heat Add'n	4.55	13.64	45.41
Reactor Heat	0.91	6.82	22.73
Gas Purify	6.82	8.18	17.05
L/G Separator	1.82	2.27	4.55
TOTAL MASS	59.14	233.18	690.68

The incineration process takes the organic material to carbon dioxide, water, and other trace materials. It is an end process, and as such, it takes no advantage of the capability of live plants to contribute to waste processing. Because the process operates at high temperature, nitrogen oxides are produced. As a consequence, the development of exit gas scrubbers along with attendant ash-handling systems must be developed for space applications.

4.3 ANIMALS AS HUMAN FOOD

Considerations associated with the use of animals as human food in an LCELSS include: efficiency of converting feed to human food, "harvest index" (percent edible material), energy/mass/volume requirements, animal growth rate, animal reproductive rate (fecundity), palatability to humans, and crew time required for preparation. Figure 4.12 provides nominal values for production efficiency based on feed conversion efficiency and harvest index for several common domestic animals.

The data in Fig. 4.12 show that some animal species are more efficient than previously recognized in CELSS design activities. The most efficient animal products are fish, milk, and chicken. Based on its area/volume requirements, (See Fig. 4.13), milk production was eliminated as an efficient means of producing an animal food. Because of the potential odor and trace contaminant control problems that poultry culture might engender in an LCELSS, aquaculture was identified as the animal production system of choice for the LCELSS conceptual design.

Figure 4.12. Efficiency Characteristics of Various Animal Species[1].

Animal/Product	Feed Conversion Efficiency (kg Feed/kg Gain)	Harvest Index (%) [2]	Production Efficiency (kg Feed/kg Edible Mass)
Beef	5.9 ± 0.5	49	10.2
Swine	2.5 ± 0.5	45	5.6
Lamb	4.0 ± 0.5	23	17.4
Rabbit	3.0 ± 0.5	47	6.4
Broiler Chicken	2.0 ± 0.2	59	3.1
Eggs	2.8 ± 0.2	90	3.1
Milk	3.0 (dry wt basis)	100	3.0
Shrimp	2.5 ± 0.5	56	4.5
Prawns	2.0 ± 0.2	45	4.4
Catfish	1.5 ± 0.2	60	2.5
Grass Carp	1.5 ± 0.2	60	2.5
Tilapia	1.5 ± 0.2	60	2.5

1. Source: Phillips, et. al., 1978.
2. (Edible Biomass/Total Biomass) X 100.

There are a number of freshwater fish species which grow to maturity rapidly (6-12 months), and therefore seem appropriate for a fish based aquaculture system. Candidates include carp, trout and *Tilapia*. All could be fed with vegetable materials produced on the moon, although a high-protein dietary supplement might be required to achieve optimum productivity.

Another aquaculture system evaluated for potential LCELSS application is one using crustaceans or molluscs. Freshwater crawfish are generalist omnivorous, and thus seem to be excellent candidates. Unfortunately, their harvest index is only about 15% (Klassen, personal communication), and they tend to be extremely cannibalistic. Saltwater organisms have some potential, but generally take 2-3 years to reach edible size. Also, breeding these organisms is difficult, as many are adapted to deep-water spawning.

Figure 4.13. Resource Requirements (per Animal) for Intensive Animal Production.*

Animal	Area (m^2)	Volume (m^3)	Water/Day (liters)	Feed/Day
Beef Cattle	Calf: 1.3 1 yr: 2.0 Adult 2.7	2.43 4.00 5.40	23-27 28-42 50	1.5-1.75 kg/100 kg live weight
Dairy Cattle	3-3.5	6-7	up to 136	10-12 kg
Swine (40-100kg)	0.7-1.0	0.7-1.0	up to 4.5	2.3-3.4 kg
Sheep (30-40kg)	1-1.5	2.3	2.6-2.8	1.3-1.4 kg
Rabbit	0.23	0.105	up to 1	6% live weight
Chicken (Broiler)	0.1	0.05	0.5	60-70 g
Chicken (Egg/Breed)	0.05	0.025	0.25-0.30	90-110 g
Shrimp (Penaeid)	0.005-0.006	0.003-0.004	N/A	0.35-0.40 g
Prawns	0.02	0.02	N/A	0.20 g
Catfish	---	0.001	N/A	4-4.5 g
Grass Carp	---	0.001	N/A	4-4.5 g
Tilapia	---	0.001	N/A	3.3-3.4 g

* Source: Phillips, et. al., 1978.

The primary problem with implementing an aquaculture system is the large mass of water required to support an adequate human food supplement (see also Section 4.4). A second, less significant problem concerns the 12 to 18 months required to bring an aquaculture system into steady-state production. However, the inclusion of a small amount of meat in the crew's diet may pay off both psychologically as well as nutritionally (Section 4.6). Also, if water can be extracted from lunar regolith, or if oxygen can be obtained and combined with hydrogen brought from earth, the mass requirement for an installed aquaculture system is lowered significantly. Using a simple combination of ion-removal and submicronic filters, an aquaculture system could also provide a large water reserve for emergency needs.

4.4 AQUACULTURE SYSTEM

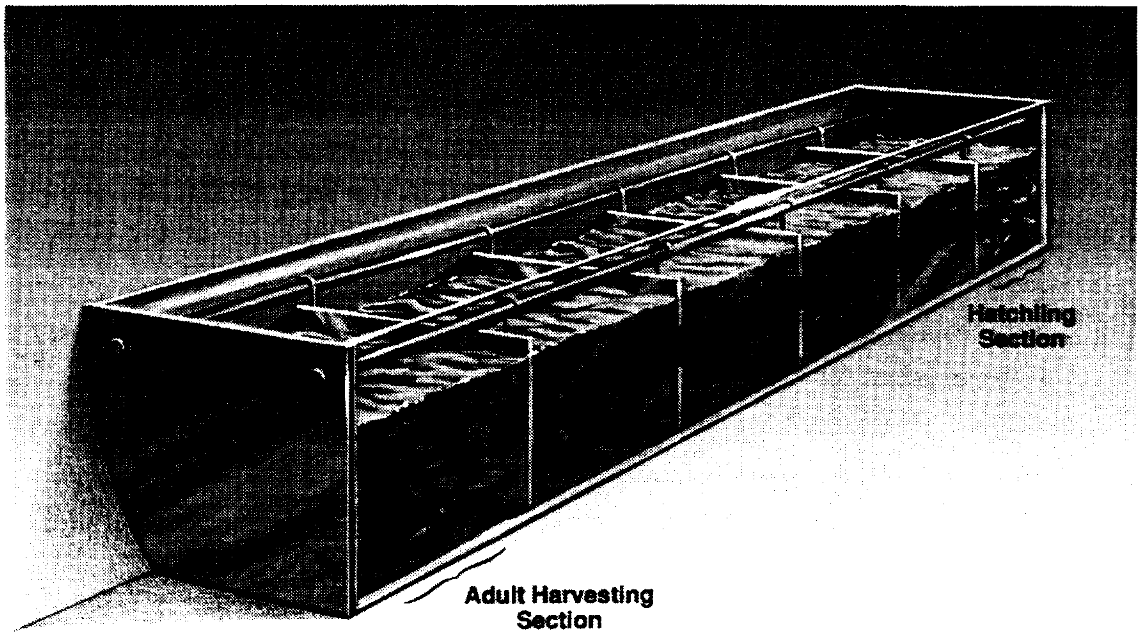
Various species of herbivorous (plant-eating) fish were evaluated as candidates for an aquaculture system. *Tilapia* was chosen for detailed analysis because the species possess several characteristics that make the species well suited for intensive culturing: 1) it is sufficiently palatable to be a commercially viable food, and is sold under the name "Nile Perch", 2) it tolerates high stocking density, which minimizes the size of the aquaculture tanks (commercial breeders typically achieve stocking densities of 5.2 to 24 kg of fish/m^3), 3) it has a high harvest index (see Fig. 4.12), and 4) unlike trout, which require very clean water, *Tilapia* is extremely tolerant of poor water conditions. Unfortunately, *Tilapia* tend to breed excessively, which crowds tanks and limits growth rates. For this reason, commercial growers control breeding by using sex hormones to reverse the sex of the males at an early age.

A *Tilapia*-based aquaculture system requires several different tanks. Small breeding tanks are used to contain mixed adult males and females, in addition to the fingerlings they produce. Since fingerlings require some form of higher quality protein, the feed for this tank would include pelletized, high-protein fish food in addition to the plant material. Upon reaching a certain size, fingerlings would be transferred to another small tank for sex-reversal hormone treatments, and then transferred to the main production tanks for growth.

The main production tanks are the largest of the aquaculture system. To minimize the total volume of the production tanks, a movable partition system in a single tank was envisioned to separate the various sizes of fish (Fig. 4.14). The fingerlings are introduced at one end, where a transverse partition keeps them separate from the rest of the population, thus preventing the larger fish from hoarding the food supply. As the fingerlings grow, the partition is moved down the tank, increasing the volume available to this set of fish. When the next group of fingerlings is ready, a new partition is placed at the end of the tank, and the new fingerlings added. As the partitioned segments of the tank are moved, the spacing between partitions is increased to keep the mass of fish per unit volume constant. Between 4 and 5 months after the cycle has started, the fish would be of uniform size and ready for harvesting. This design would halve the volume required to produce a certain amount of fish in a given amount of time.

A parametric analysis was performed to size an aquaculture system of this type, based on producing 1.0 kg of edible *Tilapia* meat per day. Since only 60% of each fish is edible, the system must produce 1.67 kg whole fish/day. The use of the movable partition tank was estimated to increase the effective stocking density by 50%, to a maximum of about 36 kg/m^3. Based upon that stocking density and published growth rates (Todd, 1980), the production tank must have a water volume of about 6.7m^3 to sustain production of 1.0 kg of edible *Tilapia* meat per day (time averaged). Including pumps, filters etc., the total tank volume was calculated to be about 7.0 m^3.

Figure 4.14. Illustration of Movable Partition Aquaculture Tank.



4.4.1 Use of Higher Plant Material as a Feedstock for *Tilapia*

Food for *Tilapia* production could be obtained from the plant material remaining after the production of human food. Alternatively, biomass or forage crops (e.g., alfalfa) could be grown specifically to provide food for the aquaculture system. Based on published recommendations (Todd, 1980), the nominal amount of vegetable food required to sustain *Tilapia* in the culture system described above was calculated to be about 1.1 kg dry weight/m^3/day, or 7.4 kg total dry matter/day. The wet weight of this vegetable material would, of course, depend on the mixture of crop species from which it was derived. Note that the total wet weight of material would also be influenced by the composition of the biomass with regard to the nutritional requirements of the *Tilapia*. Processing of this biomass would be minimal, and could range from none (i.e., direct feeding to *Tilapia*) to drying and pelletizing for easier storage and subsequent feeding.

4.4.2 Use of Algae as a Feedstock for *Tilapia*

A separate algal (phytoplankton) reactor was analyzed as an alternative means of providing food for *Tilapia*. The size of an algal reactor required to supply food for the aquaculture unit described above was estimated to be approximately 555 liters, assuming an algal biomass harvest rate of about 13.33 gm/liter/day dry weight (Matthern and Koch, 1968). Analysis indicated that a hydrocyclone unit was best suited for algal harvest, as it collects the algal cells by centrifugation.

The volume estimate for the large reactor is based on performance data obtained from a small, well stirred reactor (2.7 liter culture volume), and should therefore be considered as the minimum volume required for the reactor. Based on the small reactor, total power requirement to supply artificial light for PAR for the large reactor was calculated to be in excess of 1,000 kW. This is clearly not a feasible concept if artificial lighting is required. However, if sunlight was used to supply PAR, the large reactor would require only about 50 W for an aeration pump.

4.4.3 Aquaculture Feasibility

Based on the preliminary sizing numbers for an aquaculture system, several important conclusions can be reached . A system that requires nearly 7 m^3 of water to produce an average of 1 kg edible food/day would have a breakeven point of approximately 19 years. Several things can be done to reduce this. One approach is to amortize the cost of the water over several different subsystems. For example, since *Tilapia* tank water must be kept at certain minimum standards, that water might be used as emergency drinking water after being filtered and purified. Alternatively, the *Tilapia* tank could be used as a buffer for the hydroponic nutrient system.

Another approach to reducing breakeven time lies in the use of in-situ resources. If one of the lunar base activities is production of oxygen from lunar regolith, then supplying large quantities of water becomes much less costly. Since water is 89% oxygen, only 11% of the mass of the water (i.e, its hydrogen content) must be "paid for" in terms of transportation cost. This would reduce the breakeven point for an aquaculture system to about 2 yrs.

4.5 FOOD PROCESSING

LCELSS food processing technologies would make biological products usable for human consumption. Although this section is focused on the identification and evaluation of technologies to support processing for human consumption, consumption by other organisms and processing for manufacture of biomaterials may also be accommodated by the same processes.

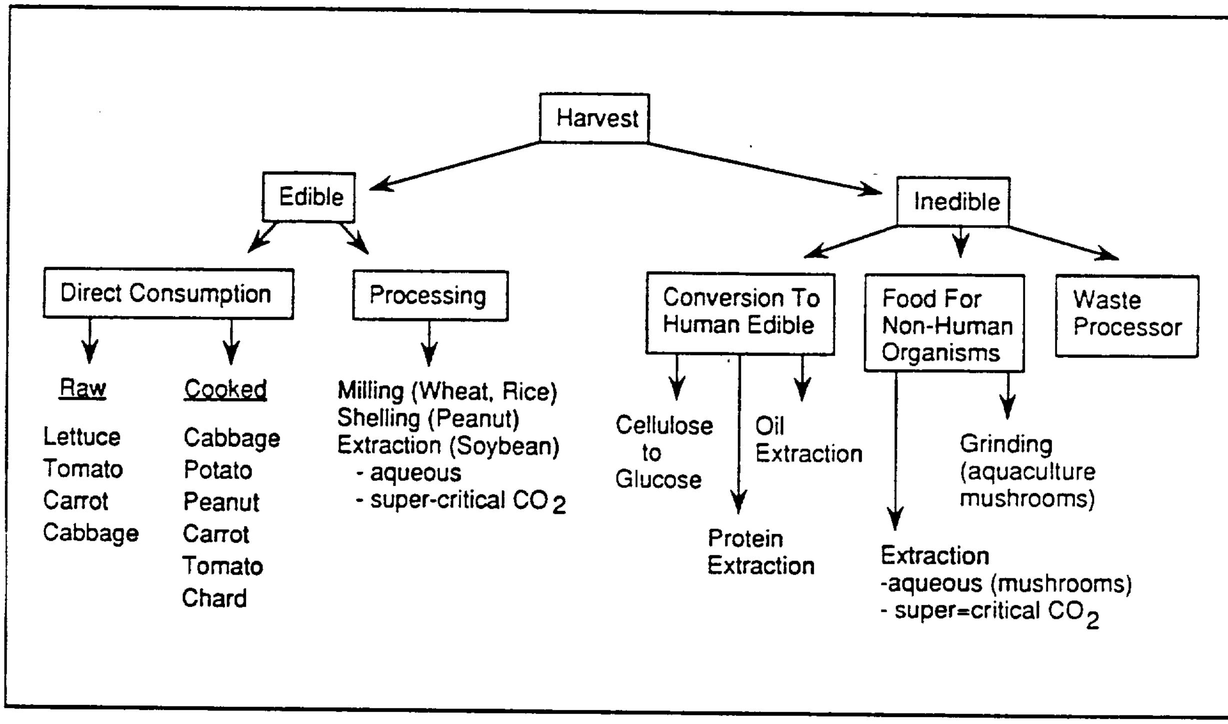
Food products are categorized as requiring little or no processing (raw), primary processing and secondary processing or extraction. The first category consists of food that is edible in its natural form, such as fresh fruits and some vegetables. Minor processing might consist of washing, peeling or cutting, but little support hardware would be required.

The primary processing category includes food products that require support hardware such as juice/oil presses, grain mills, cooking/baking utensils, etc. to make them edible. Such hardware will require adaptation to the stringent limitations of power, mass, and volume in a space environment.

The third category consists of biological products which were not edible in raw or primary processed forms, but which contain potentially digestible and nutritious food for human consumption. The importance of this category lies in the need to reduce resupply requirements and increase self sufficiency. In traditional agriculture, only part of the biomass production is considered edible and the rest is considered waste, which is either disposed of or recycled by reduction methods such as composting or rotting in the soil. These techniques might not be practical in a small system because of volume, time, energy, or technological constraints. Some of these "waste" materials still have nutritional value, which may not be as readily accessible as in the primary product. The nutritional production of an organism could be increased by using extraction processes.

Food processing technologies must be evaluated in terms of total productivity within a CELSS. This evaluation is based upon how the processed material would provide the best return. The food processing techniques described have focused on processing of biomass for direct human consumption. However, alternative uses of processed biomass utilization include both other organisms and other processes. Animals also consume biomass, and their feed may partially consist of the secondary biomass produced, which the humans cannot directly eat. Other processes vary from the extractions of oils or resins to the conversion of raw materials like indigestible cellulose into edible products. An overall view of the functional flow in the food processing subsystem is illustrated in Fig. 4.15.

Figure 4.15. Functional Flow of Materials in Food Processing Subsystem



Food products are composed primarily of carbohydrates, proteins, and lipids (fats). Because food processing technologies such as bakeries and flour mills are well established on earth, this survey only examines in detail some of the methods and solvents used to extract food components from the secondary food sources. It should also be noted that these extraction methods can be used for other biological products.

4.5.1 Carbohydrate Extraction

Extraction methods for the carbohydrate component are dependent upon the molecular composition of the material to be extracted (Fallon et.al., 1987 and Whistler et.al., 1985). First of all, for low molecular weight sugars, the extraction is performed with water at elevated temperatures. This method can be assisted for more difficult situations by blending the pulp or using organic solvents like ethanol or isopropanol. Specifically, extraction of oligosaccharides with an acetonitrile-water solution has been successful. The other primary carbohydrate recovery of noncellulose polysaccharides from cell walls is a two step process. The first step is the acid hydrolysis using 2

M trifluoroacetic acid for 1 hour at 120°C. The second step is to either deionize the solution on a mixed bed resin or elution (washing) through a Sep-Pak cartridge.

4.5.2 Protein Extraction

The first method of protein extraction from leafy plants and vegetables to be considered was analyzed by Pirie (1980). This method has been fairly well researched and developed for experimental uses of a product which is composed of up to 60-70% true protein, 20-30% lipids (rich in unsaturated fatty acids) and 5-10% carbohydrates. The first step is extraction of juice containing protein by bruising and pressing the plant through modified screw expellers (the remainder of the plant structural mass is discarded for different processing or composting). Coagulation of leaf protein from the juice is performed by acidification or heating at 70-90°C. After filtration separates the protein coagulum, the remaining "whey"-type juice is discarded as fertilizer. The suspension of the coagulate in acidic water is followed by filtration and the material is pressed into moist protein cakes.

Another method of extraction is from plant proteins suspended in the water that has been used to wash or cook plants. For example in recovery from potato starch mill effluents the solution is first coagulated by heating, then centrifuged, and finally dried (Grant 1980). A similar method of protein recovery from animal carcasses utilizes rendering the material as a first step, with the last two steps being the same as for plants. This process will yield such products as edible and non-edible fats, meat and bone meal, etc.

Three methods for recovery of animal proteins already suspended in water include: bulk protein extraction, ion-exchange and ultrafiltration. The first technique requires initial flocculation with non-toxic chemicals followed by air flotation or sedimentation of the proteins. The ion-exchange technique involves protein adsorption on resin derived from degenerated cellulose, and then protein desorption with regenerated solution (e.g., alkaline brine). For the final configuration of the protein, it is first heat coagulated, then separated by filtration or centrifugation and finally dried. Another laboratory protein extraction method involves dissolving the proteins in 0.2 M NaC1, ureawater or other organic solvents and water. (Cheftel et.al., 1985)

4.5.3 Lipid (Fat) Extraction.

Two basic categories of lipid recovery from secondary plant products are from either nonphotosynthetic plant tissues or from photosynthetic plant tissue, animal tissue or microorganisms (Kates 1986). The simplified extraction method for the first category involves blending cut tissue with chloroform and then suction filtering the homogenate. The filter residue is blended with methanol-chloroform and water, and the homogenate is filtered again and washed with methanol-chloroform. Water and chloroform are added and (gravity) phase separation is performed. Finally, the chloroform is withdrawn and the solution is diluted with benzene. Subsequent dissolving of residual lipids by chloroform-methanol is only used for laboratory analysis.

The extraction method for the second category follows similar procedures as for the first and a more detailed description can be found in Lipid Extraction Procedures (Kates 1986). The solvents used in these processes are: water, methanol, ethanol, isopropanol, chloroform, benzene, hexane, ethyl ether, acetonitrile and acetic acid. The techniques of blending, filtration, sedimentation, suction and centrifugation are again utilized as well as dilution and rotary evaporation.

4.6 DIET AND NUTRITION

The study of foods for the crew included many different plant and animal species which together could provide sufficient nutrients for continued crew health. Diets consisting of a wide range of combinations and amounts of different foods were analyzed and compared to the USDA's Recommended Daily Allowances (RDA) from NAS-NRC publication # 2941. Mid-points of the ranges for the RDA's of sodium and potassium were used in the analysis. Carbohydrate and fat RDA's were taken from Karel, 1982.

Figure 4.16 compares three previously published CELSS diets (A and B from Volk and Cullingford, 1988; C from Hoff et. al., 1982) with six diets selected for this study by the percentage of each of the RDA's that they satisfy. The nutritive content of each diet was determined using a spreadsheet and each food's nutrient composition as obtained from USDA Agriculture Handbook, "Composition of Foods" (Fig. 4.17). Each food's nutrient content was multiplied by the number of grams of that food in the diet and combined with the other foods in the diet to provide a total nutritional content profile for each diet. This profile was compared to each nutrient's RDA to determine the percentage of the recommendations satisfied by that diet.

Figure 4.16. Relative Nutritive Value of Selected Diets (Expressed as % of USDA Recommended Daily Amount).

Nutritional Characteristic	USDA RDA	Nutritive Value (% of RDA)								
		A	B	C	1	2	3	4	5	6
Energy (Calories)	2700	81.5	72.4	64.08	88.7	100.6	100.7	88.7	94.6	98.8
Protein (gm)	56	218.4	228.3	141.99	236.7	207.8	210.7	239.6	222.3	234.6
Fat (gm)	90	83.2	63.7	63.36	53.1	119.3	118.5	52.3	86.2	78.7
Carbohydrate (gm)	392	65.9	66.8	62.62	101.9	94.3	94.2	101.8	98.1	107.3
Calcium (mg)	800	123.8	96.7	48.55	140.2	101	71.8	111.1	120.6	101.7
Phosphorus (mg)	800	353.1	304.3	205.84	383.7	345.5	331.1	369.4	364.6	394.7
Iron (mg)	14	284.1	233.9	122.76	264.9	174.9	175.6	265.6	219.9	220.7
Sodium (mg)	220	14.4	13.2	15.76	85	85	98.4	98.4	85	20
Potassium (mg)	3050	270.5	224.2	115.17	233.2	167.5	166.6	232.4	200.4	164.5
Vitamin A (IU)	1000	51.6	43.3	46.42	579.3	563.3	568.6	584.6	571.3	122.3
Thiamine (mg)	1.4	381.4	319.3	223.5	340	345.7	348.2	342.5	342.9	356.6
Riboflavin (mg)	1.6	93.8	78.1	42.66	93.1	70.6	75.3	97.8	81.9	71.6
Niacin (mg)	18	97.3	98.7	150.92	144.4	311.1	332.9	166.3	227.8	212.6
Ascorbic Acid (mg)	60	79.4	93.8	55.27	176.7	176.7	176.7	176.7	176.7	31.3

For example, *Tilapia* contains 478 milligrams of calcium per 100 grams of edible material. Diet #2 (Fig. 4.17) contains 50 grams of *Tilapia* which means 239 milligrams of calcium (per 100 grams) is supplied by eating the fish. This combined with the calcium provided by the plants in the diet provides 808 milligrams per day for each person. Since the RDA for calcium is 800 milligram per day, this diet supplies 101% of the calcium needed.

The diets evaluated consist of wheat, either soybeans or peanuts, a salad and a source of meat in the quantities indicated in Fig. 4.17. All nutritive content data for the plants and chicken was taken from Agriculture Handbook #8, (USDA-ARS). The chicken data were based on an average of raw, light and dark meat without skin. *Tilapia* nutritive content was obtained from Bionetics Corporation at the Kennedy Space Center.

Figure 4.17. Composition of the Selected Diets.

Food Item	Diet Composition (in 100 gm Portions)					
	1	2	3	4	5	6
Soybean	2	-	-	2	1	1.25
Peanut	-	2	2	-	1	0.75
Wheat	4	4	4	4	4	5
Carrots	3	3	3	3	3	0.3
Lettuce	2	2	2	2	2	0.4
Tomato	2	2	2	2	2	0.4
Chicken	-	-	0.5	0.5	-	-
Tilapia	0.5	0.5	-	-	0.5	0.5

4.7 MEMBRANE SEPARATION OF GASES

Controlling the atmospheric composition in a closed loop life support system is a critical function requiring technologies which allow separation of excess or toxic elements. LiOH absorption systems have commonly been used on manned spacecraft to remove CO_2 from the enclosed atmosphere. Skylab used an adsorption/desorption system which periodically vented CO_2 overboard. Although there currently are no systems in use for O_2/N_2 separation aboard spacecraft, the various systems used in commercial ground operations include cryogenic fractionation, pressure swing adsorption and membranes.

Since removal of any substance in the LCELSS life support cycle eventually necessitates replenishment, no element should be permanently removed from the loop. Therefore, chemical absorption by LiOH or venting of CO_2 are not viable options for atmospheric control. Gas separation membranes offer a potential solution. Separation of gases by membrane permeation is phase consistent and adiabatic. The only moving parts required are those associated with a compressor or vacuum pumping system. The process allows continuous operation with virtually 100% product recovery and without generating waste or by-products. Membrane systems are inherently simple, requiring no regeneration to recover the recycled product, and very little, if any, system maintenance.

One drawback, however, is the potential for high power consumption from the vacuum/compressor system, due to limited selectivities and/or low permeabilities in conjunction with possibly high pressure differential requirements. The required pressure differential typically is inversely proportional to the membrane surface area. In certain applications, the driving function across the membrane may also be enhanced through the use of ultrasonics.

Five candidate membrane applications which were identified for LCELSS subsystems are discussed below: 1) air dehumidification (H_2O-air separation), 2) oxygen enrichment (O_2-N_2 separation), 3) carbon dioxide removal (CO_2-air separation), 4) methane removal (CH_4-air separation), and 5) separation of gases thermally released from lunar regolith, or other in situ resource utilization (ISRU)

4.7.1 Air Dehumidification (H_2O-Air Separation)

Current technology capabilities indicate that ceramic membrane systems could be a viable option. However, the laboratory experiments described require further development in order to sufficiently define information on topics such as membrane optimization, necessary modifications to apply the technology to a spacecraft system, power requirements, etc.

4.7.2 Oxygen Enrichment (O_2-N_2 Separation)

- Facilitated Liquid Membranes: For an LCELSS system, the liquid membranes proposed by Baker et al. are not recommended due to their intolerance to CO_2 in the feed gas and other technology inherent risks.

- Polymeric (polysulfone) Hollow Fiber Membranes: O_2-N_2 separation membranes made of polymeric materials are currently commercially produced and have many economical applications for low volume gas separation. Incorporation of this technology into an LCELSS type of operation appears to be feasible.

4.7.3 Carbon Dioxide Removal (CO_2-Air Separation)

This function offers a potentially valuable application for membrane technology in an LCELSS environment. As early as the 1960's, membrane systems were being proposed for removing CO_2 from spacecraft cabins, but were rejected due to lack of acceptable existing membranes. At the time, it was not deemed necessary to pursue this technology due to the relatively short mission durations. More recent research advances indicate the potential for utilizing this technology, particularly with facilitated liquid membranes. When considering the volume of consumables associated with replenishing an atmosphere in an LCELSS, this process appears to be a strong candidate for additional research to address the following problems:

(a) Available data on permeabilities and selectivities are for bulk gases. It cannot be assumed that Fick's law of diffusion holds true for low concentrations such as those encountered in the removal of CO_2 from air. It is therefore necessary to develop a database defining candidate membrane permeabilities under realistic conditions of expected use.

(b) Polymeric membranes (e.g., cellulose acetate) are primarily defined with respect to natural gas separation. Further research is required to characterize O_2 and N_2 permeabilities.

(c) Liquid and facilitated liquid membranes show the highest permeabilities and selectivities in the reviewed literature. Research is needed to extrapolate existing data to the specific conditions defined in (a). Ultimately, additional information must be compiled on membrane and carrier liquid optimization, aging and evaporation effects, and optimization of other parameters such as pressure differentials, temperature, flow rate, etc.

(d) Hollow Fiber Contained Liquid Membranes (HFCLM) utilize polymeric fibers separated by a carrier liquid for both the feed and the permeate gas flow. This prevents liquid evaporation and allows for easy liquid exchange or replacement, making it a potentially valuable candidate in meeting the stringent safety requirements necessary in an LCELSS.

4.7.4 Methane Removal (CH_4-Air Separation)

The low selectivities displayed by all membranes reviewed for this application and the low CH_4 concentrations anticipated in the LCELSS atmosphere do not make this appear to be a likely candidate with existing technology.

4.7.5 Separation of Gases Thermally Released From Lunar Regolith (ISRU)

Until the quantities and composition of the released gases are better defined, the evaluation of new membrane technologies in this area is not practical. The application of existing processes may provide potential uses as requirements are established, and should be considered.

4.8 CREW TIME REQUIREMENTS

Although the amount of crew time required to service and maintain a CELSS is an important issue, little experimental information is available to serve as a guide for time estimates. The only experimental data located during the study were obtained by Soviet researchers from the 16 month run (December 1972 to June 1973) of the Bios-3 life support system testbed (3-person capacity).

The Bios-3 configuration included 2 phytotrons, each supporting approximately 17 m^2 wheat and 3.5 m^2 of miscellaneous vegetables (total growing area = 40.8 m^2), and three algal culture units of 10 m^2 illuminated area each. During the experiment (Gitelson, et. al., 1976), Soviet investigators tracked the amounts of time spent by the 3-man crew on different aspects of system servicing and maintenance. The data are summarized in Fig. 4.18.

4.8.1 Higher Plant Growth System

The hydroponic methods used to grow the food plants are standard and therefore are amenable to extrapolation. Assuming that subsumed planting, harvesting and wheat grinding each require 1/3 of the time recorded in the first item listed in the table, then each of these activities would involve an expenditure of about 0.81 man-hours per day. On an area basis, planting and harvesting would thus require about 1.2 man-minutes/day/m^2 of area planted/harvested.

Because wheat yield per unit area can change substantially with changes in environmental conditions, the estimated time required for wheat grinding is more appropriately based on the mass of material processed than on the growing area. Using the Bios-3 production rates of 200 gm/person/day for wheat grain, it was calculated that approximately 8 man-minutes/day was required for each 100 gm of wheat ground.

Based on laboratory experience at Lockheed, it was assumed that 1/4 of the time recorded for the second activity described in the table was spent in observing the plants' condition, and 3/4 of the time was spent in preventative maintenance of the equipment. These ratios equate to about 39 man-minutes per day for observation and about 1.94 man-hours per day for preventative maintenance. Both of these activities can be related to the growing area, and provide estimates of about 1 man-minute /day/m^2 of growing area for observation, and 2.9 man-minutes/day/m^2 of growing area for equipment maintenance.

The third activity listed in Fig. 4.18 is correction of nutrient solution composition. Since the wheat and vegetable crops were grown hydroponically, the nutrient solution required daily correction of pH and elemental composition. Replacement of water to replace that removed through plant transpiration was automatic, and required no manual activity. On an area basis, this activity required 1.23 man-hours per day, or about 1.8 man-minutes/day/m^2 of growing area.

4.8.2 Algal Growth System

The three algal (*Chlorella*) growth cultivators, or reactors, used in Bios-3 were of a non-standard, multiple-chamber design with 10 m^2 of illuminated growing area and an estimated 25 liters of culture solution each. Since these units were specifically designed for one-person maintenance, it is therefore more difficult to extrapolate crew time requirements for algal reactors from the Bios-3 data than it is for higher plant time requirements. With the exception of algal cell harvesting, the time estimates in Fig. 4.19 were developed for application at the reactor level, and assume that the entire reactor volume was well-mixed and homogeneous.

Based on previous laboratory experience, it was assumed that of the 3.33 hours devoted each day to monitoring operations and preventative maintenance, 1/4 was monitoring and 3/4 maintenance. These ratios were further corrected because they were applicable to the 3 reactors. As in the case of wheat grinding, the time requirement for algal cell harvesting was assumed to be related more directly to the amount of biomass harvested than to any of the other characteristics of the reactor. It was also assumed that the amount of dry cell mass harvested each day was equal to the maximum productivity of the algal reactors (i.e. 800 gm D.W./day for each reactor).

Figure 4.18. Crew Time Requirements for Various Activities.*

Activity	Observation Period (Days)	Average work input per day, (manhours)
Support of higher plants Harvesting and planting plants, grinding wheat	60	2.42
Observation of condition of plants, preventive maintenance of equipment	60	2.58
Correction of nutrient solutions	60	1.23
Total	60	6.23
Collection of material for analysis, conduct of analyses	120	2.28
Centrifuging, drying crop biomass	120	1.22
Preparation of nutrient solutions	120	0.66
Monitoring cultivator operation, preventive maintenance of equipment	120	3.33
Total	120	8.49
Performance of domestic operations Food preparation and eating, kitchen cleanup	180	5.1
Preparation of conditioned water	180	0.42
Personal hygiene procedures	180	1.17
Living compartment hygiene	180	0.81
Total	180	7.5

* Data derived from the Bios-3 Program.

Figure 4.19. Crew Time Requirements by Activity.*

Higher Plant Activities	
Activity	**Time Requirement**
Planting	0.0199 man-hrs/day/m^2
Harvesting	0.0199 man-hrs/day/m^2
Wheat grinding	0.135 man-hrs/day/100 gm
Observation	0.0158 man-hrs/day/m^2
Preventative maintenance	0.0475 man-hrs/day/m^2
Nutrient solution maintenance	0.030 man-hrs/day/m^2
Algal Reactor Activities	
Activity	**Time Requirement**
Sampling and analysis	0.760 man-hrs/day/reactor
Harvest (centrifuge and dry)	0.0508 man-hrs/day/100 gm
Nutrient solution preparation	0.22 man-hrs/day/reactor
Monitoring operation	0.278 man-hrs/day/reactor
Preventative Maintenance	0.833 man-hrs/day/reactor
Domestic Activities	
Activity	**Time Requirement**
Food preparation, eating and cleanup	1.7 man-hrs/day/crew member
Water preparation	0.14 man-hrs/day/crew member
Personal hygiene	0.39 man-hrs/day/crew member
Monitoring operation	0.278 man-hrs/day/reactor
Living compartment hygiene	0.27 man-hrs/day/crew member

* Based on data derived from the Bios-3 Program.

In addition to the higher plant and algal system time requirements, the Bios-3 experiment tracked the amount of time devoted to domestic activities such as food preparation, eating, personal hygiene, etc. The last series of activities in Fig. 4.19 summarizes these data expressed on a per crew member basis.

Using the data presented in Fig. 4.19, the amount of time required to support a higher plant growth unit (disregarding wheat grinding) is 0.133 man-hrs/day/m^2 of growing area, or about 8 minutes/day/m^2. For the algal reactor, the total amount of support time required (disregarding harvest) is approximately 2 man-hrs/day/reactor.

4.8.3 Reduction of Crew Time Requirements

There are several means to reduce the need for crew time. One of the most obvious is through the use of automation. For higher plant growth, automating the nutrient solution maintenance is both simple and straightforward. Planting and harvesting can also be automated, although not quite so easily. Although the amount of direct crew time required will be reduced by automation, the amount of preventative maintenance will probably increase slightly. In the best case, we expect that crew time requirements for planting, harvesting and nutrient solution maintenance would be eliminated, while the maintenance requirement would increase by about 10%. This would result in a lowering of the crew time requirement for higher plant growth to about 4.1 minutes/day/m^2 (0.0681 man-hrs/day/m^2) of growing area. For the algal reactor, automation could largely eliminate sampling, analysis and nutrient solution preparation times. Again, assuming an increase in preventative maintenance requirement of about 10%, automation of the algal reactor procedures could reduce crew time requirement to about 1.2 man-hrs/day/reactor.

Another method for decreasing crew time requirements is to change species. Potatoes or soybeans, for example, will require less planting time than wheat. Harvesting time requirements will have to be analyzed, however, to ensure that the time saved in planting is not spent later in harvesting the edible portions. In a similar fashion, selecting filamentous algae species for cultivation may prove advantageous to lowering time required for specific operations. Again, operational verification will be required to ensure that time saved on one operation is not used on another operation.

Another method for decreasing the crew requirement is to increase shift lengths, (i.e. 10 hour versus 8 hour work days). In this situation, the time requirement remains the same but the work is accomplished by fewer crew members. Requiring each crew member to spend a particular fraction of his/her leisure time in support of the higher plant or algal systems is also a means for decreasing the crew requirement. Previous work by Soviet investigators suggests that this may be an attractive alternative, since people seem to enjoy spending part of their free time working with growing plants.

4.9 TRANSPARENT STRUCTURE COOLING/HEATING

One of the options for providing light to plants in an LCELSS employs transparent greenhouse-like structures on the lunar surface. To help determine the feasibility of this concept, the cooling and heating requirements for such structures were calculated according to the following assumptions:

- The greenhouse cross section is hemispherical, with a footprint area A = L x D, where L = greenhouse length and D = greenhouse basal diameter.
- The greenhouse is shielded from view of the proximal lunar surface to prevent heating by sunlight reflected from the surface.
- Greenhouse covering transmittance is 100%.
- Heat transfer by conduction through the greenhouse floor is 0, due to insulating ability of lunar regolith.
- Maximum solar gain is calculated with sun at zenith.
- Emittance of the greenhouse interior is 1.0 for the heating requirement calculation and 0.8 for the cooling requirement calculation.
- The greenhouse is at steady state.

With these assumptions, the maximum solar heat gain during lunar day is calculated to be:

$$\begin{aligned} Q_s &= I_{dn} - Eb\,(T_i^4 - T_s^4) \\ &= 1353 - (0.8)\,(5.67\times10^{-8})\,(298^4 - 4^4) \\ &= 1353 - 0.8\,(447) \\ &= 995 \text{ W/m}^2 \end{aligned}$$

where:

Qs	=	solar heat gain in W/m^2
Idn	=	incident direct normal solar radiation per unit area (1353 W/m^2)
E	=	emittance (0.8)
b	=	Stefan-Boltzman constant (5.67×10^{-8} $W/m^2\text{-}^{o}k^4$)
Ti	=	interior temperature (assumed to be 298 ^{o}k)
Ts	=	temperature of deep space ($4^{o}k$)

The total greenhouse heat load is thus 995 W/m^2 x A. This heat load is similar to that found in a number of controlled environment plant growth chambers, where artificial lighting often produces a load of 1 kW/m^2 of growing area.

In a similar fashion, the maximum heating requirement during lunar night is calculated to be:

$$\begin{aligned} Q_e &= Eb\,(T_i^4 - T_s^4) \\ &= 1.0\,(5.67\text{x}10^{-8})\,(298^4\text{-}4^4) \\ &= 478 \text{ W/m}^2 \end{aligned}$$

and the total heating requirement is equal to 478 W/m^2 x A. If the greenhouse was designed so that the external surface is covered with a reflective material during lunar night, the heat lost to space could be significantly reduced. The emittance of a highly polished reflector is approximately 0.04 or less. If an emittance of 0.04 is used in the calculations, and it is assumed that the dome is at a (worst case) temperature of 303^{o}K, then the heat loss due to radiation is only 4% of the calculated value.

Note that these calculations do not include the heat loads imposed by people, animals, plants, or equipment in the greenhouse. Any such internal heat sources will increase the maximum lunar day cooling requirement and reduce the maximum lunar night heating requirement.

4.10 IN SITU RESOURCE UTILIZATION (ISRU)

The use of in situ resources has the potential for increasing the self sufficiency of the LCELSS. Figure 4.20 provides elemental composition data for lunar regolith obtained from a variety of locations. Figure 4.21 provides representative data on the elemental composition of plant and human tissues, as well as nominal elemental compositions for carbohydrate, fat and protein. As Fig. 4.21 indicates, over 95% of plant tissue is composed of only four elements; oxygen, carbon, nitrogen and hydrogen. Similarly, over 87% of human tissue is composed of the same four elements. Consequently, ISRU is most appropriately applied to the supply of those four elements in the context of contributing to life support. Alternatively, if low cost (e.g., low mass, low power) technologies can be developed to recover other elements, the recovered materials may be extremely useful in achieving full self sufficiency of the LCELSS. The primary findings of the study analysis are described below.

Figure 4.20 Composition of Lunar Regolith by Site.*

Element %	Source of Regolith									
	Mare					High		Basin		
Al	7.29	5.8	7.25	5.46	8.21	14.3	12.2	9.21	9.28	10.9
Ca	8.66	7.59	7.54	6.96	8.63	11.2	10.0	7.71	6.27	9.19
Cr	0.21	0.31	0.24	0.36	0.2	0.07	0.1	0.15	0.19	0.18
Fe	12.2	13.6	12	15.3	12.7	4.03	5.71	10.3	9	6.68
K	0.12	0.06	0.22	0.08	0.08	0.09	0.06	0.46	0.14	0.13
Mg	4.93	5.8	5.98	6.81	5.3	3.52	5.59	5.71	6.28	6.21
Mn	0.16	0.19	0.17	0.19	0.16	0.05	0.08	0.11	0.12	0.08
Na	0.33	0.26	0.36	0.23	0.27	0.35	0.26	0.52	0.31	0.3
O	41.6	39.7	42.3	41.3	41.6	44.6	44.6	43.8	43.8	42.2
P	0.05	0.03	0.14	0.05	0.06	0.05	0.05	0.22	0.07	0.06
S	0.12	0.13	0.1	0.06	0.21	0.06	0.08	0.08	0.08	0.06
Si	19.8	18.6	21.6	21.5	20.5	21.0	21	22.4	21.7	21
Ti	4.6	5.65	1.84	1.29	2.11	0.34	0.29	1.02	0.79	0.97

* Source: Phinney, et. al., 1977.

4.10.1 Oxygen From Regolith.

As Fig. 4.20 indicates, of the four elements named above, only oxygen is present in regolith in large concentrations. Thus, regolith provides an excellent potential source for one of the most common constituents of both plant and animal tissue. The production of oxygen by ilmenite reduction is one of the best defined ISRU technologies. Analysis indicates that it is also one of the most feasible technologies, based on power and mass estimates. As such, oxygen extraction from regolith should be a primary candidate for ISRU contribution to LCELSS implementation. Obtaining oxygen from regolith would make it possible to focus on bringing the other major elements (carbon, nitrogen and hydrogen), which are in much shorter supply in regolith, from Earth. These other elements could be combined with lunar oxygen to provide water and the necessary atmospheric gases (e.g., CO_2) for the LCELSS.

4.10.2 Gases From Regolith.

The trace amounts of nitrogen, carbon and hydrogen left in lunar regolith by the solar wind could make an important contribution to LCELSS self sufficiency. If these gases could be obtained as by-products of another process (e.g., He^3 mining), or if a low-cost method of extracting them from regolith (e.g., thermal extraction) was developed, these elements could be combined with LCELSS oxygen to provide water and the necessary atmospheric gases. The technologies proposed for this type of extraction are not well defined at this point, and require further definition. (See also Section 4.7).

Figure 4.21. Relative Elemental Composition of Selected Tissues and Compounds*.

Element	Plant (Zea mays)	Man	CHO (Sucrose)	Fat	Protein
O	44.43	14.62	51.42	11.33	24
C	43.57	55.99	42.10	76.54	52
H	6.24	7.46	6.48	12.13	7
N	1.46	9.33	-	-	16
Si	1.17	.005	-	-	-
K	0.92	1.09	-	-	-
Ca	0.23	4.67	-	-	-
P	0.20	3.11	-	-	-
Mg	0.18	0.16	-	-	-
S	0.17	0.78	-	-	1
Cl	0.14	0.47	-	-	-
Al	0.11	-	-	-	-
Fe	0.08	.012	-	-	-
Mn	0.04	-	-	-	-
Na	-	0.47	-	-	-
Zn	-	0.01	-	-	-
Rb	-	.005	-	-	-

* Epstein, 1972.

4.10.3 Bacterial Mining.

Materials such as calcium, potassium, iron, magnesium, etc. are also present in regolith in quantities which might be useful for LCELSS implementation. Bacterial mining of these elements may be one viable low cost method for their recovery, but research will be required to develop bacterial strains which bioaccumulate these elements. If low cost methods could be developed, they could contribute to both the macro- and micro-nutrient element closure of the LCELSS.

SECTION 5
DESCRIPTION OF SELECTED CONCEPTUAL DESIGN

During the study, five candidate LCELSS configurations were developed and analyzed. A hybrid system with plant and animal food production was recommended to NASA by Lockheed for more detailed development. This candidate promised the highest degree of self sufficiency, maximum nutritional quality, and maximum crew acceptance. It also had the largest mass and the highest power requirement. Because the objective of this study was to develop a design with a high level of self sufficiency, however, NASA agreed with Lockheed's recommendation, and approved this candidate configuration as the focus of the second part of the study.

5.1 GENERAL DESCRIPTION

The conceptual design described here reflects the requirement to provide life support for a nominal crew of 30 persons, with the capability to accommodate a range from 4 to 100. This design should not yet be considered optimal, but was intended to serve as a reference baseline. Figure 5.1 illustrates the overall structure of the LCELSS conceptual design. As noted above, this concept incorporates full food production (both plant and animal materials) for the crew, as well as complete water and air recycling. To minimize cost and maximize reliability, many of the components illustrated in Fig. 5.1 are identical modules (e.g., condensing heat exchangers, trace contaminant control).

In Section 5.2, a more detailed description of each of the LCELSS subsystem concepts is provided. Section 5.3 describes in more detail the interfaces between the LCELSS and the other Lunar base and surface systems (EV/HA, ISRU and System Monitoring and Maintenance). Because of their significant contributions to the overall LCELSS design characteristics, Section 5.4 provides detailed descriptions of the three plant growth unit concepts developed during the study. Section 5.5 outlines an architecture for integrating the LCELSS with the base habitats. Finally, the results of the parametric analysis (including mass, power, and volume estimates) of the LCELSS design are described in Section 5.6.

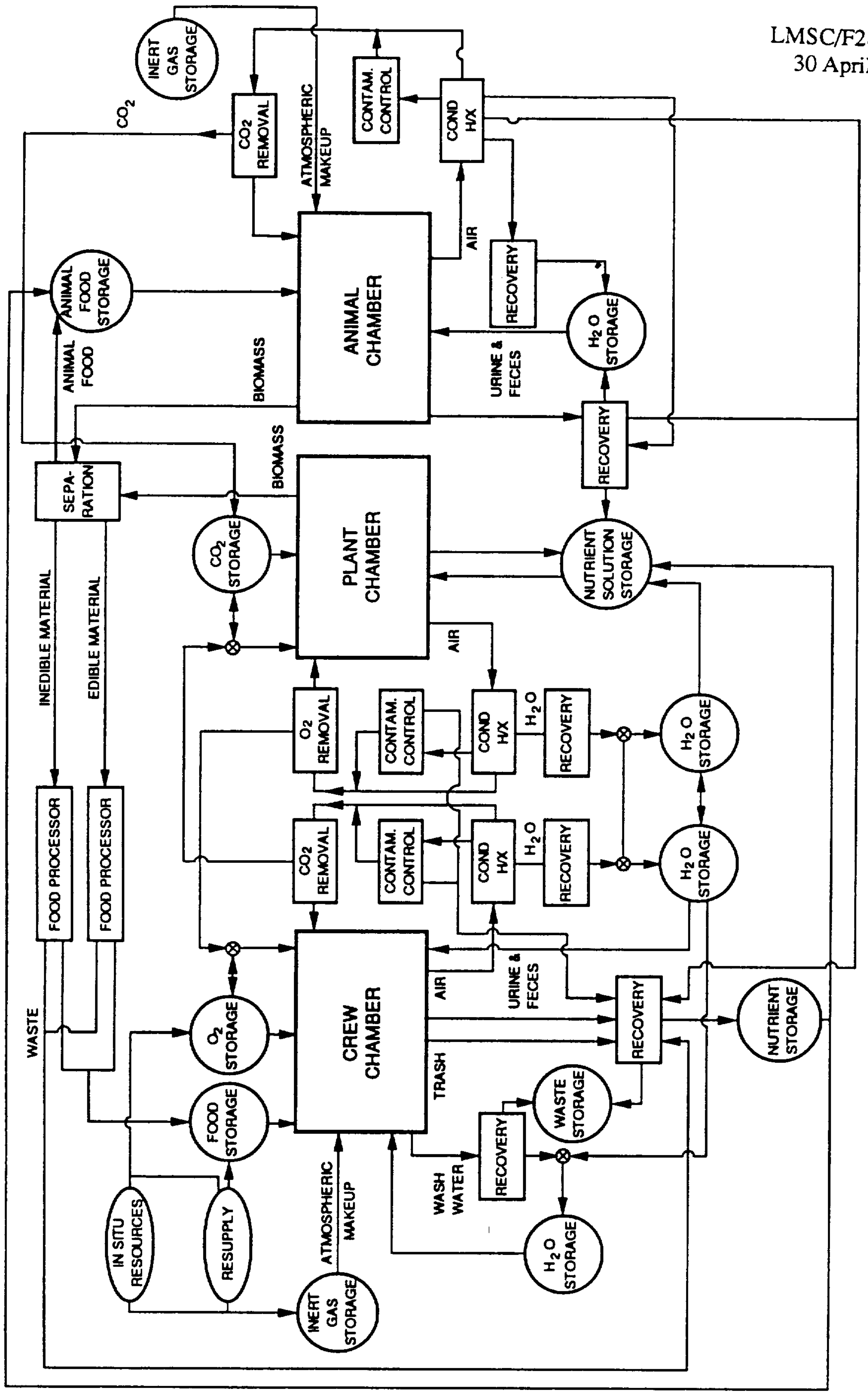


Figure 5.1. Block Diagram of LCELSS Conceptual Design.

5.2 SUBSYSTEM DESCRIPTIONS

In the following subsections, the conceptual designs for each of the six LCELSS subsystems are described in more detail. In some instances, it was not possible to select specific technologies as the best candidates for a particular function. As a consequence, the concepts presented below may identify two or more technology candidates which met the overall requirements for specific functions.

5.2.1 Atmosphere Regeneration

Atmosphere regeneration includes CO_2 removal, CO_2 reduction, O_2 production, temperature and humidity control and trace contaminant control. The LCELSS conceptual design for atmospheric revitalization is illustrated in Fig. 5.2. This concept uses higher plants for all CO_2 reduction and O_2 production. The atmospheres of the crew, plant, and animal chambers are isolated from one another by separate physicochemical CO_2 and O_2 removal systems (liquid scrubber/stripper/-concentrators). This atmospheric isolation provides for independent control of the respiratory gas concentrations in the different chambers and helps to prevent potential contamination. Temperature and humidity control are handled by standard condensing heat exchangers. Trace contaminant control (TCCS) is handled by modified Space Station Freedom technology. The TCCS must be regenerated periodically by applying heat and vacuum to the adsorbent beds. The effluent material would be captured and stored as waste, or would be processed by the waste processing system.

5.2.2 Water Purification

In the conceptual design, drinking and food preparation water are obtained by purifying condensate collected from the crew chamber or cabin. To avoid resupply, evaporative technology was chosen despite its higher power use. Thus, the concept could use VCD, TIMES, or a comparable technology. Because condensate water is not sufficient to fill the need for drinking and food preparation, the design provides for the required makeup by recovering condensate from the plant growth chamber and purifying it with the same systems. Hygiene and clothes wash water are taken from the plant condensate collection and treated by ultraviolet light (UV) polishing to remove bacteria and degrade trace organic compounds. The remainder of the condensate from the plant chamber and aquaculture unit is recycled by return to the nutrient solution, or addition to the aquaculture system to make up for evaporative losses.

5.2.3 Solid Waste Processing

The low pressure wet oxidation system shown in Fig. 5.3 receives all solid waste materials not fed into the aquaculture unit, degrades them to an organic "soup" and then feeds the effluent into the plant growth chamber as part of the nutrient solution. Wet oxidation systems for each crew size utilize the same technology.

Figure 5.2. Proposed LCELSS Atmosphere Regeneration Subsystem.

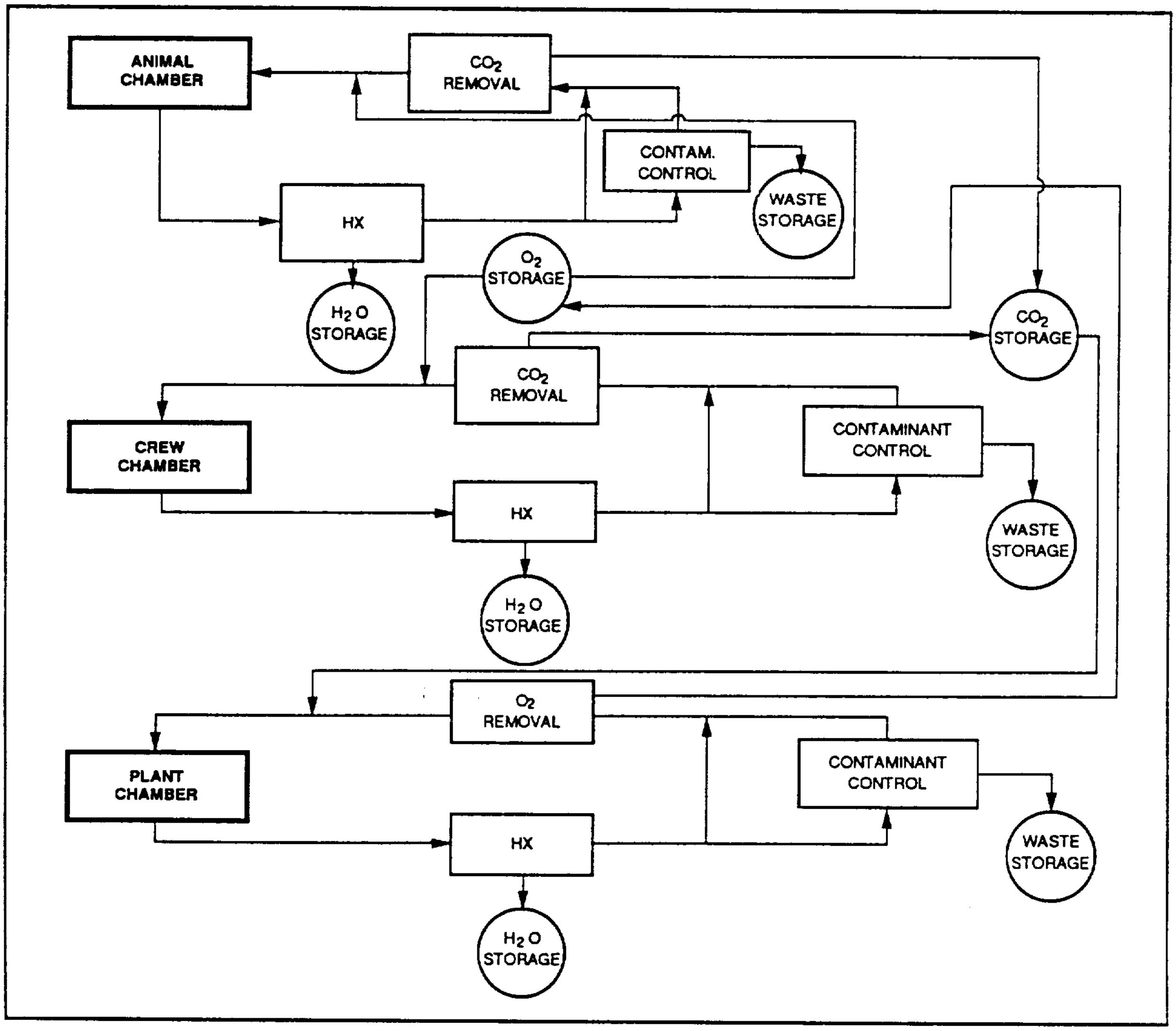
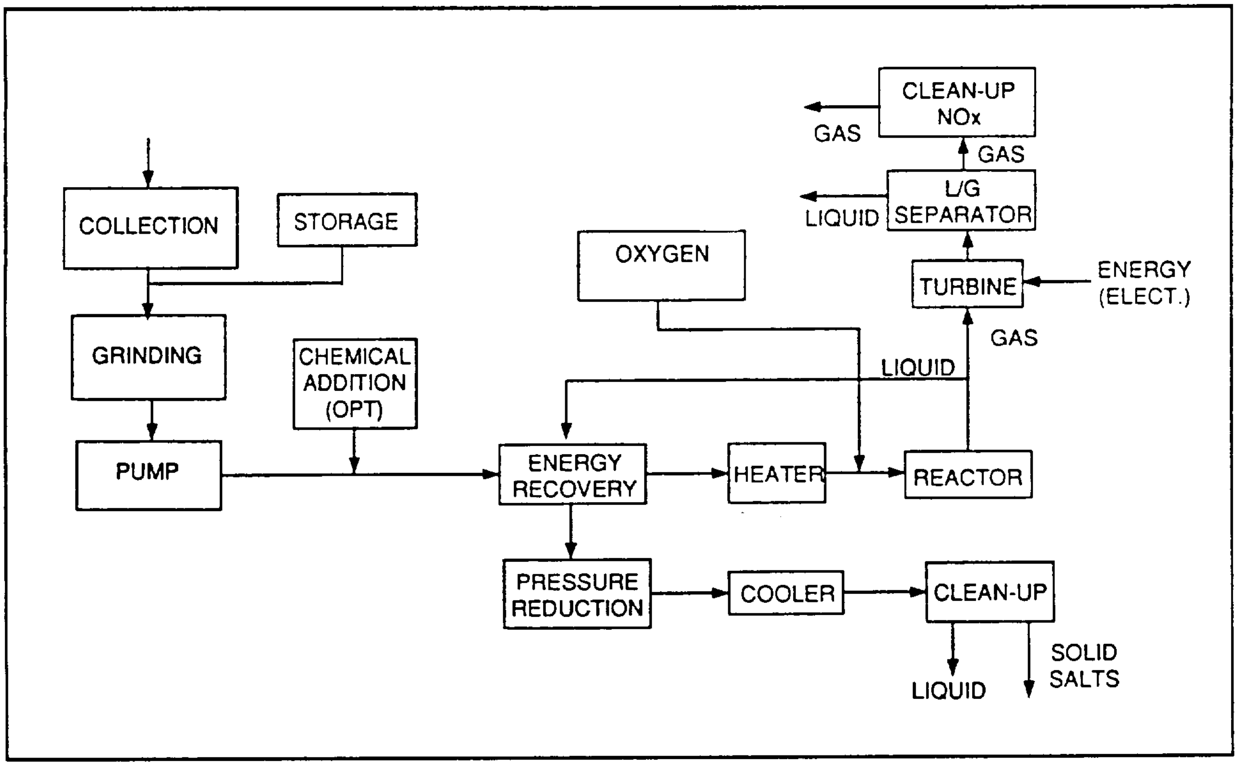


Figure 5.3. Proposed LCELSS Solid Waste Processing Subsystem.



5.2.4 Food Production

Food production involved two components, the plant growth chamber and the aquaculture unit. The plant growth system was designed to include wheat, soybean, peanut, lettuce, tomato and carrot, based on dietary analysis. With this minimum set of plant species, supplemented by about 50 gm per person per day of *Tilapia* meat and some multiple vitamins, a nutritionally adequate diet can be produced.

In developing the conceptual design for the plant growth part of the food production system, three different agricultural unit designs were developed. The first is based on the Space Station Freedom module, and provides about 100 m^2 of growing area. The second design is a hybrid inflatable/rigid wall structure with about 224 m^2 of growing area, and the third design is a large transparent-walled inflatable with approximately 528 m^2 of plant growing area. Because of the substantial contributions of the plant growth unit designs to the mass and power requirement of the LCELSS, detailed descriptions of these three units are provided in Section 5.4.

5.2.5 Food Processing

In keeping with the ground rule of using only available or near-horizon technologies, food processing hardware was minimized (grain mill, automated bread bakery). Processing operations such as preparation of grain for milling or fish meat for cooking were assumed to be manual. It was also decided to process the human-inedible plant material by feeding it to the *Tilapia*. This material could be fed to directly or after drying and grinding into smaller pieces. Uneaten plant materials and accumulated fish feces would be removed from the aquaculture system periodically and sent to the waste processor along with any unfed vegetable material.

5.2.6 Biomass Production

A number of plant and animal species produce compounds which would be very valuable in maintaining LCELSS self sufficiency. These products include oils, resins, natural rubber, gums, waxes, flavorings, fragrances, pharmaceuticals and pesticides. The biomass and/or products synthesized by higher plants are of particular interest in LCELSS. Inedible biomass (by humans) has several potential uses, one of the most direct of which is as bulk feedstock for animals. Biomass can also be formed into paper to use for writing, tissues and wipes, all of which can be recycled within the LCELSS.

Higher plants synthesize two general kinds of useful chemicals; primary metabolites and secondary metabolites. Primary metabolites include vegetable oils, fatty acids, and carbohydrates, compounds which are clearly useful in an LCELSS. Oils can be used for lubrication of machinery; in some cases (e.g, *Jojoba*) the vegetable oil produced is of extremely high quality and provides an excellent substitute for mineral- or animal-derived lubricating oils. Fatty acids are used in making soaps and detergents, which will clearly be required during normal LCELSS operations. Carbohydrates such as starch, sucrose, pectin and cellulose may be used for a variety of purposes, including direct consumption, or as feedstock for an animal LCELSS component.

Secondary metabolites are derived from primary metabolites, but have no obvious function in the plant's primary metabolism. Often they function in an ecological or environmental fashion, serving as attractors of pollinators, allelochemicals (produced for defense against other plants), or as pesticides (to protect the plant from insects, bacteria or fungal parasites). Some examples of secondary metabolites are nicotine and rotenone (insecticides), the alkaloids codeine and morphine (used as pharmaceuticals), and virtually all of the active ingredients in cooking spices.

Clearly, many of these substances are important to long-term operation of an LCELSS. However, since they are secondary to the LCELSS food production requirements and still require substantial amounts of power, biomass production is anticipated to play only a buffer role in LCELSS operation. This is particularly likely to occur during intervals in which there are reductions in crew size, and consequently less demand for food. At such times, alternative crops could be planted for production of other useful materials which would be stored until required. Such an arrangement will keep the LCELSS plant growth system operational, but not produce food which might otherwise go unused.

5.3 INTERFACES

The LCELSS must interface with other lunar base systems and activities. This section describes the major interface issues identified with regard to three of these systems.

5.3.1 In-Situ Resource Utilization (ISRU)

The elements oxygen, carbon, hydrogen, and nitrogen compose over 95% of plant tissue and in excess of 87% of human tissue. Thus, on a mass basis these four elements are the most important to LCELSS implementation. Of the four, only oxygen is present in lunar regolith in large amounts. As a consequence, from a life support perspective the extraction of oxygen from regolith must be the initial target for ISRU technology development as well as the primary focus for interfacing with the LCELSS. The conceptual design described in this section includes two methods by which oxygen can be added to the LCELSS. First, oxygen can be directly added to the crew atmosphere on an as required basis. Second, the atmosphere control subsystem includes an oxygen storage buffer to which oxygen from ISRU could be added. The conceptual design assumed that at worst, the oxygen would be isolated by the same kind of component used to isolate oxygen from the plant growth unit(s). At best, the oxygen stream from the ISRU technology would be filtered to remove particulates and then added to the crew chamber or buffer. Thus, both interfaces are simple and direct, and neither involves any unique or specific hardware.

Carbon, hydrogen and nitrogen are also available in regolith, but at much lower concentrations. Accordingly, the development of ISRU technology for their extraction is a lower priority than that of oxygen. The addition of nitrogen to the LCELSS would be as straightforward as the addition of oxygen, and should require no unique hardware. Carbon and hydrogen addition would be easiest as CO_2 and water, respectively. Specific hardware would be required to oxidize either element prior to adding it to the LCELSS, however addition of the compounds themselves presents no problems as storage buffers for both H_2O and CO_2 exist in the conceptual design.

The third ISRU candidate addresses the recovery of macro- and micro-nutrient elements from regolith. The interfacing requirements for this type of technology are more difficult to derive, as the form of the elements following extraction determine the method of addition to the LCELSS. For elements obtained through bacterial mining, the easiest method of addition would be to simply add the element-bearing bacterial biomass to the solid waste processing system. After processing, the extracted elements would be carried by the processed waste stream, while the oxygen, carbon, hydrogen, and nitrogen derived from the biomass would be treated in the same fashion as those obtained from the processing of LCELSS wastes.

5.3.2 Extravehicular/Extrahabitat Activity (EV/HA)

Six aspects of EV/HA activity were evaluated for LCELSS interface definition. They included: 1) suits (self-contained), 2) suits (umbilical connection), 3) open rovers, 4) closed rovers, 5) storm shelters, and 6) hyperbaric chambers. The simplest interface requirements were with self-contained suits, open rovers and storm shelters. In those three cases, the study indicated that any regenerative technologies used would be best interfaced to the LCELSS in batch fashion. Each of the respective EV/HA subsystems would accumulate waste products, which would be batch loaded into the LCELSS for processing. For example, solid waste materials would be accumulated in the suit and added to the waste processing stream when the crew member(s) returned to the habitat. This processing would also serve to regenerate the life support systems of these devices. The only issues identified with regard to these interfaces are: 1) the need to select EV/HA technologies which are compatible with the LCELSS technologies, 2) the need to meter the flow of waste materials into the LCELSS for recycling, and 3) the need to either supply the EV/HA subsystems with direct physical interfaces to the corresponding LCELSS subsystems and/or the need to design EV/HA subsystems in a modular fashion so that they could be removed from the EV/HA system for regeneration by the LCELSS.

Two areas of EV/HA interface were identified as being particularly important. The most crucial interface is the need for high purity oxygen to supply a hyperbaric chamber for decompression treatment. Since the hyperbaric chamber oxygen must be very pure, it would probably have to be supplied directly from the LCELSS oxygen storage reserve. In addition, this requirement leads to a need for extremely efficient systems to remove CO_2, N_2 and trace contaminants from the oxygen stored for such use.

The second interface is an umbilical connection between the EV/HA suit and the LCELSS. Such an interface could potentially provide basic atmospheric regeneration and drinking water for very long surface stay-times in the vicinity of the habitat. Food would be provided from storage in the suit, and waste materials would be accumulated for addition to the LCELSS upon the crew member's return to the habitat.

A potential application for bioregenerative life support systems was identified for use on closed rovers. These vehicle systems would probably be able to use the atmospheric regeneration capabilities of a bioregenerative systems, combined with food and waste storage. For closed rovers, algal reactors have the potential for being useful during lunar day, when sunlight could be used to power photosynthetic gas exchange. For this application, it was expected that the rover would have a physicochemical atmosphere regeneration system of sufficient size to enable the rover to return to base if the photosynthetic gas exchanger malfunctioned. As with the suits, stored wastes would be added to the LCELSS for processing and recycling.

5.3.3 System Monitoring and Maintenance.

This system is responsible for maintaining the operational health of the entire lunar base. The LCELSS study addressed the sensors, actuators, process controllers, and software required to monitor and maintain each of the constituent LCELSS subsystems. As a result, many of the control functions which this system would perform are already incorporated into the LCELSS conceptual design. As a result, the primary life support functions are provided with autonomous control capabilities, and the interface connections to the base Monitor and Maintenance System involve communication for status monitoring and coordinating overall system operation.

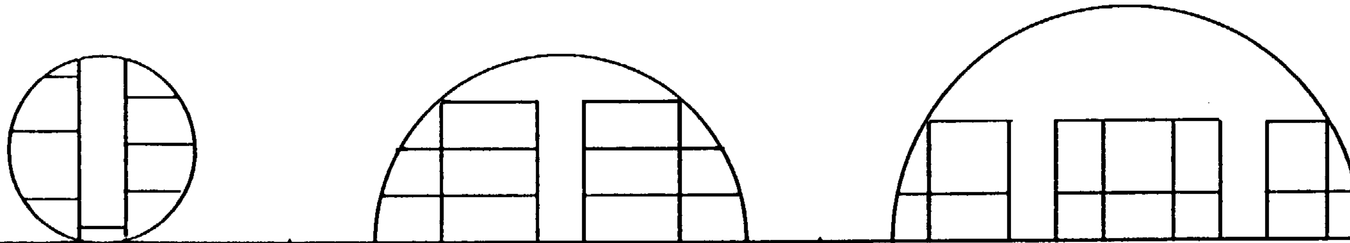
Thus, virtually all interfaces between this system and the LCELSS involve sensor or state monitoring, and are computer-to-computer interfaces or direct electronic connections. As the design of the lunar base becomes better defined, this control system must be designed to assure complete integration of all functions; in addition, its interfaces must be specified in sufficient detail to provide the capability for the overall lunar base system to record the state of the LCELSS, predict its future behavior, and ensure that it functions to sustain human life.

5.4 PLANT GROWTH SYSTEM

Several design philosophies for satisfying the crew size requirement were discussed with NASA. The design options discussed ranged from a single, 4-person-sized module which could be replicated as many times as necessary to support the necessary crew size, to one or two large units capable of accommodating 50-100 persons each. After reviewing these options with NASA, it was decided that the most valuable way in which to approach this issue was to develop three different plant production unit concepts, each of which expressed certain desired characteristics. By doing so, it was possible to compare and contrast the effects these different design concepts had on the overall system. The three different design concepts for the higher plant growth units are described in detail below, and cross sections of the three concepts are illustrated in Fig. 5.4, along with a summary of the physical characteristics of each concept.

Concept 1 - Space Station Freedom Module-based System. This concept (illustrated in Fig. 5.5) uses a SSF module to house plant growing and aquaculture subsystems. This design concept was developed to estimate the physical characteristics which would typify a prefabricated unit based on SSF hardware. The module is outfitted with both artificial lights and a reflector/light pipe/window system to allow direct utilization of sunlight. The design provides 100 m^2 of plant growing area. This growing area is sufficient to meet the food production requirements of about 4 crew members. This unit is designed to be covered with regolith as the LCELSS evolves to accommodate larger crew sizes. The regolith covering provides radiation shielding which enables use of this system for the production of seeds/breeding stock for the other design concepts. This concept is fully self-contained, and would require only connection to the base power and cooling to begin operation.

Concept 2 - Hybrid System. This concept incorporates a 5 mm thick aluminum "backbone", 4.2 m wide by 11.8 m in length. Attached to this spine are a flexible, inflatable shell, and all of the major utility runs for the unit (nutrient solution supply and drain, electrical wiring, etc.). Total plant growing area is 224 m^2, which is sufficient to satisfy the food production requirements of a 9-person crew. Artificial lighting is provided, although it was assumed that the envelope would transmit between 15 and 20% of the incident solar radiation, so that power would not be required for illumination during Lunar day. This concept is designed to function as a surface unit, with no protective regolith covering. This design concept requires a moderate amount of crew time for assembly of the supporting structure, etc., but features a prefabricated frame to which necessary supporting structure can be attached on Earth prior to launch.



Design Concept / Design Parameter	Space Station Freedom Module	Hybrid - Inflatable with Rigid Backbone	Inflatable
Dimensions	4 m dia x 11.4 m long	8 m wide x 11.4 m long	10 m wide x 60 m long
Growing Area	100 m^2	224 m^2	528 m^2
Mass	12,322 kg	17,999 kg	43,480 kg
Power Maximum	72 kw	617 kw	1,700 kw
Power Minimum	12 kw	94 kw	226 kw
Volume	148 m^3	1,187 m^3	8,255 m^3

Figure 5.4. Plant Growth Unit Concepts (Cross Sectional Views).

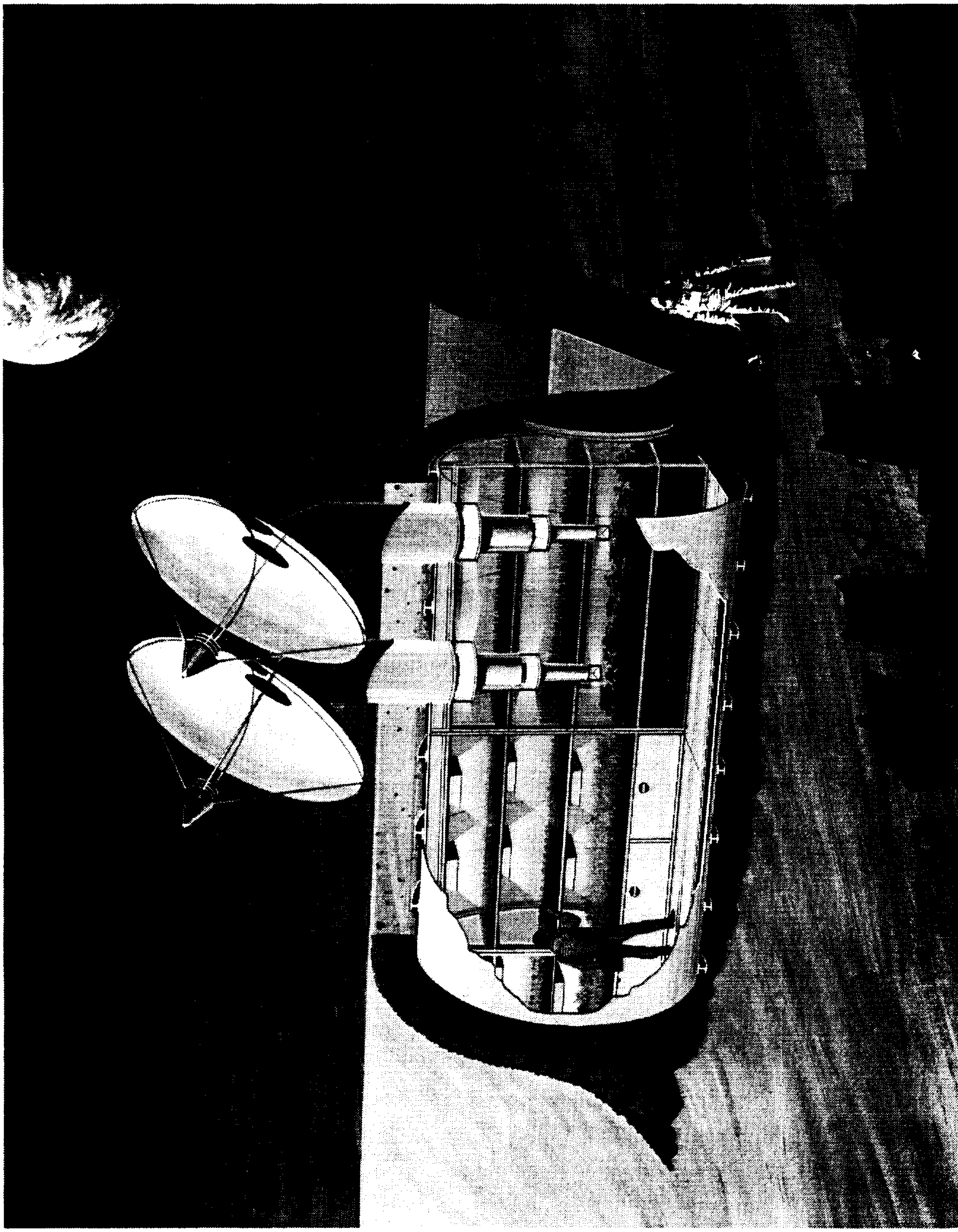


Figure 5.5. Artist's Concept of Space Station Freedom Plant Growth Unit Design.

Concept 3 - Inflatable System. This concept is at an early stage, but is envisioned as an inflatable structure with a footprint of 10 m by 60 m. It utilizes a shell made of a material similar to that envisioned for the envelope of the hybrid system. The design provides 528 m^2 of plant growing area, and is sufficient to supply the plant- and animal-based food requirements of 22 people. This concept assumes that the shell would be less opaque than the Hybrid (about 50% transmission of incident solar radiation), but with an equal mass per unit area. The structure is equipped with artificial lights for use during lunar night. Also, as with the Hybrid System, this design is envisioned as a surface unit with no protective covering of regolith. This concept has no prefabricated framing or utility runs, however, and requires complete on-site crew assembly.

To meet the requirements of the 4, 30 and 100 person crew sizes, combinations of these three concepts were envisioned. Four crew members require one of the SSF Module-based units. Increasing the crew size to 30 requires the addition of a second SSF Module-based System and three of the Hybrid Systems. A further increase in the crew to 100 persons adds 3 of the large Inflatable Systems to those previously required for the 30 person crew. An additional benefit which accrues from combining the modules in this fashion is an increase in overall system reliability

5.4.1 Detailed Description.

During the study, each of the above concepts was specified to a level of detail sufficient to allow the estimation of mass, volume and power requirement. Seven generic subsystems were identified to support this specification. Detailed mass estimates for each of the three plant production unit concepts are given in Fig. 5.6, and summarized by subsystem in Fig. 5.7 (itemized mass data is presented in Appendix B). The subsystems and their constituent parts are described below:

Module. This included the shell or envelope and all associated secondary structure (electrical wiring, structural supports, access hatch, etc.). For the SSF Module concept, the module sizing information and mass estimates for the primary and secondary structure were provided by Space Station Freedom Work Package 01 (T. Ball and W. Hoffert, personal communications). For both inflatable envelopes, mass calculations were made assuming a fiber-reinforced, polyurethane-coated nylon material similar to that used to construct inflatable hyperbaric Chambers (J. D'Andrade, personal communication). This material has a slightly lower mass than Kevlar-29 (1.68 kg/m^2 vs 1.99 kg/m^2) with the approximately equivalent physical characteristics. It has

Figure 5.6. Detailed Mass Breakdown for the Three Plant Production Unit Design Concepts.

Item/Subsystem	Mass in kg		
	SSF Module	Hybrid	Inflatable
Module			
Primary Structure	3,515	1,726	3,135
Secondary Structure	878	0	0
Total Module	4,394	1,726	3,135
Support Framing			
Frame	498	1,200	3,899
Floor Grate	156	156	1,565
Total Support Framing	654	1,356	5,465
Nutrient Delivery			
Supply Pipe	113	254	598
Return Pipe	295	661	1,558
Trays	1,477	3,309	7,800
Solenoid Valves	35	78	185
Pumps	95	214	504
Nutrient Solenoid Reservoirs	25	55	130
Total Nutrient Delivery	2,041	4,570	10,774
Lighting			
Artificial Lights	1,227	2,750	6,480
Heliostats/Reflectors	430	0	0
Total Lighting	1,658	2,750	6,480
Atm. Circulation & Control			
Fans	245	491	1,178
Ducting	316	633	1,265
Heat Exchangers	182	363	1,818
Total Atm. Circulation & Control	744	1,486	4,262
Computer Monitor/Control			
Atmospheric. Monitor/Control	11	11	23
Nutrient Solution Monitor/Control	368	810	957
Ion Chromatograph	50	50	50
Computer Controller	36	36	36
Total Computer Monitor/Control	466	908	1,066
Water	2,365	5,203	12,298

a very low leak rate; ILC measured the maximum leakage to be 26 ml/hr per m^2 of material (using pure CO_2 at a ΔP of 83 kPa (12 psi)).

Support Framing. Internal framing (including floor grating) was required to physically support all of the plant growing equipment listed below for Subsystems 3-7. To minimize mass, the framing mass was calculated assuming that it was made of graphite-reinforced epoxy material (framing, floor gratings, tankage, etc.) which has a nominal density of 1.6 g/cm^3.

Nutrient Delivery System. This included all pipes, pumps, valves, storage reservoirs, and plant root chambers. The root chambers were designed as boxes which allow the use of a wide variety of nutrient supply systems, including aeroponics, nutrient film technique (NFT), solution culture, and substrate culture (which could use Lunar regolith as the rooting substrate). The mass of the pipes in this subsystem was calculated assuming that all piping was made of polyvinylidiene fluoride because of its antifouling, temperature and abrasion resistance characteristics. Storage reservoir and plant root chamber masses were calculated assuming that they were fabricated from graphite-reinforced epoxy material. The overall system was divided into 20 m^2 sections of growing area (each section with its own reservoirs, plumbing and nutrient solution controls) to provide isolation if it became necessary for pathogen control.

Lighting. This subsystem included all lamps, ballasts, reflectors, and light pipe hardware required to illuminate the plant growing area at a photosynthetically active radiation flux (PAR) of 600 $\mu mol/m^2/s$. Lamp mass (including fixtures, ballasts and reflectors) was calculated using the results of the lighting analysis described in Section 4.1 (based on an estimated 12.3 kg per m^2 of growing area to produce 600 $\mu mol/m^2/s$ PAR as an average for 1000 W HPS and MH lamps).

Atmosphere Circulation & Control. This subsystem included all fans, heat exchangers and flexible ducting for directing air flow through the plant growth unit.

Computer Monitor/Control System. This subsystem includes the process control computer (and backup computer), atmospheric sensors (CO_2, O_2, temperature, pressure, and relative humidity), nutrient solution sensors and control components (pH, dissolved oxygen, electrical conductivity, submicronic filters, UV sterilizers, metering pumps, and composition control reservoirs), and ion chromatograph. The SSF and Hybrid concepts were designed with one set of atmospheric sensors and one set of nutrient solution sensors and control components per 20 m^2 of growing area. The

Inflatable concept was designed with two sets of atmospheric sensors and one set of nutrient solution sensors and control components per 40 m^2 of growing area.

Water/Nutrient Solution. This subsystem included the volume of water required to make up nutrient solution, nutrient solution composition control solutions, and the average amount of water bound by growing plant biomass (which was assumed to average 6.35 kg/m^2, based upon experimental data collected on wheat growth and yield in closed plant growth chambers; Schwartzkopf, unpublished data).

Figure 5.7. Mass Breakdown for the Three Plant Growth Unit Designs.

	Estimated Mass by Design Option (kg)		
Subsystem/Component	SSF Module	Hybrid	Inflatable
Module	4,394	1,726	3,135
Support Framing	654	1,356	5,465
Nutrient Solution Storage and Delivery	2,041	4,570	10,774
Lighting	1,658	2,750	6,480
Atmosphere Circulation and Control	744	1,486	4,262
Computer Monitor/Control	466	908	1,066
Water/Nutrient Solution	2,365	5,203	12,298
TOTALS	12,322	17,999	43,480

As this figure illustrates, for the SSF Module-based design option, the module mass is about 36% of the total mass. In the hybrid and inflatable options, the module makes up only 9.6% and 7.2%, respectively, of the total mass. The other primary mass contributors in the three designs are the water/nutrient solution (from 19% to 28%), nutrient solution storage and delivery (from 17% to 25%), lighting (from 13% to 15%), and support framing (from 5% to 13%).

The overall mass per square meter of growing area ranges from 123.2 kg/m^2, to 80.4 kg/m^2, to 82.3 kg/m^2 for the SSF Module, Hybrid, and Inflatable options, respectively. Based on these estimates, it is clear that the use of inflatable technology has the potential for lowering the mass per unit growing area of the plant production units by approximately one-third over that of a solid-shelled structure. In addition, any further design efforts aimed at reducing the mass of these plant production units would be best applied on the water/nutrient solution volumes, storage and distribution. As an example, the total amount of water stored as working nutrient solution could be decreased even further if the nutrient solution storage and delivery subsystem was redesigned to function at a lower solution volume per square meter of growing area. Such a redesign would also require redesign of the atmosphere circulation and control subsystem for even more rapid recovery (and return to storage) of transpired water vapor, and/or redesign of the nutrient solution composition control subsystem to enhance its efficacy.

Because of their contribution to the overall mass, the lighting and support framing subsystems are both candidates for mass decreases. However, this study attempted to optimize the overall mass of each of these subsystems. Lighting mass could be decreased if lower PAR values were desired (i.e., 300 $\mu mol/m^2/sec$ PAR would decrease lighting subsystem mass by 50%), or if an alternative technology could be used (e.g., LED lighting). The productivity rates and power requirement would both be altered by such changes. The framing subsystem already incorporates a strong, lightweight material, so mass decreases could probably be obtained only through wholesale changes in the design layout used.

5.4.2 Plant Growth Unit Hazard Analysis.

As part of the conceptual design process, consideration was given to the potential hazards facing the three plant growth unit concepts. Three primary hazards were identified; UV radiation exposure, exposure to ionizing radiation (cosmic and solar), and exposure to meteorite penetration. The topic of UV exposure was discussed in Section 4.1.

Based on the lunar environment data recorded in the study data base, ionizing radiation is not a significant hazard for plants growing in an unshielded structure on the Lunar surface. In fact, under the nominal dose rate recorded for the Lunar surface, most crop species would require over 10 year's exposure before exhibiting observable damage (See Appendix A, pages 9-12), and it is unlikely that a seed to harvest cycle time for any species would approach that value. The single exception to this result is the exposure to solar flares. Data indicates that in extremely large flares, dose rates would be sufficient to cause the death of several, though not all, common crop plants. As a consequence, two recommendations must be incorporated into the LCELSS design. First, although they occur infrequently, to survive large solar flares sufficient amounts of life support essentials must be stored to allow time to replant an entire crop and let it grow to harvest. Second, data on the mutational effects on crop plants of long-term exposure to lunar surface radiation is nonexistant. Thus, to ensure a viable, true-breeding set of crop species, the LCELSS should provide radiation shielding for the SSF-Module based plant growth units. These units could then be used as seed and propagule production facilities to support the unshielded plant growth units.

The hazard of meteorite penetration was evaluated by calculating the strike frequency of meteoroids of various diameters on the Lunar surface. These calculations indicate that the Inflatable plant growth unit (with a 10 m by 60 m footprint) would be hit by a meteoroid of 0.1 cm diameter or greater about once every 20 years. A meteoroid of 0.2 cm or greater would hit an object of this size about once every 200 years. As a result, actual impacts of meteoroids on surface plant growth units will be relatively infrequent. Even when an impact does occur, calculations indicate that the crew would have sufficient time to repair any puncture (neglecting impact damage inside the unit). For the Inflatable plant growth unit, the rate of atmospheric leakage into space through a 0.1 cm diameter hole would allow 94.8 days to repair the puncture (based on a low pressure limit of 63.6 kPa (9.2 psi), with an initial atmospheric pressure of 101.7 kPa (14.7 psi)). A 1 cm diameter puncture would allow 22.8 hours for repair. Thus, the initial analysis indicates that meteoroid puncture of surface structures is not a significant concern within the bounds of the assumptions made here.

5.5 HABITAT CONCEPTUAL DESIGN

The LCELSS conceptual design developed in this study was not required to incorporate crew habitats. However, because the life support system and the structural design of the lunar base are strongly related, an architecture was developed to illustrate how the habitats could be interfaced with the life support system. This architecture was developed to illustrate accommodation of housekeeping functions such as atmosphere, water, and waste recycling, food production and processing, thermal control, electric power, communication and access (EV/HA, airlock, separation) throughout the lunar base. The ground rule was that the design should be capable of installation with minimum crew effort and must be readily expandable to accommodate evolution of the initial 4-person lunar outpost to a fully operational installation with a 100-person crew. The habitat concept is described in the following paragraphs.

5.5.1 The Habitat Concept

The concept utilizes three standardized components: a cylindrical habitation/laboratory module (HLM), a suite of constructible/inflatable habitats (CIH's), which provides larger volumes for plant production (and eventually, for habitats or laboratories), and an interface/resource node

(IRN) for connecting the components. Base evolution from 4 to 100 people is achieved through multiple use of these three components.

The key element in this design is the interface/resource node (IRN) which provides all interfaces and housekeeping functions, minimizing the number of internal lines and plumbing due to the arrangement of hardware in the IRN. The IRN permits construction of different lunar base configurations, as well as flexible arrangement of components, without the need for specialized, uniquely-designed structures. The IRN can also be used as a safe-haven in case of emergencies, significantly reducing the volume to be maintained at habitable conditions. Basic life support functions in an emergency are easily accessible. Depending on size and configuration of the lunar base, up to two interface/resource nodes are connected to each habitat module, providing multiple redundancy for all vital functions. The use of large numbers of identical components, rather than uniquely-designed components reduces cost and allows for easier maintenance and replacement of failed/aged components.

The dimensions of all three basic components are designed so that everything 'fits' without special adapter interfaces in different/new configurations (i.e., node spacing is a multiple of other unit's length). Growth, adaptability and expansion for the future are easily possible.

Figure 5.8 schematically shows the three basic habitat components, the IRN, the cylindrically-shaped HLM, and the CIH (which has the three modular size variations discussed above). In this concept, one IRN with one HLM form an autonomous unit, with a second IRN providing redundancy if required (See Fig. 5.9). Figure 5.10 illustrates the expandability and flexibility of the modular concept by showing how module geometry and dimensions permit different configurations of a hypothetical lunar installation without special adapters. Redundancy for housekeeping functions is provided through use of multiple IRN's. The modules are generally arranged with one IRN at each end, thus providing redundant access for safety.

<u>Habitation/Laboratory Module (HLM)</u>. The HLM is a standardized cylindrical core with two conical end caps. Only the interior is custom-fit, the exterior and the interfaces connecting to the IRN are invariant. The HLM can be landed on the lunar surface with an attached IRN as an autonomous and operational unit, requiring no assembly or construction. Several of these units may be combined to form a larger lunar base. Constructible habitats may also be attached to the IRN's to add volume to the base.

Figure 5.8. The Fundamental Building Block Modules of the Conceptual Design.

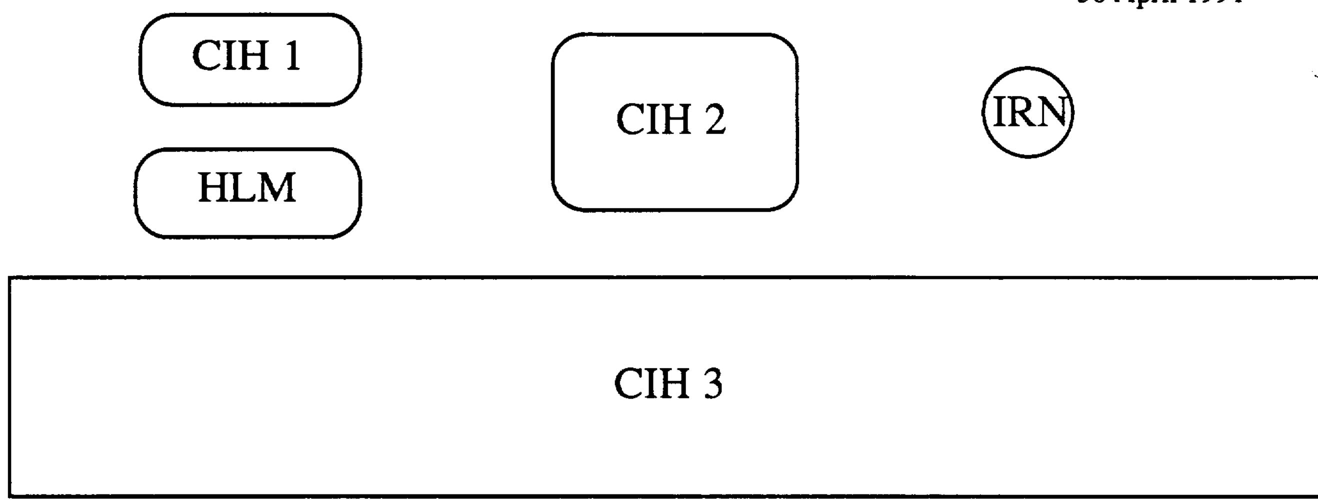


Figure 5.9. The Basic Autonomous Unit of the Conceptual Design.

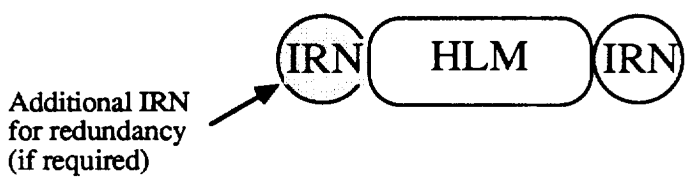
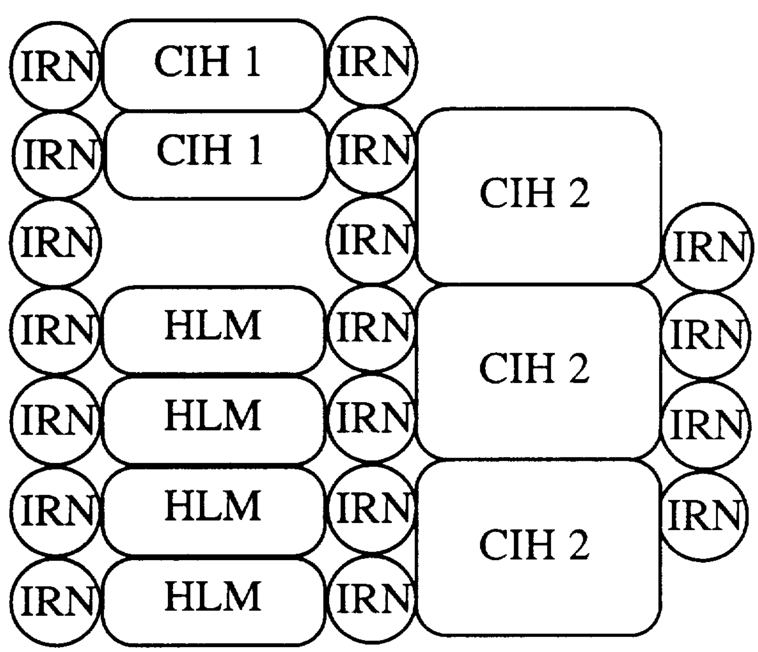


Figure 5.10. One Example of a Module Layout for the 30 Person LCELSS Conceptual Design.



Interface/Resource Node (IRN). The IRN contains all utility runs and provides all interfaces to the HLM, as well as to other IRN's and the constructible/inflatable habitat(s). The IRN also includes all equipment (e.g., fans, pumps) for mass and energy transfer to and from other modules of the lunar base. The IRN is the key element in the conceptual design. The IRN serves as an airlock, provides centralization of all life support and housekeeping interfaces, and serves as an emergency safe-haven for the crew. In case of emergency (failure of the habitation module or the life support system, meteoroid impact, etc.), the small volume of the IRN would be easier to maintain at habitable conditions. Due to the proximity of all reservoirs in the IRN, very simple approaches to an emergency life support system are possible.

Constructible/Inflatable Habitat (CIH). Where larger volumes are required, such as for large scale plant production, constructible or inflatable habitats may be added to one of the interface/resource nodes. In these cases, all basic mass and energy flows to and from the CIH are still provided by the IRN. Unique equipment, such as the increased number of condensing heat exchangers for a plant growth unit, would be implemented within the constructible habitat. The CIH will required. With a CIH-based plant production unit, the IRN would mainly be used to transport and distribute material flows (water, air, food, waste, etc.).

5.5.2 Design Advantages for Evolutionary Expansion

This concept supports the evolution from a core lunar base consisting of IRN's and HLM's to a larger facility with the addition of several constructible habitats. Even when densely packed, each module has multiple access for safety. Using this concept, new biological and/or physicochemical life support components may be easily incorporated without alterations to the initial base design. The IRN will accommodate and provide all interfaces needed for housekeeping functions. Multiple redundancy is built-in at low cost due to the decentralized systems in the adjacent IRN's. The component-efficient design would also minimize the infrastructure mass (e.g., plumbing, wiring, ducts) required. If a large volume greenhouse were to be added, the IRN would route all mass and energy flows to and from the greenhouse to adjacent users in the habitation modules.

5.5.3 Habitat Failure Analysis

In conjunction with the study, a failure analysis was performed for the habitat conceptual design, and five failure modes were identified.

1) Functional (partial) loss of one biological life support component (plants) in the constructible habitat.
2) Loss of atmosphere (penetration) in the constructible habitat or the habitation module.
3) Functional loss of support/housekeeping hardware (power failure, life support system component failure).
4) Loss of atmosphere (penetration) in the interface/resource node.
5) Functional loss of interface/resource node.

The failure analysis assumes that HM's and CIH's are connected to other components by means of IRN's which provide all interface tubing, wiring, and ducting. These IRN's also serve as airlocks to the lunar surface as well as to separate the different volumes (modules) from each other. Mass/energy flows may be interrupted or re-routed within the IRN.

Depending on the degree of failure, several redundancies and safe-haven options are available using the proposed conceptual design. The failure modes considered for this analysis are summarized below.

<u>Failure Mode 1: Functional (Partial) Loss of Biological Life Support Component (Plants) in the CIH.</u> The affected volume can be isolated from the rest of the base by closing the IRN airlock to contain possible contamination; mass flows from this volume may also be interrupted. Life support functions provided by that constructible habitat can be taken over by other adjacent modules.

<u>Failure Mode 2: Loss of Atmosphere (due to penetration) In the CIH or the HM.</u> The IRN airlocks would be closed to avoid further loss of atmosphere. Mass flows into the affected module would be interrupted and re-routed through adjacent IRN's and HM's. If only one habitat was available, the IRN could be used as an emergency safe-haven or habitat until repair work was finished.

<u>Failure Mode 3: Functional Loss of Support Hardware (Power Failure, Life Support System Component Failure).</u> Reduced life support functions for emergencies would be provided in the IRN from buffers and storage. The smaller volume of the node will be easier to maintain at habitable conditions than the larger habitation/laboratory modules. Proximity of all essential functions within the IRN allows simple, low- or no-power consuming technologies (bleed air flow, gravity flow of water from buffer, food from storage, etc.).

Failure Mode 4: Loss of Atmosphere (Penetration) in the IRN. Hardware within the IRN would not be affected by exposure to vacuum conditions, although access to all adjacent structures would be interrupted. In a more advanced lunar base, each module would have at least two IRN's for safety (two access possibilities or airlocks in case of failure or emergencies), therefore access would be preserved and the functional integrity of the base would not be affected.

Failure Mode 5: Complete Functional Loss of IRN. All functions can be taken over by adjacent IRN's working at higher loads. The lost airlock connection would be provided by the remaining IRNs. If repair was not possible, the node would be replaced with a new IRN.

5.5.4 The Interface/Resource Node as a Safe-Haven

In case of major system failure and/or loss of the larger habitation volumes, the node may be used as an emergency safe-haven, providing all essential life support functions, but at a reduced level. Due to the proximity of all buffers in the IRN, simple methods may be used to meet life support needs (e.g., simple gas bleed systems, gravity-driven fluid flow, hand pumps, passive thermal control). The resource node would have sufficient storage volume to provide consumables for 4 persons for 180 days. A rough estimate of required mass and volume is presented in Fig. 5.11.

Figure 5.11. Interface Node Emergency Capabilities (Consumables for 4 persons, 180 days).

Item	Estimated Volume Per Person (m^3)	Estimated Mass
Food	18	108 kg (0.6 kg/day)
Water	1	1,000 kg (930 kg + tanks)
Potable		810 kg (4.5 kg/day)
Hygiene		120 kg (0.64 kg/day)
Oxygen		450 kg (190 kg +tanks)
Nitrogen		145 kg (45 kg + tanks, 0.25 kg/day leakage) to be dumped for later use
Power	0 - 1,000 W	Depending on failure mode, system may run without power.
Thermal Control	100 - 1,100 W	Human heat + any additional electric energy to be rejected.

5.6 PARAMETRIC ANALYSIS

The estimated mass of the LCELSS supporting each of the three crew sizes is summarized in Fig. 5.12. As this figure shows, the plant growth units constitute the largest subsystem in all three concepts. In the 4 person crew, the SSF Module-based plant growth unit accounts for about 82% of the total mass, while in the 30 and 100 person crews the plant growth subsystems account respectively for 79% and 74% of the total mass. The second largest mass item is the aquaculture system, which accounts for 9%, 10% and 12% of the total system mass for 4, 30 and 100 crew members, respectively. It should also be noted that because of the mass differences between the three plant growth unit design concepts, the total mass of the system does not increase linearly with crew size. As the crew size increases, the production of plant-based foods shifts to larger, but lighter units.

Figure 5.12. LCELSS Mass Estimates by Crew Size.

Subsystem/Component	Estimated Mass by Crew Size (kg)		
	4	30	100
Plant Growth Unit(s)	12,322	78,641	209,081
Solid Waste Processing	63	273	808
Atmosphere Regeneration	271	1,169	3,016
Water Purification	31	233	778
Aquaculture (*Tilapia*)	1,366	10,169	33,695
Food Processing	26	52	122
Inflation Gas	N/A	1,446	12,014
90 Day Food Reserve	565	4,239	14,130
30 Day Oxygen Reserve	394	2,952	9,840
TOTALS	15,038	99,174	283,484

As indicated in this figure, the food and oxygen reserves were calculated for different time intervals. Food was calculated on a 90 day basis, as a problem with the food production system could take up to one full crop cycle (as high as 60-90 days from seed to harvest) to return to equilibrium. Oxygen production, on the other hand, would be adequate to support the crew approximately 30 days after starting a new crop.

Estimates of the electrical power required to operate the LCELSS for each crew size are presented in Fig. 5.13. Power for artificial lighting was calculated from the bulb wattage estimates described in Section 4.1, with a 17.5% overhead added to account for nominal losses (e.g., ballast). All other power requirements were estimated from individual components (e.g., fans, pumps, sensors). Appendix B gives itemized values for the three plant production units.

Figure 5.13. LCELSS Power Estimates (Maximum and Minimum) by Crew Size.

Crew Size	LCELSS Power Requirement (kW)	
	Lunar Night - Max.	Lunar Day - Min.
4	72	12
30	617	94
100	1,700	226

The maximum power listed would be required only during lunar night, when all of the artificial plant lighting was turned on. Power requirement could be decreased by changing the photoperiod; for instance, decreasing the 100% duty cycle used to develop these estimates to a 50% duty cycle (12 hours day + 12 hours night) cuts the power requirement in half. This kind of decrease in day length could also lead to lower productivity of some crop plants, however, and its impact on growing area must therefore be considered carefully. Minimum operating power during lunar day is also presented for comparison, and is based upon the assumption that all PAR is supplied by natural sunlight. It is evident from these estimates that the use of electrical power to supply PAR is an extremely strong driver of the system power use, but also that use of sunlight can significantly reduce this requirement.

Figure 5.14 summarizes the volume estimates for the LCELSS at the three crew sizes. Estimates were made for the erected volumes, based on the dimensions of the plant growth units, which contain virtually all of the life support hardware.

Figure 5.14. LCELSS Volume Estimates by Crew Size.

Crew Size	LCELSS System Volume (m^3)
4	148
30	1,187
100	8,255

SECTION 6
LCELSS VS RESUPPLY - BREAKEVEN ANALYSIS

A breakeven analysis was conducted to determine the mission duration at which an LCELSS design began to provide mass savings over a resupply scenario. Rather than develop new values previously published data were used for the resupply scenario, (Gustan and Vinopal, 1982). Gustan and Vinopal's closure scenario D provides data for a physicochemical system in which air and water are recycled, and food and replacement parts are provided by resupply flights. This scenario has been used extensively in the past as a baseline for breakeven analysis of CELSS-based life support systems. The analysis described here is presented in a fashion that will allow easy updating as more detailed information accumulates on the physicochemical systems.

6.1 COMPARISON OF 4-PERSON PLANT GROWTH UNIT MASS ESTIMATES

For reference purposes, a comparison was made the between the SSF Module-based design concept developed in this study and a mass estimate previously published for a four-person plant growth unit concept (Gustan and Vinopal, 1982). Although the subsystem masses were allocated somewhat differently for these two concepts, the subsystems were analyzed and grouped to provide as similar a basis for comparison as possible. The grouped subsystem mass estimates for both concepts are listed in Fig. 6.1.

As this table indicates, the most significant mass differences exist for the module shell, lighting, atmosphere circulation and control, computer control system and water. The higher mass of the module in the LCELSS SSF-Module based unit is expected, as that estimate reflects a more detailed understanding of the actual module structure than the earlier study.

The difference in lighting subsystem mass estimates is directly due to the multiplication factor for calculating lamp system mass. In Gustan and Vinopal's study, the factor was 34 kg/m^2, while the factor used in this study was 6.14 kg/m^2. A portion of this difference is directly attributable to the incorporation of lighting support structure in the earlier study. In this study, the lamp support framework is included in the estimated mass of the support framing subsystem.

The mass of the atmosphere circulation subsystem was estimated by formula in the Gustan and Vinopal study. For the SSF Module-based design developed in this study, the subsystem mass was estimated directly by summing the mass values of the major individual components. The mass of the computer control subsystem is significantly larger in this study, since it includes all hardware for completely monitoring the air and nutrient solution portions of the plant environment. In the earlier study, the subsystem included only the control computer and a CO_2 analyzer.

Figure 6.1. Mass Breakdown for the Two 4-Person Plant Growth Unit Designs.

Subsystem/Component	Estimated Mass by Design Option (kg)	
	LCELSS SSF Module	Gustan & Vinopal SSF Module
Module	4,394	3,395
Support Framing	654	720
Nutrient Solution Storage and Delivery	2,041	2,336
Lighting	1,658	3,400
Atmosphere Circulation and Control	744	1,708.5
Computer Monitor/Control	466	16
Water	2,365	7,470
TOTAL	12,322	19,045.5

The mass estimated for the water/nutrient solution was significantly higher in the Gustan and Vinopal study. This difference is attributable to two factors. First, the earlier study assumed that the amount of water sequestered in plant biomass ("plant cellular water") amounted to approximately 23.9 kg/m^2, while this study assumed the amount to be about 6.35 kg/m^2. This difference seems to be due to the overall plant production method assumed in the two studies. Here, it was assumed that a continuous culture system would be employed. This decision means that all ages of plants from seedlings to mature are present at the same time, and implies that the average amount of water held in the plant tissue can be calculated from the mid-sized plants. In Gustan and Vinopal's study, plant growth apparently involved a batch culture system, implying that the water content of the plant tissue had to be sufficient to hydrate fully mature plants across the entire growing area. If the same approach had been taken in this study, the plant cellular water figure equivalent to that of the Gustan and Vinopal Study would have been about 12.7 kg/m^2.

The second difference in water mass concerns the volume of water required to maintain the nutrient solution. In the earlier study, nutrient solution water was estimated to require about 5.1 kg/m^2. In this study, the derived estimate was about 1.7 kg/m^2. The later estimate was developed independently, based on currently existing hydroponic plant production systems, but it requires rapid recovery and return of transpired water to the nutrient solution reservoirs. As such, it should be regarded as a practical minimum.

Also, in the Gustan and Vinopal paper nutrient delivery subsystem mass was based on tankage. In contrast, the tankage mass in this study is only 25 kg, and the remainder of the system mass is attributable to pumps, piping, etc. The dramatic difference in tankage mass values is directly due to the fact that Gustan and Vinopal used 73.5 liter Shuttle water tanks in their mass estimate, while this study used 946 liter graphite epoxy tanks, each of which has a mass of only 5 kg.

6.2 MASS BREAKEVEN POINT CALCULATION

Using Gustan and Vinopal's data on physicochemical life support systems with food resupply (Scenario D), breakeven graphs were developed for the LCELSS crew sizes of 4, 30 and 100. Note that the LCELSS mass values do not include any mass penalty for either power use or heat rejection. These graphs are shown in Figures 6.2 through 6.4. These three figures show that the LCELSS conceptual designs have breakeven times ranging from about 1.7 to 2.6 years (for 100- to 4-person crews, respectively), when compared with the physicochemical mass estimates. With regard to self sufficiency, the LCELSS conceptual design was estimated to be capable of achieving over 99% mass closure. This characteristic is illustrated by the extremely shallow slope of the LCELSS mass lines as mission duration increases. The slight increase is due only to the need for replacement parts and vitamin supplements for the crew. As Gustan and Vinopal found in their study, the LCELSS breakeven point decreases as crew size increases.

6.3 POWER REQUIREMENT AND VOLUME ESTIMATES

Power requirement and volume estimates were developed for a physicochemical life support system with food resupply, using data presented by Gustan and Vinopal. The corresponding estimates for the LCELSS conceptual design are presented below. Figure 6.5 presents the estimated power requirements for the LCELSS conceptual design with estimates for a physicochemical system (based on Gustan and Vinopal). As indicated, the minimum LCELSS power requirement (during lunar day) ranges from about 2 to 1.5 times greater than the physicochemical requirement for a comparable crew size. In contrast, the maximum power requirement (during lunar night) is just over ten times greater than the physicochemical requirement for a comparable crew size.

Figure 6.2. Breakeven Point Graph for a Crew of 4 Persons.

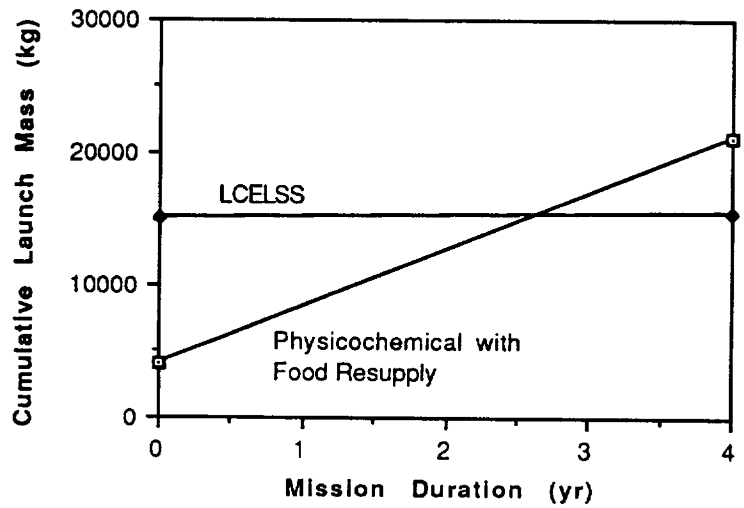


Figure 6.3. Breakeven Point Graph for a Crew of 30 Persons.

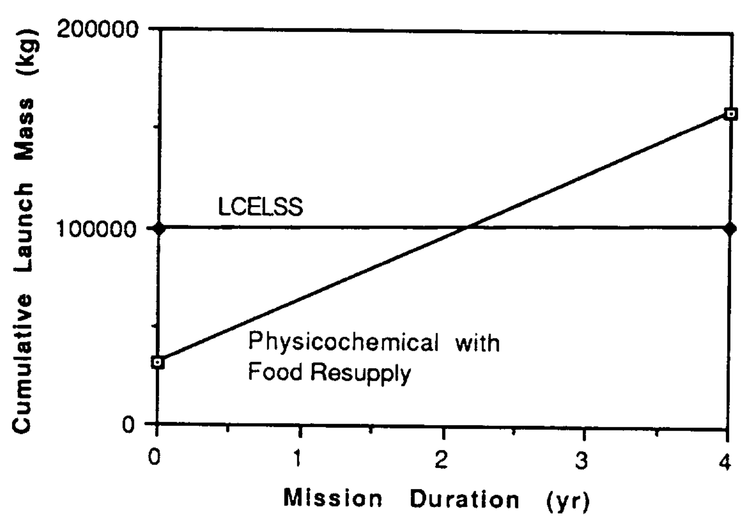


Figure 6.4. Breakeven Point Graph for a Crew of 100 Persons.

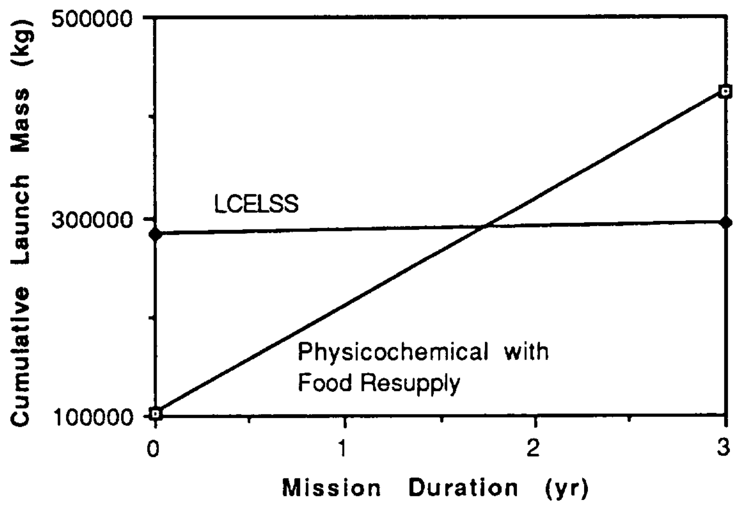


Figure 6.5. Power Estimates for LCELSS and Physicochemical Systems by Crew Size.

Crew Size	LCELSS System (kW)		Physicochemical
	Maximum	Minimum	System (kW)
4	72	12	6.2
30	617	94	46
100	1,700	226	154

Volume estimates for the LCELSS conceptual design are compared with the volume estimates calculated from Gustan and Vinopal's data in Fig. 6.6. This data shows that the LCELSS volumes range from ten to twenty times greater than either the initial launch volumes or the yearly resupply volumes of the corresponding physicochemical systems.

Figure 6.6. Volume Estimates for Erected LCELSS and Physicochemical Systems by Crew Size.

Crew Size	Physicochemical System (m^3)		LCELSS
	Launch	Yearly Resupply	System (m^3)
4	15.3	16.0	148
30	115	120	1,187
100	383	400	8,255

SECTION 7
TECHNOLOGY RESEARCH AND DEVELOPMENT NEEDS

This section describes the technology areas identified as requiring further research and development, as well as providing estimates of the resources necessary to conduct the research and to develop the first hardware units. A broad range of needs have been identified as requiring further research and development. This section highlights these needs and provides estimates for the manpower time lines likely to be required. Where major technology hurdles remain, the estimates reflect best scientific and engineering judgement, including safety and reliability issues.

7.1 RESEARCH REQUIREMENTS IDENTIFICATION

Three categories of life support must be considered. Broadly speaking, they are long-term consumable storage, physicochemical regeneration and biologically-based regeneration:

1) Storage systems and simple physicochemical systems have been successfully used in space applications and adapting them to the Lunar surface should be reasonably straightforward. Only questions of longevity and durability remain to be investigated.

2) More elaborate physicochemical systems await testing and performance evaluation. These systems may be excellent candidates for baseline or even complete life support functions in the Lunar environment. Input-output relations are reasonably easy to characterize but questions of safety, reliability and resupply are difficult to answer with existing data.

3) Finally, while bioregenerative systems are the major life support system on Earth, they are inherently complex with many parallel processes and with undetermined sensitivities to the space environment. Yet, the robustness of biological systems has been well documented both on Earth and in space.

Research and technology needs differ considerably depending on the life support functions being considered. However, certain commonalties occur in underlying support requirements. While storage implies considerable mass and volume costs and regenerative technologies raise reliability, safety and power issues, all of these systems must be housed in enclosures that permit less leakage than currently experienced in most space vehicles. Mass losses associated with leakage will take a large toll over the extended periods of use planned for a Lunar base. The concept of complete, or near complete, leakage prevention is even now, crucial to engineering design evaluations of a variety of potential life support system components.

It is unlikely that protracted space missions will depend solely on any regenerative life support system. Sufficient "on-hand" supplies will have to be available to fully support emergency return scenarios. Storage improvements will be needed to support both long-term and volume conservation technologies. Distributed storage systems will prevent the risk of single point failure. Since waste mass is directly related to storage mass, storage of consumables should also accommodate exchanges for the storage of waste, preferably in the same volume.

Both physicochemical and biological regenerative life support technologies are dynamic processes, dependent on the reliable, predictable functioning of both constituent and support components. Commitments to research and development of either option for space use have been very modest. Thus, neither technology should be perceived as having definite advantages over the other. It seems likely, however, that a highly reliable regenerative life support system will have considerable redundancy, incorporating overlapping bioregenerative and physicochemical subsystems.

Atmosphere regeneration and water purification technologies appear to be the best candidates for physicochemical solutions while waste reuse may benefit from combined physicochemical and biological solutions. Food production appears, at present, to be the prime candidate for bioregenerative approaches. Even in food production processes, the bioregenerative systems could have desirable impacts on atmosphere regeneration, water purification and waste reduction. Thus, the integration of physicochemical and bioregenerative life support systems will be a major challenge to creating an overall space-qualified regenerative system for life support.

7.1.1. Bioregenerative Technology Research Areas

Since several recent symposia and reports (e.g., NASA-Ames Research Center, 1989) have covered the research and technology development requirements in physicochemical systems, so they will not be discussed here. Bioregenerative technologies are summarized, together with the major technical challenges in Fig. 7.1. Major areas of application in atmosphere, water, food and waste functions are presented and the associated support considerations shown.

Atmospheric regeneration technologies dependent on biological processes are likely to exhibit reduced mass flow rates compared to physicochemical systems. Gas membrane filters used for gas separation or enrichment may meet the requirements of bioregenerative systems, and could provide simple, low power means for acquiring enriched gas streams. The need for regular filter changes and resupply must be avoided and is a major technological challenge. Since the gases would arise from "open" biological sources (crew, plants and animals), major commitments would be required for the monitoring and control of trace contaminants and disease organisms. The automated control of biological gas production; the analysis of emanating gases; the storage, separation, and release of gases; and the overall balancing of gas mixtures are the major research challenges to be met for bioregenerative technologies.

From a consideration of masses involved, the water regeneration problem must be considered most pressing. Filtration offers an effective method of treatment but exacts high resupply costs unless these filters can be readily restored through backwashing, sterilization or other techniques. Filters designed to be biodigestible are another possibility requiring development. Water regeneration is inherent to most plant-based systems. In producing a unit of plant mass, between 200 and 1000 units of water are taken up the plant and transpired into the atmosphere. Thus, plants can be considered as ultrafitration mechanisms capable of producing high quality water. The technologies that would relate to transpiration water recovery in space remain relatively unsophisticated. Micro-organisms might play a major role in preprocessing water prior to plant use. These possibilities have received only limited research attention. The potential payoff seems to dictate the need for much enhanced research activity. A variety of uses may be considered for plants or plant parts used for water filtration but not suitable as food. As above, a variety of monitoring and control challenges are associated with bioregenerative water treatments.

Food production, as stated above, is likely to remain in the domain of bioregenerative life support technologies. The food products, through familiar freshness, texture and taste, will be important psychological considerations in protracted missions and in the relative isolation of space. Much of the food will be derived from plants because of dietary habits, and because plants have a fundamental reciprocity with humans in regard to inputs and outputs. Desirable water and atmosphere regeneration functions were noted above. Underlying concerns for plant-based food production relate to reliability, as well as the need to demonstrate plant viability through multiple

Figure 7.1. Research Needs and Priorities.

Atmosphere Regeneration
1. Gas Separation Methods
2. Long-term Gas Storage Methods
3. Gas Monitoring Methods
4. Contamination Monitoring and Control

Water Processing
1. Water Quality Monitoring Methods
2. Acceptability of Plant Transpiration Water Condensate Reuse
3. Bio-compatible Contamination Control

Waste Processing
1. Ancillary Processes (Separation, Filtration, Grinding, etc.)
2. Biological (Microbial) Reactors
3. Recycling, Including Non-Life Support Uses (fuel, power, materials, etc.)
4. Increased Processing Efficiency

Food Production
1. General Performance Identification
2. Power-Efficient Lighting Systems
3. Automation of Planting/Harvesting/Handling Tasks
4. Control of Plant Nutrition
5. Rapid Recovery and Recycle of Transpired Water

Food Processing
1. Processing Technology Identification and Performance
2. Processing, Preservation and Long-Term Storage Techniques
3. Automation of Processing Machinery

In Situ Resource Utilization (ISRU)
1. Requirements for Site Selection
2. Definition of Potential Interfaces Between ISRU and Life Support System

EV/HA
1. Performance of Candidate Technologies
2. Definition of Potential Interfaces Between EV/HA and Life Support System

System Monitoring and Maintenance
1. Identification of Critical Parameters to be used for Sensing System State
2. Integration (Simulation Models, Process Control Methods, Monitoring Devices)

generations grown in the space environment. Repeated seed-to-seed life cycles have yet to be demonstrated in space. Many questions remain with regard to a choice of nutrient delivery and substrate support for plants.

Perhaps most critical is the need to maintain complete closure in plant growth systems during ground-based research, and the need to make comprehensive performance measures during such closure. Neither has been done, and the required monitoring equipment is extremely costly or simply unavailable. It appears that in developing the required monitoring capability, the development of new types of sensors is desirable, since fractional gravity may severely impact many surface-active transducer devices. Finally, the light harvesting characteristics of plants dictate the provision of power-intensive artificial light sources, at least during Lunar night. Potential modifications include research and development into the development of more efficient light sources, as well as the selection and breeding of plants which are more efficient in harvesting light. Whether or not crop rotation or other Earth-based agricultural techniques are practical in closed growth environments also remains to be demonstrated.

Food production using micro-organisms or animals in addition to plants requires more support hardware. Both, however, may represent significant opportunities in converting "waste" materials to consumables. Both biodigestion and bioconversion activities, in such regards, must be examined in small, closed systems over extended periods. A major challenge is the subsequent separation and preparation of useful products. Animal use, fish or fowl (based upon bioconversion efficiencies), may create a special class of preparation problems. Small scale processing of animal protein sources remains a labor intensive activity and may not be easily adapted to space use. Consequently, both multicellular and unicellular (e.g., protozoa, bacteria) sources of food may require the development of special processing technologies. This processing must, of course, reproduce the form, texture and tastes of the food products normally experienced in conventional dietary uses.

In the waste processing domain, bioregenerative technologies appear to be excellent options. Processing on a small scale remains to be achieved, and waste separation technologies must be refined. Nevertheless, bioconversions of waste may be possible to enhance atmosphere and water regeneration or food production. Monitoring and sterilization technologies appear to be needed to handle waste effectively. It seems likely that physicochemical handling of waste can be used as a preprocessor for bioregenerative systems. Recovery of water, dispersion and disruption functions are required for currently envisioned waste bioconversion. These functions are complicated by the heterogeneity of waste. One distinct advantage, however, is that waste inputs can be more carefully controlled than in ordinary terrestrial applications of waste processing.

For all of the above bioregenerative systems, the development of engineering demonstration models is required. These models must have closure and must include sufficient monitoring capability to assess system performance. Such models lend themselves to evaluations of power use and heat rejection requirements as well as to evaluations of system reliability. Data collected from these model systems would support the development of control and monitoring strategies, in both physical and biological domains. A suitable enclosed volume structure must be developed for research on bioregenerative systems. Closure needed for some of the other technological challenges also provides test opportunities for structures, structural interfaces, and structural integrity evaluation.

In any evaluation of life support on the Lunar surface, questions of in situ resource utilization arise. It is inappropriate to consider these issues in reasonably well-closed life support systems since neither the quantity nor quality of such resources can be determined at this time. Specification of the quantity and quality of input materials could, at least initially, change the mass balances achieved in successful bioregenerative life support systems. Following successful experiments, experimental additions of in situ-derived materials may be feasible.

The general categories of research and development needs summarized above provide a challenging vista. Bioregenerative life support understanding is consistent with much of the understanding that is required for protection of the terrestrial environment. Thus, cooperative ventures may help leverage both the funds and time needed to develop bioregenerative life support systems. What is most abundantly clear is that certain engineering test models are needed now to assure the data bases required in the near future. Extrapolations from widely varying system designs or from partially closed systems will not suffice. Also, simpler, more reliable monitoring systems are needed for assuring nominal monitoring and implementing the required controls. With these kinds of technologies at hand, it will be possible to more effectively evaluate hybrid systems composed of both physicochemical and bioregenerative components.

7.2 HARDWARE DEVELOPMENT ESTIMATES

Figure 7.2 presents the cost estimates for each component subsystem of the LCELSS conceptual design. These estimates were produced with a cost-estimating model that is based on the RCA

PRICE-H model. The Lockheed model is specifically tailored to life sciences and life support hardware cost estimation. The model input variables include mass, subsystem complexity and equipment category. The cost of each subsystem was estimated as if it were independently developed, and as a result, these estimates do not reflect potential cost savings which might accrue through concurrent implementation of large subsystems as groups of small, identical modules. Both development cost (first unit research, design, development and production costs) and unit cost (production costs of the second and all subsequent units) were estimated with the model.

Note that the Lockheed cost model does not include software development costs. Consequently, these cost estimates do not include the development of the overall LCELSS process control system nor do they include the costs of developing any subsystem process control software. Also, practical experience has shown that the Lockheed cost model tends to slightly underestimate both the amounts of systems engineering and integration effort required to produce the first unit. As a result, these estimates are internally consistent and can be directly compared with one another, but comparisons with cost estimates produced by other methods is inaccurate. It is recommended that more precise cost estimates be developed by a detailed "bottoms-up" cost estimating procedure in a future study.

By calculating the difference between the estimated development and unit costs presented in Figure 7.2, and dividing by a nominal aggregate labor rate, estimates of the manpower required to design and construct the first unit of each LCELSS subsystem were made (Fig. 7.3). This approach also assumed that each subsystem was developed as a new, stand alone unit. These labor estimates seem realistic for the most part. Both the cost and labor estimates for the 8- and 10-meter plant growth units appear to be too high, however. This difference seems to be attributable to the conceptual design's use of several modular components/subsystems for these units, which the estimating algorithm does not take into account.

Figure 7.2. Estimated Costs for LCELSS Subsystems.

Hardware Item	Estimated Development Cost ($M)	Estimated Unit Cost ($M)
SSF-Module Plant Growth Unit	$29-35	$ 7-13
8-m Plant Growth Unit (Hybrid)	35-43	9-16
10-m Plant Growth Unit (Inflatable)	68-85	18-35
Wet Oxidation Reactor - 4 Person	$0.8-1.5	$0.2-0.4
Wet Oxidation Reactor - 30 Person	2.5-3.5	0.7-1.2
Wet Oxidation Reactor - 100 Person	5.8-8.3	1.7-2.5
Atmosphere Regeneration - 4 Person	$1.5-2.7	$0.4-0.7
Atmosphere Regeneration - 30 Person	4-6	1.1-1.6
Atmosphere Regeneration - 100 Person	10-15	3.2-4.8
Water Recycling - 4 Person	$1.1-1.7	$0.2-0.4
Water Recycling - 30 Person	4.8-7	0.9-1.5
Water Recycling - 100 Person	11.6-18	2.6-4
Aquaculture Module - 4 Person	$1.3-1.8	$0.2-0.4
Trace Contaminant Control System - 4 Person	$3.2-5	$0.6-1

*NOTE: These cost estimates are for informational and comparison purposes only and do not in any way constitute a bid by Lockheed for the development of these items.

Figure 7.3. Estimated Manpower Requirements for LCELSS Subsystem Development.

Hardware Item	Estimated Manpower Required (Man-Years)
SSF-Module Plant Growth Unit	175
8-m Plant Growth Unit (Hybrid)	200
10-m Plant Growth Unit (Inflatable)	400
Wet Oxidation Reactor - 4 Person	5
Wet Oxidation Reactor - 30 Person	14
Wet Oxidation Reactor - 100 Person	33
Atmosphere Regeneration - 4 Person	9
Atmosphere Regeneration - 30 Person	23
Atmosphere Regeneration - 100 Person	54
Water Recycling - 4 Person	7
Water Recycling - 30 Person	31
Water Recycling - 100 Person	72
Aquaculture Module - 4 Person	9
Trace Contaminant Control System - 4 Person	21

SECTION 8
DATABASE DESCRIPTION

The LCELSS Database is partitioned into 5 primary databases which address different key CELSS aspects. Initial database software analysis suggested that the Macintosh computer was the most appropriate means of creating the LCELSS database because of its general ease of use, ease of creating complex diagrams and graphs, and availability of appropriate database management systems. Of the various Macintosh database management systems available when the database work began, FOXBASE+ was selected based on general database flexibility, high power combined with relative simplicity of use, and ease of database creation and report generation,. The FOXBASE form generation utilities greatly simplified formatting and layout of the various fields (including integration of drawings and graphs) into the report printouts. This approach has helped the various team members in creating and inputting the database figures and data, and greatly simplified the inevitable modifications to the data base structure and output format which arise as the databases evolve. FOXBASE also has the additional advantage of being upward-compatible with the DBase IV language, which is familiar to key database personnel.

The final layout of database reports is customized by individual report-generation format files. Although the database can be printed out in many different possible layouts, each of the 5 primary databases comprising the LCELSS database can be accessed in several standard FOXBASE displays. The "browse" access format is a convenient way of visualizing the database structure. The browse consists of a speadsheet-like data storage array in which the rows are records (individual data entities), and the columns are fields, where the structure of entries permitted in that particular column is uniform throughout all records. That is, once a particular character length, memo or picture definition, or particular numeric format for a particular column is set, new entries must comply with that format unless the database is restructured (generally a relatively simple operation).

Simple character fields are used where the maximum text entry lengths likely to be encountered are less than 254 characters. Where appropriate, shorter field are specified to help keep the database file sizes as small as possible. Memo fields are used for longer text passages, especially where multiple lines or paragraphs are typically required to express the data to be represented. Picture field are used to store complex drawings or other graphics. Numeric fields are typically used to store variables or parameters.

After the database structure was created, data for each field "cell" in the database was entered one at a time. Character, memo and number fields were entered directly into database using standard Macintosh click and enter methods. Block diagrams and graphs were created with separate drawing and spreadsheet programs and were transferred using the scrapbook for copy and paste importation.

The relationships of the 5 primary LCELSS database partitions are shown in Fig. 8.1. The primary database partitions include Lunar Environmental Data, Crew Material Flows, Atmosphere Composition, Technology Data, and General References. Each of these partitions generally includes a mixture of Character, Memo, Picture and Numeric fields. A sixth auxiliary partition defines the scoring levels used for the technology evaluation summaries contained in the Technology Data partition.

Figure 8.1. LCELSS Database Organization.

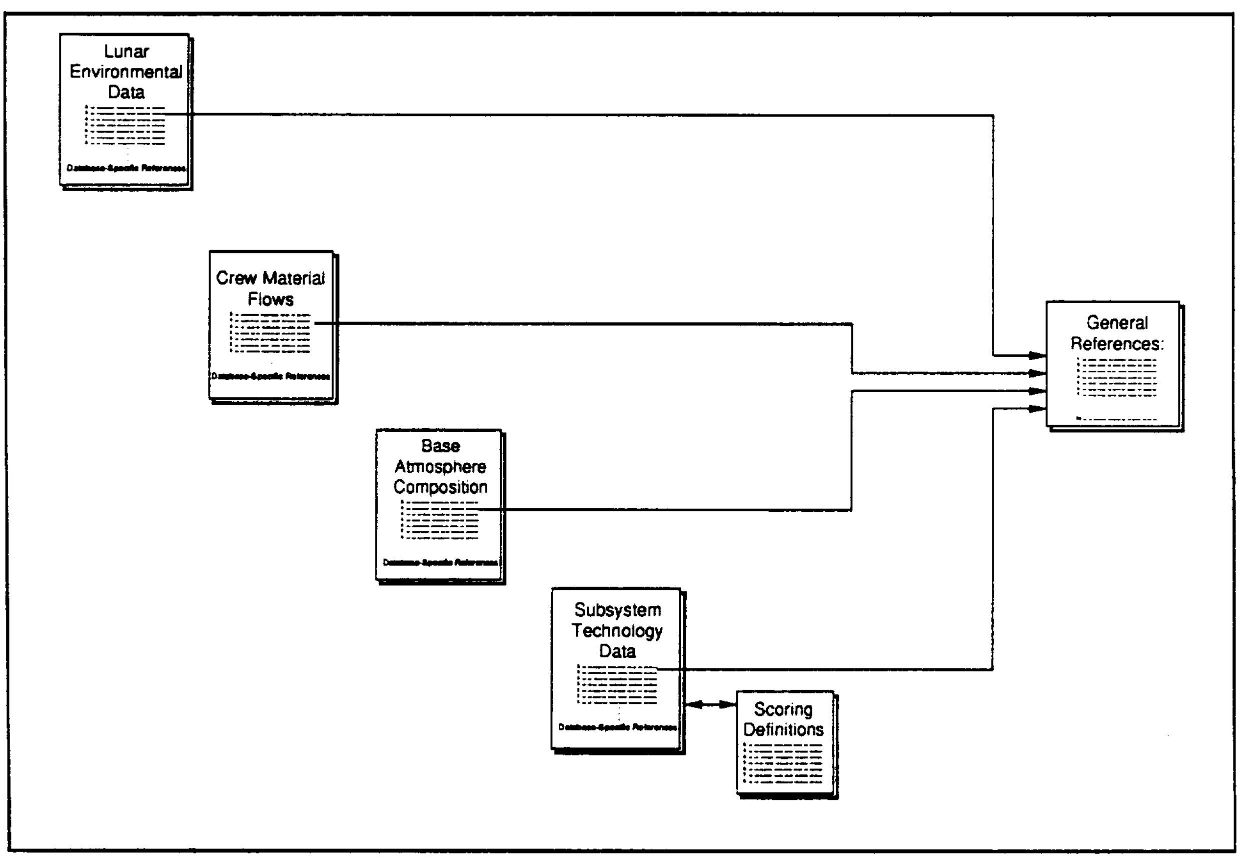


Figure 8.2 summarizes the structure and content of the primary database partitions by field names, field types and examples or a brief description of the field contents for the various database partitions. Of course, the final layout of the database report depends on the custom-programmed form specified in ordering the printout. Inclusion of particular fields, the size allocation and order of the fields on the layout depends on the form created for generating a particular report.

Lunar Environmental Data		
Field	Field Type	Examples of Entries
Data Parameter	28 Characters	"Temperature"
Condition or Data Type	45 Characters	"Lunar Surface"
Method Used	25 Characters	"Apollo-17"
First Parameter Label	4 Characters	"Min"
First Parameter Value	Number	9.2x10^1
Second Parameter Label	5 Characters	"Max"
Second Parameter Value	Number	3.84x10^2
Parameter Units	18 Characters	"°K"
Data Source	10 Characters	"Ref (1)"
Section or Author	30 Characters	"Langseth & Klen"

Crew Material Flows Database		
Field	Field Type	Examples of Entries
System Element	10 Characters	"Crew"
Flow Direction	10 Characters	"In"
Flow Material	10 Characters	"Water"
Form or Use	25 Characters	"Shower"
Weight from Ref. 1	Number	8
Weight from Ref. 2	Number	6
Weight from Ref. 3	Number	5
Weight Units	15 Characters	"lb/person-day"
Mass from Ref. 1	Number	3.629
Mass from Ref. 2	Number	2.9485
Mass from Ref. 3	Number	2.268
Mass Units	70 Characters	"kg/person-day"
Notes	Short Memo	(References and Assumptions)

Atmosphere Composition		
Field	Field Type	Examples of Entries
Subject/Data Source	75 Character	"Oxygen Pressure Effect"
Notes	Short Memo	(Description from Source Doc)
Plotted Results	Picture	(Pressure Effects Curves)
Source	254 Characters	(Reference Citation)

Technology Data		
Field	Field Type	Examples of Entries
LCELSS Subsystem	125 Characters	"Grey H2O Recycling"
Candidate Technology	125 Characters	"Reverse Osmosis"
Candidate Type	80 Characters	"Putnam Type"
Sort Code	Number	2
Block Diagram	Picture	(Complete Block Diagram)
General Description	Short Memo	(Description from References)
Subsystem Inputs	254 Characters	Waste Wash Water
Subsystem Outputs	254 Characters	Reclaimed Water
Scale Flow Rate	125 Characters	51.5 lb/day wash H2O
Fundamental Reaction	254 Characters	(Chemical Reaction Equations)
Significant Features	Short Memo	(Positive and Neg. Features)
Launch Mass	125 Characters	(Value, Units and Comments)
Launch Volume	125 Characters	(Value, Units and Comments)
Power Consumption	125 Characters	(Value, Units and Comments)
Heat Rejection	125 Characters	(Value, Units and Comments)
Design Maturity Score	125 Characters	(Score and Comments)
Self-Sufficiency	125 Characters	(Score and Comments)
Operational Autonomy	125 Characters	(Score and Comments)
Reliability Score	125 Characters	(Score and Comments)
Maintainability	125 Characters	(Score and Comments)
CELSS Compatibility	125 Characters	(Score and Comments)
Lunar Environ. Compat.	125 Characters	(Score and Comments)
Evolutionary Growth	125 Characters	(Score and Comments)
References	Short Memo	(Reference Citations)

REFERENCES		
Field	Field Type	Examples of Entries
Author/Doc Code	25 Characters	Averner [85]
Auth.1	25 Characters	Averner, M.
Auth.2	25 Characters	(Other author(s))
Auth.3	25 Characters	
Auth.4	25 Characters	
Auth.5	25 Characters	
Auth.6	25 Characters	
Editors	25 Characters	(Individual Editors or Orgn.)
Key Topics	100 Characters	(Bullet Key Topics)
Article/Individual Title	200 Characters	"Mathematical Modelling of ..."
Main Title	100 Characters	-
Document Number	60 Characters	"CR-166331"
Organization/Publisher	35 Characters	"NASA"
City	25 Characters	"Johnson Space Center"
Date	10 Characters	1981
Volume	10 Characters	-
Pages	10 Characters	-
Notes	Short Memo	(A brief summary of Ref.)

Figure 8.2. LCELSS Database Structure and Content by Field.

SECTION 9
LITERATURE CITED

Cathey, H.M., and L.E. Campbell. 1974. Lamps and lighting - a horticultural view. Lighting Design and Application, Nov. 1974.

Cheftel, J.C., J.-L.Cuq, and D. Lorient. 1985. Amino Acids, Peptides, and Proteins. In: Food Chemistry, O.R. Fennema, Ed. Marcel Dekker, Inc., New York, N.Y.

CRC Handbook of Chemistry and Physics: 60th Edition. 1980. R.C. Weast, Ed. CRC Press, Boca Raton, FL.

Epstein, E. 1972. Mineral Nutrition of Plants: Principles and Perspectives. John Wiley and Sons, New York, N.Y.

Fallon, A., R.F.G. Booth, and L.D. Bell. 1987. Carbohydrates. In: Laboratory Techniques in Biochemistry and Molecular Biology, Vol. 17. R.H. Burdon and P.H. van Knippenberg, Eds. Elsevier, Amsterdam.

Gitelson, I.I., B.G. Kovrov, G.M. Lisovskiy, Yu. N. Okladnikov, M.S. Rerberg, F. Ya. Sidko, and I.A. Terskov. 1976. Problems of Space Biology, Vol. 28: Experimental Ecological Systems Including Man. NASA Technical Translation TT F-16993. NASA, Washington, D.C.

Gitelson, I.I., I.A. Terskov, B.G. Kovrov, G.M. Lisovskiy, Yu. N. Okladnikov, F. Ya. Sidko, I.N. Trubachev, M.P. Shilenko, S.S. Alekseev, I.M. Pankova, and L.S. Tirranen. 1989. Long-term Experiments on Man's Stay in Biological Life Support Systems. In: Controlled Ecological Life Support Systems: Natural and Artificaial Ecosystems. NASA Conf. Publ. 10040, Proc. XXVII COSPAR Meeting, Espoo, Finland, July, 1989.

Grant, R.A. 1980. Utilisation of Waste Protein Sources. In: Applied Protein Chemistry, R.A. Grant, Ed. Applied Science Publishers, Ltd., London.

Gustan, E. and T. Vinopal. 1982. Controlled Ecological Life Support System: Transportation Analysis. NASA CR-166420. NASA, Ames Research Center.

Hightower, T. Mark. 1989. Physical/Chemical Closed-Loop Life Support Solid Waste Management. Presentation to the P/C CLLS IWG Meeting, October 24, 1989. NASA, Ames Research Center.

Hoff, J.E., J.M. Howe, and C.A. Mitchell. 1982. Nutritional and Cultural Aspects of Plant Species Selection for a Controlled Ecological Life Support System. NASA CR-166324. NASA, Ames Research Center.

Karel, M. 1982. Evaluation of Engineering Foods For Controlled Ecological Life Support Systems (CELSS). NASA CR-166359. NASA, Ames Research Center.

Kates, M. 1986. Lipid Extraction Procedures. In: Laboratory Techniques in Biochemstry and Molecular Biology, Vol. 3(2). R.H. Burdon and P.H. van Knippenberg, Eds. Elsevier, Amsterdam.

Matthern, R.O., and R.B. Koch. 1968. The Continuous Culture of Algae Under High Light Intensity. Am. Biol. Teach.

NAS-NRC. 1980. 1980 Recommended Daily Allowances. Ninth Edition NAS-NRC publication # 2941.

National Aeronautics and Space Administration, Ames Research Center. 1989. Pathfinder Project Plan - Physical/Chemical Closed Loop Life Support. January, 1989.

Oleson, M.W., T.J. Slavin, and R.L. Olson. 1987. Lighting Considerations in a Controlled Environmental Life Support System. Proc. 17th Intersoc. Conf. Environ. Syst., Seattle, WA. Paper 871435, July, 1987.

Phillips, J. M., A. D. Harlan, K.C. Krumhar, M.S. Caldwell, C.M. Crowlie, L. Ramsbacher, and B.S. Meyer. 1978. Studies of Potential Biological Components of Closed Life Support Systems for Large Space Habitats: Research and Technology Development Requirements, Costs, Priorities and Terrestrial Impacts. Final Report, Grant NSG2309. NASA-Ames Research Center.

Phinney, W.C., D. Criswell, E. Drexler, and J. Garmirian. 1977. "Lunar Resources and Their Utilization", in Space-Based Manufacturing from Nonterrestrial Materials, G. O'Neill; Ed.

Pirie, N.W. 1980. Leaf Protein Production and Use. In: Applied Protein Chemistry, R.A. Grant, Ed. Applied Science Publishers, Ltd., London.

Ride, S.K. 1987. Leadership and America's Future in Space. Report Submitted to the NASA Administrator, August, 1987.

Todd, Nancy Jack. 1980. The Journal of the New Alchemists. Vol. 6. The New Alchemcy Institute. Stephen Greene Press. Brattleboro, VT.

USDA-ARS. 1975. The Composition of Foods (Revised 1975). USDA Agricultural Research Service.

Volk, T. and H.S. Cullingford. 1988. Crop Growth and Associated Life Support for a Lunar Farm. Proc. Lunar Bases and Space Activities of the 21st Century, Houston, TX, April 5-7, 1988.

Whistler, R.L. and J.R. Daniel. 1985. Carbohydrates. In: Food Chemistry, O.R. Fennema, Ed. Marcel Dekker, Inc., New York, N.Y.

APPENDIX A

LUNAR CHARACTERISTICS: RESOURCES AND BASE SITES

LUNAR CHARACTERISTICS: RESOURCES AND BASE SITES

Table of Contents:

1. Lunar Parameters

1.1 Lunar Characteristics

Mass	7.359×10^{22} kg
equivalent to	$0.0123\ m_{earth}$
Mean Density	3.34 g/cm^3
Diameter	3,476 km
Radius	1,738 km
Equatorial Surface Gravity	1.62 m/s^2
Equatorial Escape Velocity	2.38 km/s

1.2. Lunar Orbital Characteristics

Mean Value of Semi-Major Axis	384,400 km
Perigee	364,400 km
Apogee	406,730 km
Ellipticity	0.002
Inclination of Axis to Ecliptic	1°32'
Incl. of Lunar Equator to Lunar Orbital Plane	6°41'
Inclination of Orbital Plane to Ecliptic	5°9'
Sidereal Month (time for one orbit and revolution, back to the same position relative to the stars)	27.32 Days
Synodic Month (lunar day; time between same alignment of Sun, Earth, and Moon)	29.53 Days

Moon's orbital and rotational period coincide, therefore always the same side of the Moon is facing the Earth.

See Figures 1.2.a., b.,and c.

COMPARATIVE QUANTITIES FOR EARTH AND MOON

	Equatorial diameter (km)	Surface area (Earth = 1)	Volume (Earth = 1)	Density (kg/m^3)	Surface gravity (Earth = 1)	Escape velocity (km/s)
Earth	12,756	1.000	1.000	5.52×10^3	1.000	11.2
Moon	3,476	0.075	0.020	3.34×10^3	0.165	2.4

Table 1.1. [232]

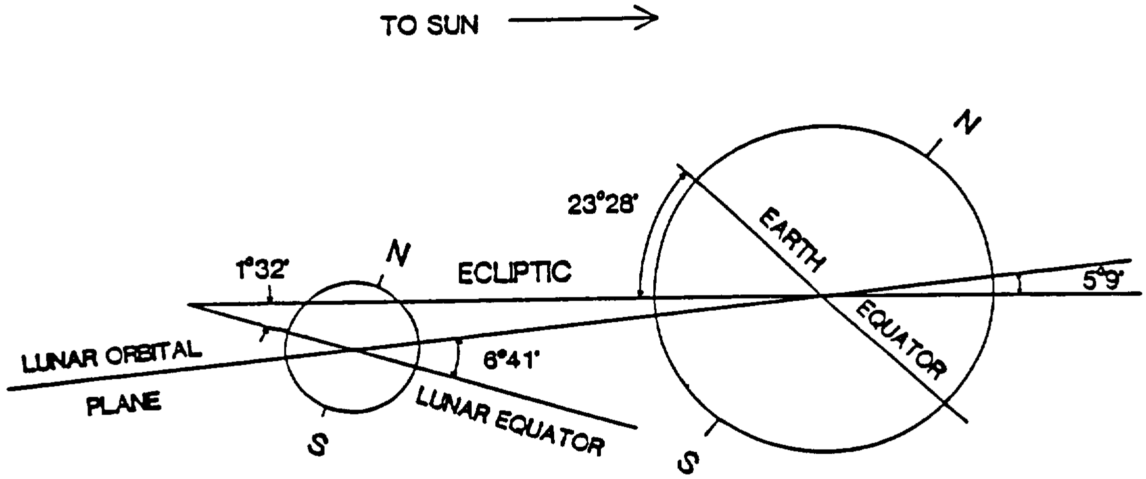


Figure 1.2a. Schematic drawing showing relative orientation of Earth, Moon, and ecliptic. [233]

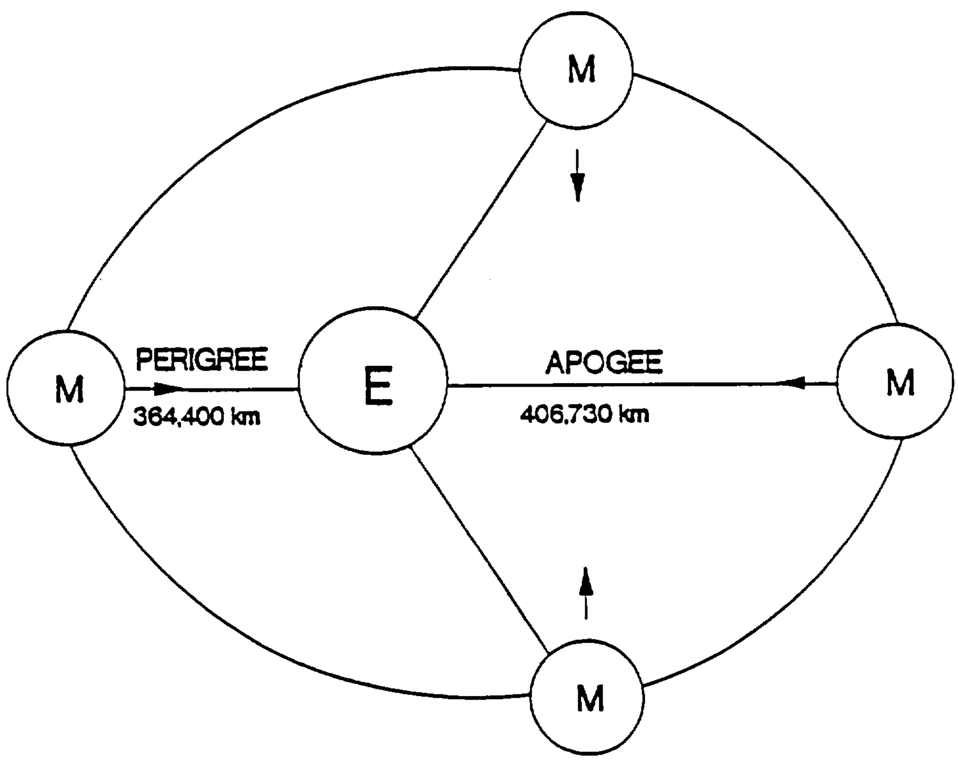


Figure 1.2b. A representation of the Moon's elliptical orbit around the Earth. The Moon (M) rotates so that the same side always faces the Earth (E). The center of the nearside disc is marked with an arrow showing that in parts of the orbit the nearside does not point directly at Earth (deviation 6¾°) allowing an observer on Earth to see parts of the limb region not seen at apogee and perigee. There is also a similar effect in longitude owing to differences in the orbital planes of Earth and Moon; this is known as optical libration and allows us to see, at different times from Earth, 59 % of the Moon's total area. [232]

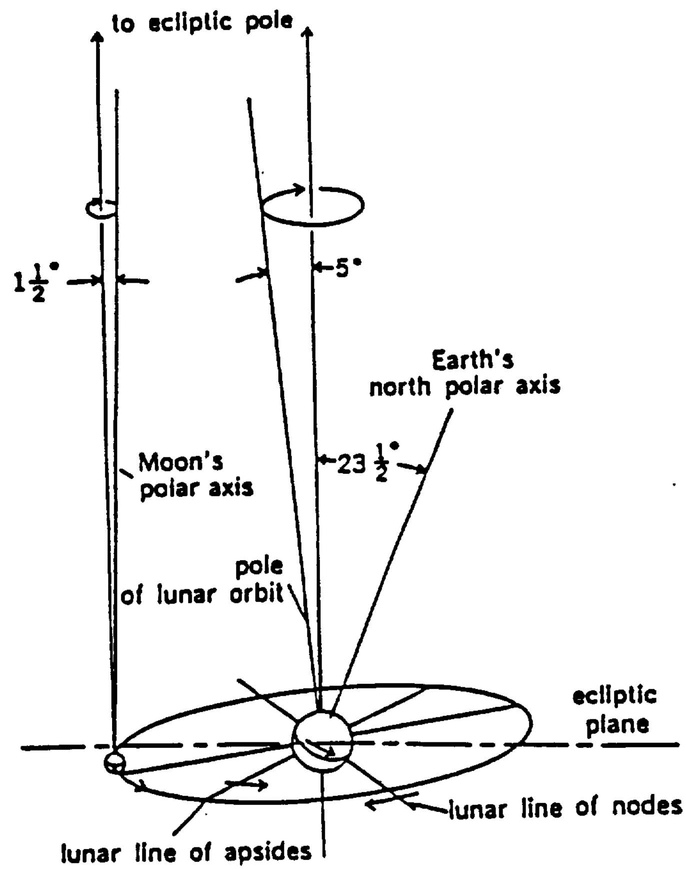


Figure 1.2c. An illustration of the motions of Earth and moon with reference to the pole of the ecliptic. While Earth's polar axis is inclined $23\frac{1}{2}$ degrees and precesses with a period of about 25,000 years, giving us seasons and the progression of signs of the Zodiac, the Moon's polar axis is inclined only $1\frac{1}{2}$ degrees. Thus, despite the five-degree inclination of the lunar orbit plane and the eighteen-year precession of the lunar polar axis and orbit plane (as discovered in the 18th century by Cassini), sunlight is always nearly horizontal at the lunar poles. [314]

IMPACT OF ORBITAL PARAMETERS

- Affect availability and direction of sunlight (see 2.1.1).
- Influence temperature at lunar base (see 2.3).
- Low gravity of Moon affects systems layout and processes (see 4.1).
- Important for communication link to Earth:
  - On Earth facing side, constant direct link possible.
  - On back side, no communication possible without a relay system (in orbit or on the surface).
  - At the pole, relay system needed for at least half the time.
- Need to be considered for transportation to and from base.

2. Environment of the lunar surface

2.1 Radiation Environment

- Visible sunlight
- UV light
- Ionizing radiation

2.1.1 Radiation Input

- Total solar radiation (0.2 to 3.0 μm) input is around 1390 W/m^2 on the lunar surface.

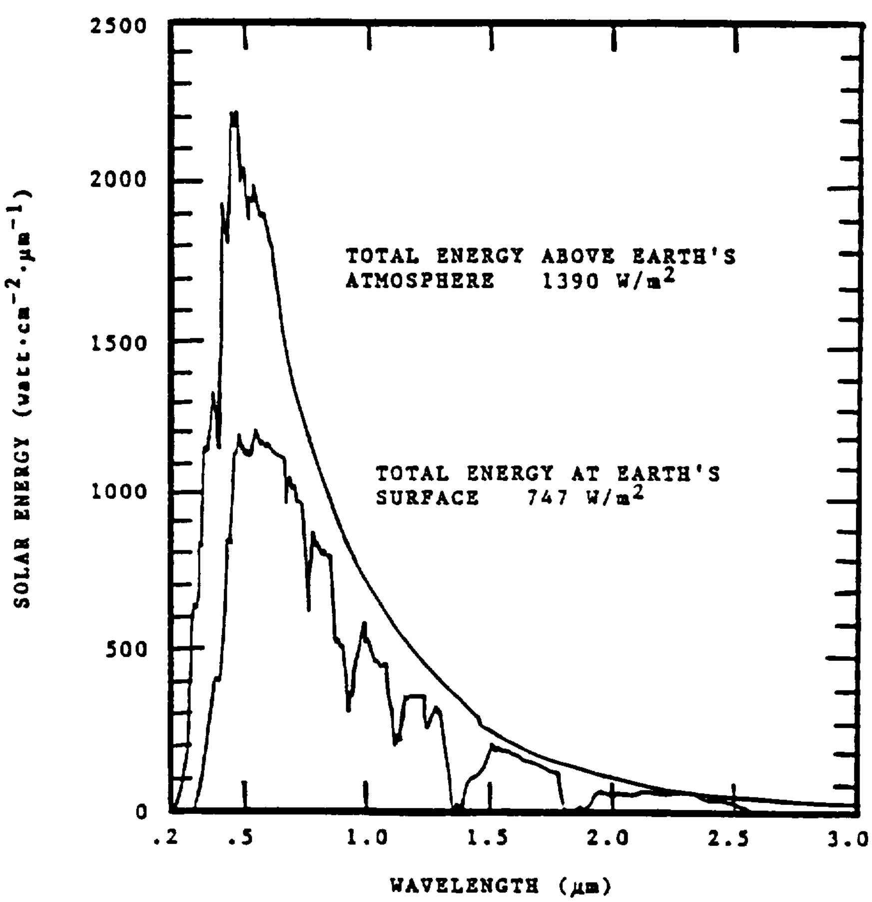


Figure 2.1.1.a. Solar radiation spectrum in space and at Earth's surface. *Courtesy of NASA*. [175]

Availability of Sunlight:

For polar site:

- On poles, due to orbital parameters, Sun elevation is only +/- 1°32'.
- 1/2 year day, 1/2 year night cycle.
- Some craters are permanently shaded (estimated: 2% of the lunar surface).
- Multiple collectors would have to be stacked vertically in order not to shade each other.
- Light collectors would have to be rotated 360°/28d = 0.5°/h around a vertical axis.

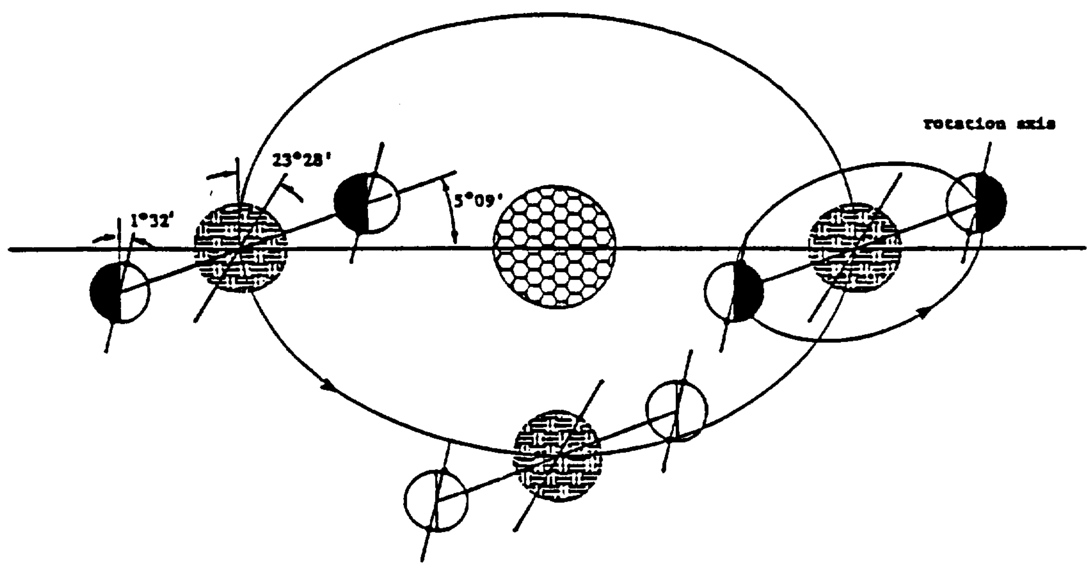


Figure 2.1.1.b.

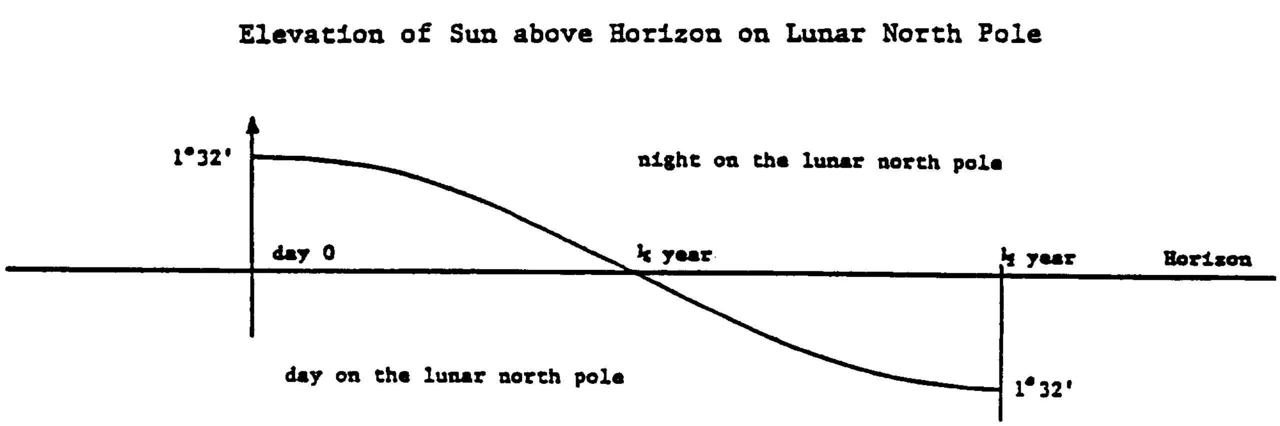


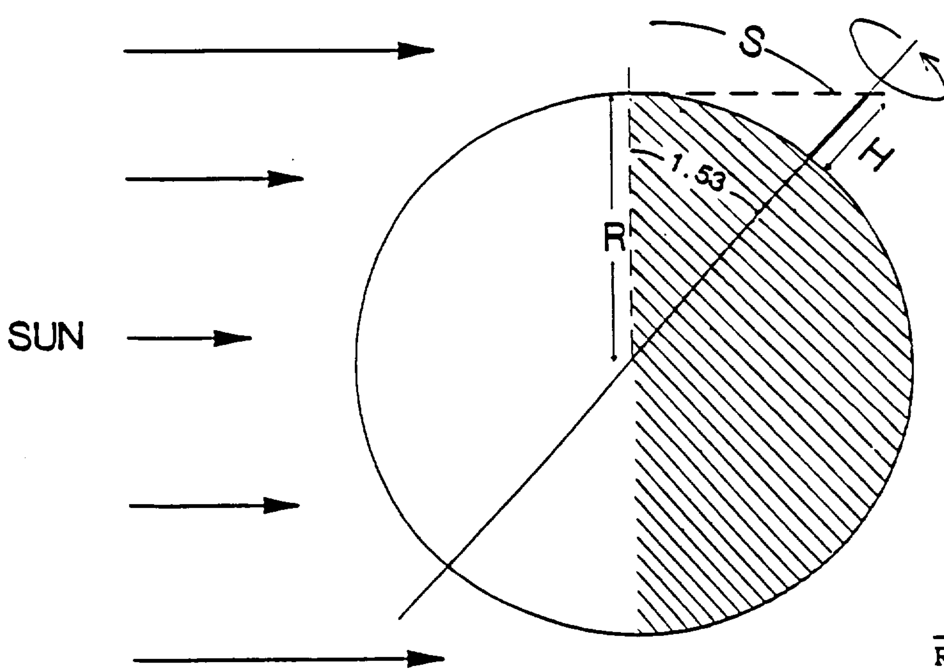
Figure 2.1.1.c.

Lighting considerations for a polar site:

- Assuming no shading from other mountains and a spherical shape of the Moon, a collector tower would have to have a minimum height of H > 623 meter (or stand on an equivalently high mountain) in order to provide a constant supply of solar power (see sketch).
- Assuming collectors reflecting sunlight into a receiver at the pole, probably three to four collectors would be needed distributed around the pole in order to provide continuous energy supply. The collectors would have to be at a distance of approximately 60 km, and the minimum height of each collector and the receiver would be H > 120 meter (estimates)
- Permanent presence of terminator may cause twilight haze (due to small particles moving in electrostatic suspension close to the terminator) and this may influence astronomical experiments.
- Most of the area shaded/dark, which might have psychological impact.
- Communication link to Earth requires relays, either in orbit or on the surface (as with solar collector, see 1.).
- Thermal environment is more constant than on equator (see 2.3).
- Permanently shaded areas at polar regions may allow for trapped water and volatiles (see 2.2).
- Polar regions more likely similar to highland material (materials of industrial value such as Ilmenite may not be as abundant as at the equator (see 3.3).

Equator:

- On equator, 14 day night / 14 day light cycle.
  (same for all latitudes except very close to the poles)
- Multiple collectors may be added on a North-South axis without shading each other.
- Collectors would have to be rotated 180°/14 days around a horizontal (North-South) axis.



$$\frac{R}{R+H} = (\cos 1.53^\circ)$$

-> H >= 623m

2.1.2 Ultraviolet Radiation

UV Input

- UV-wavelengths from 0.01 to 0.4 x 10^{-6} m
- Total radiation input is about twice as that on Earth surface, same as for LEO. (see figure in 2.1.1)

IMPACT OF UV

- Some materials (especially plastics) are destroyed by UV radiation.
- Plants are sensitive to UV radiation and may require shielding.

2.1.3 Ionizing Radiation

2.1.3.1. Sources of ionizing radiation

THE LUNAR SURFACE

"SUNBURN" EFFECTS IN LUNAR ROCKS AND SOIL

Source And Energy of Particles	Nature of Particles	Effect Produced by Particles	Maximum Depth of Effect
Solar Wind low energy (about 1,000 ev*)	Light atoms (hydrogen and helium) dominant, rarer heavier atoms (carbon, nitrogen, oxygen, etc.)	Atoms trapped in amorphous surface layer of lunar dust grains; chemical reactions	Less than 0.001mm*
		Very small particle tracks	Less than 0.001mm*
Solar flares *high energy* (1-100 million ev*)	Light atoms (hydrogen and helium) dominant rarer heavy atoms (e.g., calcium, iron)	Nuclear reactions**	About 6 cm*
		Particle tracks**	About 3mm*
Galactic cosmic rays very high energy (1-10 billion ev*)	Light atoms (hydrogen and helium)	Nuclear reactions**	1-2 meters
	Heavy atoms (e.g. calcium, iron)	Particle tracks**	About 10 cm*

* ev = electron volts; mm = millimeter (about 1/25 inch); cm = centimeter (10 mm).
** indicates effects most commonly used for measuring exposure ages in lunar samples.

Table 2.1.2. [32] page 191.

2.1.3.1. Sources of ionizing radiation (cont.)

- Solar wind
  - Emitted constantly.
  - Typically 99% H, 1% He ions, energies in keV range.
  - Output varies with 11 year solar cycle.
  - Normal output 40-50 rem/year.
- Solar flares
  - Relative short peaks of solar activity.
  - Typically 90% H, 9% He,1% larger atomic ions.
  - Much higher energies (MeV-GeV range) and fluxes.
  - Occur several times a year, output of 100 rem/event average.
  - During solar maxima, extremely large events with up to 5000 rem output may occur (infrequently and irregularly).
- Cosmic radiation
  - Lower flux, but higher energy than solar radiation.
  - About 85% H, 13% He, 2% heavier atoms.
  - Energies in range of 1-10^{10}GeV
  - 20-40 rem/year in open space, at lunar base only half as much due to shielding from Moon
  - Varies with solar cycle. At maximum, cosmic radiation is a minimum of 20 rem/year.

APPROXIMATE DOSE RATES ON LUNAR SURFACE

(SOLAR MINIMUM)

Normal Solar	50 rem/yr	
Cosmic radiation	20 rem/yr	
Solar Flares	300 rem/yr	100 rem/event
AL Flares		5000 rem/event
APOLLO Surface dose	TBD	

Figure 2.1.3.1.

2.1.3.2 Radiosensitivity

RADIOSENSITIVITY OF MAN AND LIVING COMPONENTS OF A LCELSS

(ACUTE RADIATION EXPOSURES)

Organism	Observable Effects	Death LD100
Man	25 REM	450 REM
Onion (1)	377 REM	1491 REM
Wheat (1)	1017 REM	4022 REM
Corn (1)	1061 REM	4197 REM
Potato (1)	3187 REM	12,608 REM
Rice (1)	4974 REM	19,677 REM
Kidney Bean (1)	9137 REM	36,149 REM
Algae	TBD	TBD
Bacteria	TBD	TBD

1) Reference: Casarett, Alison P., Radiation Biology, 1968, Prentice Hall.

Figure 2.1.3.2.a.

Further explanations:

- Table is for acute exposures, such as during a solar flare.
- Observable changes means changes in the blood (humans) or slight (10-15%) reduction in plant growth.
- Current chronic exposure (extended time period) limit for U.S. radiation workers is 5 rem/year.
- Current projected radiation limits for astronauts are 50 rem/year and 400 rem lifetime exposure.

IMPACT FOR LUNAR BASE

- Shielding required for men for most of the time.
- Plants do not need as much shielding, can possibly be grown under unfiltered sunlight (may need UV protection)

2.1.3.3 Shielding

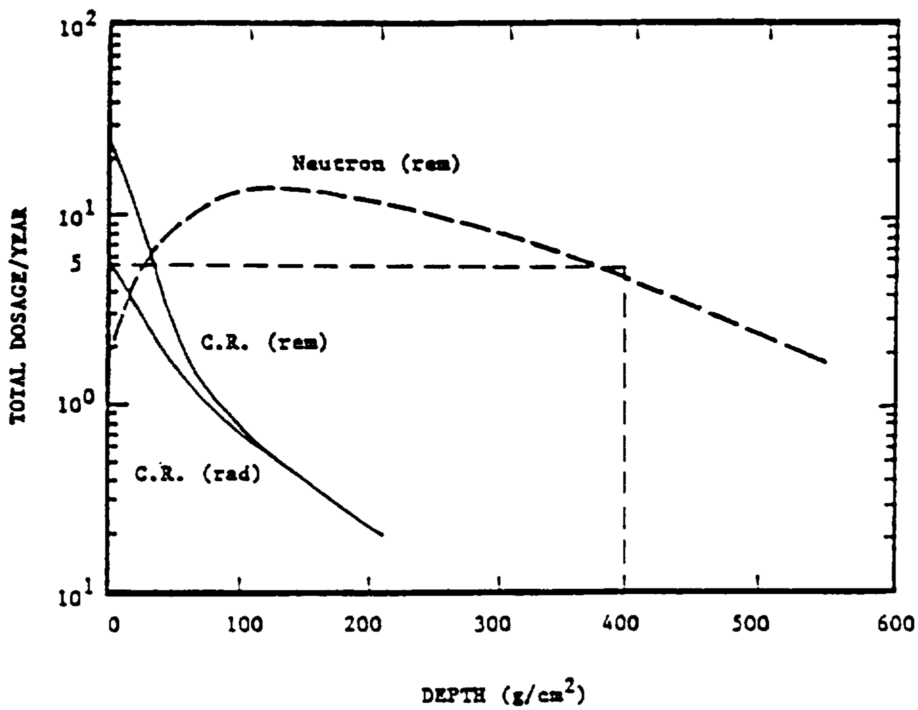


Figure 2.1.3.3. A comparison of the annual dose equivalent due to secondary neutrons and cosmic-ray nuclei, as a function of shielding. Also, the absorbed dose rate due to cosmic-ray nuclei is shown.[241]

Other considerations

- Lunar regolith is not the ideal shielding material, but it is abundant and freely available.
- Optimization of regolith shield with Earth manufactured materials possible.
- Water tanks in regolith shield may act as neutron shield.
- Shielding should be provided based on a 5 rem/year limit.
- Protection is especially important for radiation sensitive fetuses.

IMPACT ON LUNAR BASE

- Permanent residents on the Moon can spend only 20% of their time (or 40% of the two-week daylight time) without significant shielding.
- Most of the time should be spent in shelters of >400 g/cm^2, or about two meters of densely packed lunar soil (for cosmic ray protection).
- This can be realized either below the surface or at the surface beneath a shielding mound.
- For extremely large solar flares, required shield thickness is not clear. Two estimates are:
    1) >700 g/cm^2 (based on ref. 241)
    2) 150 g/cm^2 (based on ref. 315)

2.2 Temperature on the lunar surface

2.2.1. At poles:

- Basically unknown. but guesses are it might be as low as 40 K in some permanently shaded areas (inside craters, < 2% of lunar surface)
- Occurrence of cold trapped volatiles possible (see 2.2.)

2.2.2. At high latitudes:

- NASA recommends the following approximation for the latitude ß:

$$T = T_{equator} * \cos^{1/4} (\beta)$$

- $T_{equator}$ from next section (2.2.3.) (Ref. 240)

2.2.3. At the equator:

- Changes between 80 K and 390 K during one lunar day (see Figure 2.2.3.a.)
- Temperature change depends on thermal inertia parameter gamma (determines rate of cooling or heating of material).
- Subsurface temperatures change much less due to low thermal conductivity of lunar soil (conductivity in the range of styrofoam; for temperature changes see Figure 2.2.3.a.)
- Below one meter depth temperature can be assumed constant over time at approximately 230K.

IMPACT ON LUNAR BASE

- Extreme temperature loads for any exposed materials on the surface.
- Difficult to radiate heat into space during daytime at equator.
- More details together with thermal properties of the lunar soil, see 3.2.

2.2 Temperature on the lunar surface

2.2.3. At the equator, (cont.):

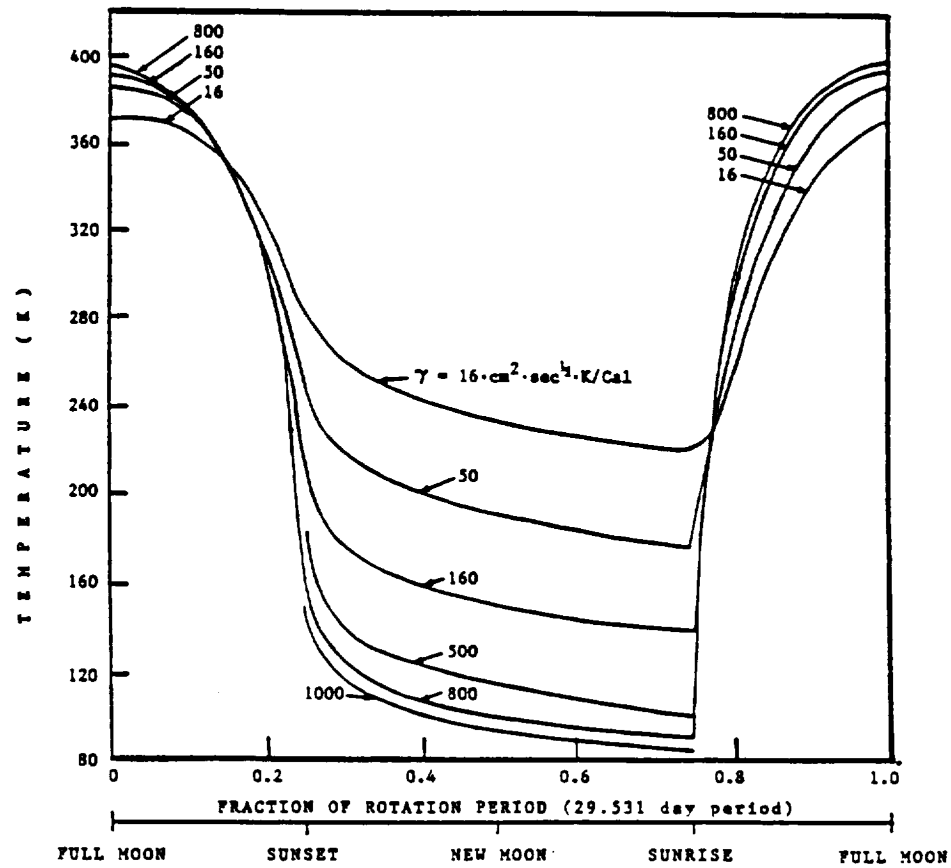


Figure 2.2.3.a. Temperatures nearest surface for different thermal parameter values. [240]

2.3 Lunar Atmosphere

- Practically non-existent
- Less than 10^{-13} atmospheres
- Low gravity cannot retain light atoms such as hydrogen or oxygen.
- Light atoms found come from constant resupply from solar wind and out of the lunar interior.
- Solar wind supplies H, He, Ne and most of Ar (32).
- Rest of Ar apparently supplied out of lunar interior.
- During hot daytime, CH_4, CO, and H_2S have been discovered in minor amounts in the top layers of the soil.
- Cold trappings of lead, mercury, bromide, antimony and others have been found in permanently shaded areas (32).
- Cold trappings of volatiles might be possible at the poles (10).

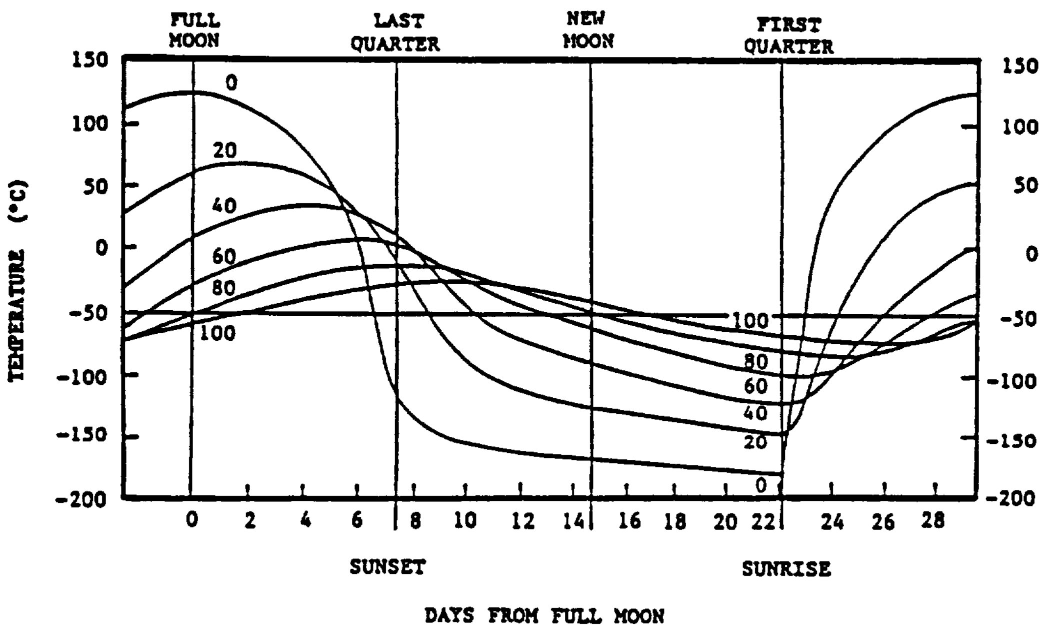


Figure 2.2.3.b. Variations in surface and near-surface temperatures at different times during the lunar day and night. Individual curves represent depths below the surface marked in centimeters. (*From Bowell, 1971*). [232]

IMPACT OF LUNAR ATMOSPHERE (OR LACK THEREOF)

- Operational and other considerations are similar to those of a location in outer space, i.e.:
    - Exposed materials need to be stable (non-outgassing).
    - Loss of cabin atmosphere due to leakage and airlock operation.
    - Cooling only by radiating into space or by heating of lunar soil (see sec. 3.2.)
    - Outer space background temperature 4 K
    - Radiators need shading from Sun

2.4. Meteorite environment

- NASA gives the following average annual cumulative meteoroid model for the lunar environment as follows (ref. 240):

For $10^{-6} < m < 10^{0}$,

$$\log N_t = -14.597 - 1.213 \log m$$

For $10^{-12} < m < 10^{-6}$,

$$\log N_t = -14.566 - 1.584 \log m - 0.063 (\log m)^2,$$

with N_t = number of particles/($m^2 \cdot s$) of mass m or greater
m = mass in grams.

- A lunar base would only receive half of this flux, because of the shielding by the Moon.
- During periods of meteorite streams (esp. during summer months), these values might be higher by a factor of two or so.

IMPACT ON LUNAR BASE

- the radiation shield of 400 g/cm^2 (as required according to section 2.1.3.) will be enough for all but the most severe impacts.
- dual shielding might be considered for sensitive equipment which stays on the lunar surface permanently.
- when leaving the station, stay out of their way!

2.5 Magnetic field

- Moon's actual magnetic field is negligible.
- Moon's orbital movement induces changes in terrestrial and solar magnetic field in lunar vicinity.

3. Physical Properties of Lunar Surface

3.1 Physical properties of lunar soil

PHYSICAL PROPERTIES OF LUNAR SOIL

Parameter	Value
Composition (Atomic Percent)	
Oxygen	60
Silicon	20
Aluminum	7
Iron Content (Percent)	
Mare Terrain	5
Upland Terrain	2
Grain Size (μm)	2 to 60
Cohesion (N/cm^2)	0.02 to 0.2
Nominal	0.05
Internal Friction Angle (deg)	31 to 39
Effective Friction Coefficient (Nondimensional)	
Metal to Soil or Rock	0.4 to 0.8
Adhesive Strength (N/cm^2)	0.0025 to 0.01
Permeability (cm^2)	$1x10^{-8}$ to $7x10^{-8}$
Seismic Velocities (m/s)	
Compressional Wave	30 to 90
Shear Wave	15 to 35
Bulk Density (g/cm^3)	
at 5 cm	1.6
at 40 cm	2.0
Porosity (Nondimensional) at 5 cm depth	0.465

Figure 3.1 [240]

IMPACT FOR LUNAR BASE:

- Important parameters for using the soil as a support for a lunar base, for driving and walking on plains and slopes and for digging or stacking of soil.
- Mechanical devices need proper design for "dusty" environment (rotating parts, bearings.)
- Fine particles may take a long time to settle after being thrown up (e.g. by landing rocket or by bulldozer).
- Lunar dust might get into station.

3.2 Thermal properties of lunar soil

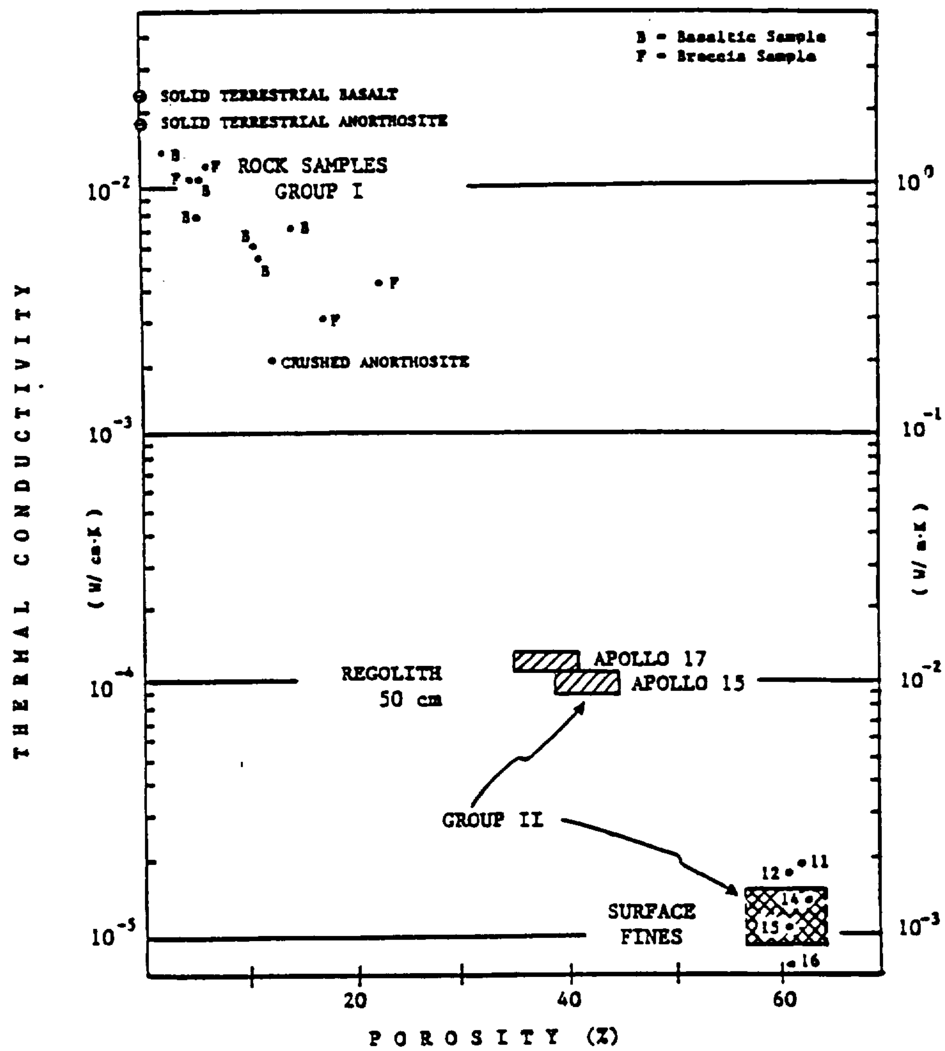


Figure 3.2.a. Published conductivity values of lunar materials vs. porosity. For laboratory measurements, values at 300 K are shown as points in the plot. The doubly hatched box is the range of *in situ* values determined from nighttime cooldown data (*Keihm and Langseth*, 1973) and the singly hatched boxes are the results reported in this paper. Rock data are summarized in *Horai and Winker* (1976) and soil data in *Cremers and Hsai* (1974). [242]

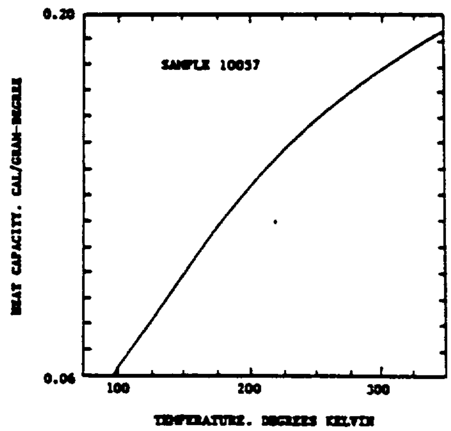


Figure 3.2.b. Specific heat of Apollo 11 sample 10057. The full line is the least-squares fit to the data. solid rock (vesicular basalt). [243]

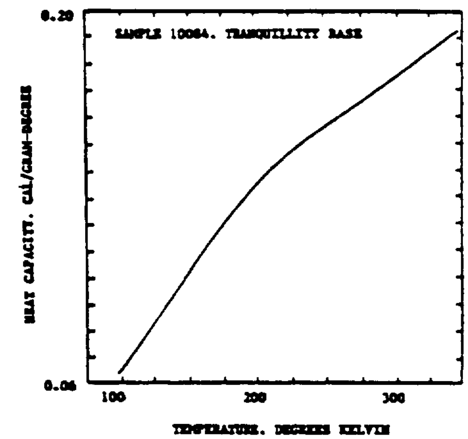


Figure 3.2.c. Specific heat of Apollo 11 sample 10084. The full line is the least-squares fit to the data. porous lunar soil. [243]

THERMAL CONSTANT, y, FOR APOLLO 11 SAMPLES 10057 AND 10084

Temp.(K)	y ($cm^2 sec^{1/2} K\ cal^{-1}$)	
	10057	10084
100	34.33*	1543**
150	27.12	1231
200	23.40	1078
250	21.51	1000
300	20.29	941
350	19.41	898

* Using $k = 0.004$ cal $cm^{-1} deg^{-1} sec^{-1}$ and $p = 3.4\ g\ cm^{-3}$.
** Using $k = 0.000004$ cal $cm^{-1} deg^{-1} sec^{-1}$ and $p = 1.6\ g\ cm^{-3}$.

Figure 3.2.d. [243]

LUNAR SURFACE THERMAL PROPERTIES

Surface Material	Parameter, y $cm^1\, s^{1/2}$ K/joule ($cm^2\, s^{1/2}$ K/cal)	Density, p kg/m^3 (g/cm^3)	Specific Heat, c joule/(kg K) (cal/g K)	Conductivity, k W/(m K) (cal/cm s K)
Total Range	5.97 to 334 (25 to 1400)	500 to 3000 (0.5 to 3)	755 to 1007 (0.18 to 0.24)	2.14×10^{-3} to 1.13 (5.1×10^{-6} to 2.7×10^{-3})
Range for Particulate Material Heavily Mixed with Blocks	57.2 to 119 (240 to 500)	1200 to 2000 (1.2 to 2.0)	837 (0.20)	7.12×10^{-3} to 1.8×10^{-2} (1.7×10^{-5} to 4.3×10^{-5})
Blocks (Rocks)	7.2 (30)	2500 (2.5)	837 (0.20)	9.22×10^{-1} (2.2×10^{-3})
Range, Excluding Blocks	95.5 to 238 (400 to 1000)	500 to 1100 (0.5 to 1.1)	837 (0.20)	4.18×10^{-3} to 1.17×10^{-2} (1×10^{-5} to 2.8×10^{-5})
Average Maria	95.5 to 191 (400 to 800)	800 to 1500 (0.8 to 1.5)	837 (0.20)	4.18×10^{-3} to 8.8×10^{-2} (1×10^{-5} to 2.1×10^{-5})

Figure 3.2.e. [240]

3.2 Thermal properties of lunar soil

see Figures 3.2.a. through e.

IMPACT ON LUNAR BASE:

- Thermal inertia parameter (gamma) determines rate of cooling of the soil.
  - Rocks cool down faster, heat up faster than regolith.
- Thermal conductivity of soil is very low (comparable to styrofoam), but dependent on porosity; the value for compacted or processed soil likely to be different (but still low).
- Low thermal conductivity of lunar soil results in:
  - Difficult to use soil as a heat sink.
  - Good thermal insulator; lunar soil on top of base will provide constant temperature environment.
  - Soil on top will also be good for shielding against radiation and meteorites.
- The specific heat of soil is comparable to that of bricks, and about one fifth of water.
  - In order to dump 10 kW of waste heat by heating lunar soil (e.g. provided with a conveyor belt from a mining operation) and depositing it at a certain distance (to let it cool down there), a mass flow of 450 kg/h with a temperature rise of 100 K would be necessary.
  - This might be feasible, especially if the soil is being mined for lunar resources processing.
  - For safety considerations, only useable as secondary system.
  - Only other heat sink available is radiation into outer space (see sec. 2.3.)

3.3 Geological features

- Classification
- Composition
- Location

3.3.1. Classification

Maria/Mare: dark, level plains (floors of basins); in general on near side, not on far side; in general extrusion of basaltic lava; 3000-3700 million years old; few kilometers thick; covers approximately 1/5th of lunar surface

Terra/Terrae (Highlands): lighter; older than mare, around 4600 million years; densely cratered; tens of kilometers thick crust; higher in aluminum; breccia is dominant near surface bedrock; makes up all the far side and around 50% of near side (about 4/5th total of surface)

Circular basins: resulting from large meteor impacts.

Caley-plains: light, smooth planes within highlands; light and dark breccia; estimated to be 200-300 m deep;

3.3.2. Composition:

3.3.2.1. General features:

- Well graded sandy silts.
- Average (by weight) particle size: 0.040 - 0.130 mm.
- Density (from large diameter tube samples): 1.4 - 1.9 g/ccm.
- Particle shapes: spheres, angular shards, vesicular grains (fragile, reentrant).
- Particle compositions include: igneous or breccia lithic grains, mineral grains, glass fragments, unique lunar agglutinates.

3.3.2.2. Maria-material:

1. Pyroxene XYZ_2O_6 with X = Ca, Y = Mg,Fe,Ti,Al,Mn,Cr; Z = Si,Al;
2. Plagioclase feldspar - a calcium aluminosilicate.
3. Ilmenite $FeTiO_3$.
4. Olivine ($(K = Mg,Fe)_2SiO_4$) - an iron/magnesium orthosilicate solid solution.

Soils:
- Mainly crushed basalt similar to terrestrial basalt but more chemically reduced.
- Contains metallic iron (0.1%) in form of alloys with cobalt and nickel, many fragments trapped in glassy shards (agglutinates).
- Most soils contain significant quantities of highland rocks.
- Border regions between mare and highland areas contain mixture of mare/highland characteristic components.
- Major components (average): 41% O_2, 19% Si, 13% Fe, 6% Mg, < 6% Ti and others.

Fragments and rocks:
- Range in size from clay particles to boulders.
- Rich in plagioclase feldspar, pyroxene.
- Minor component: ilmenite.
- Some rocks are nearly monomineralic: anorthosite (nearly pure plagioclase feldspar) and dunite (nearly pure olivine) .
- Basalts are richer in titanium than soils derived from them.

3.3.2.3. Highland Material:

Soils:
- Developed on anorthositic bedrock.
- Similar to mare regions except: lower abundances of iron and magnesium.
- Rich in aluminum - 14%.
- Rich in calcium - 11% .
- Apollo 16 station 11 site: rich in anorthosite.

Fragments and Rocks:
- Dunite fragments rare at Apollo sites.
- Anorthosite fragments (abundant at Apollo sites) found as isolated pieces in soil and as large clasts in breccia boulders.
- Breccia (composed of broken fragments of prior rocks compressed together to form mixed rocks) are most common rock.
- Clasts in breccia include: troctolite (olivine-plagioclase) and norite (pyroxene-plagioclase).
- Central peaks and large craters - principally olivine.
- Other craters - principally plagioclase.

3.3.3. Location

The locations of landing sites/sample origin are shown on Figures 3.2.3.a. and b.

IMPACT ON LUNAR BASE

- Availability of certain resources at the base location will determine the possibilities of using and processing them.
- If lunar resources processing is planned, this will be a major driver for the site selection of the base.
- For possibly utilizable resources, see sec. 4.2..
- For processing options of these resources, see sec. 4.3. and 4.4..

3.3 Geological features

3.3.3. Location

The few landing sites with investigated soil composition are shown in Figure 3.3.3.a.

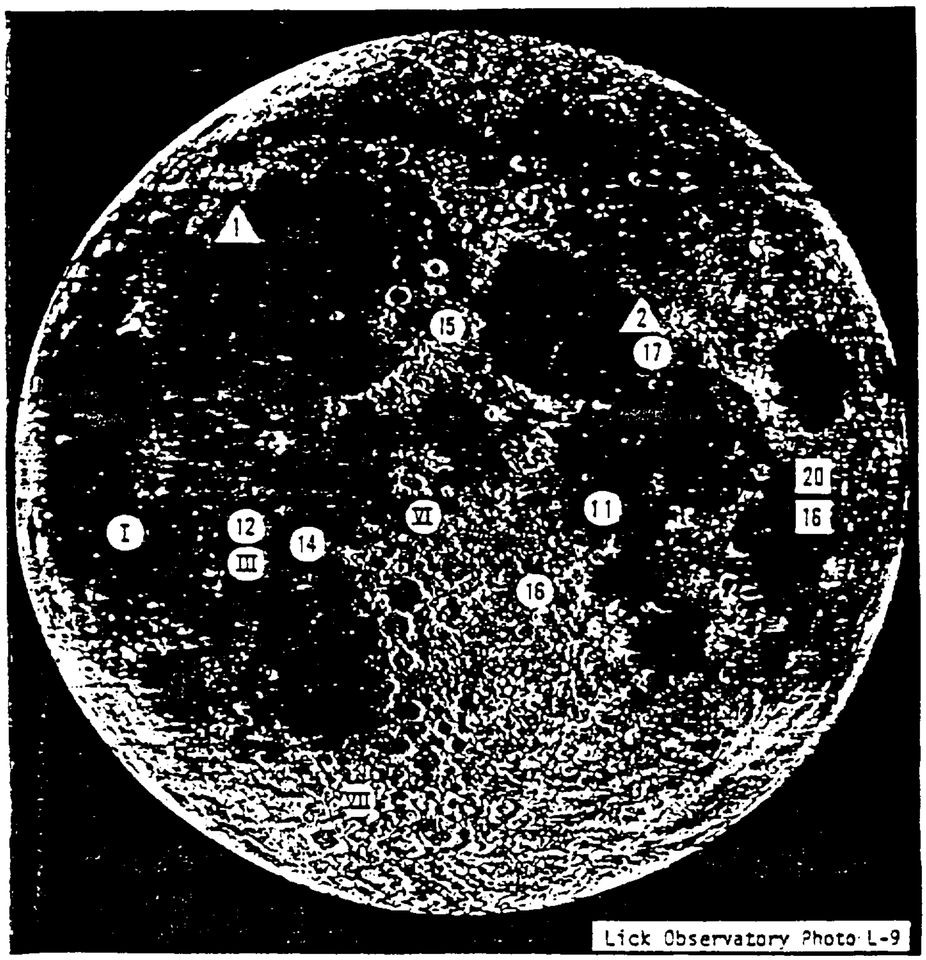


Figure 3.3.3.a. Lunar exploration via successful manned and unmanned landings. Roman numerals in circles are unmanned U.S. *Surveyor* spacecraft; arabic numbers in circles are U.S. manned *Apollo* landing site; triangles and squares are Soviet unmanned *Luna* sites. Spacecraft impact sites are not shown. (*From Lunar Science Institute Map.*) [232]

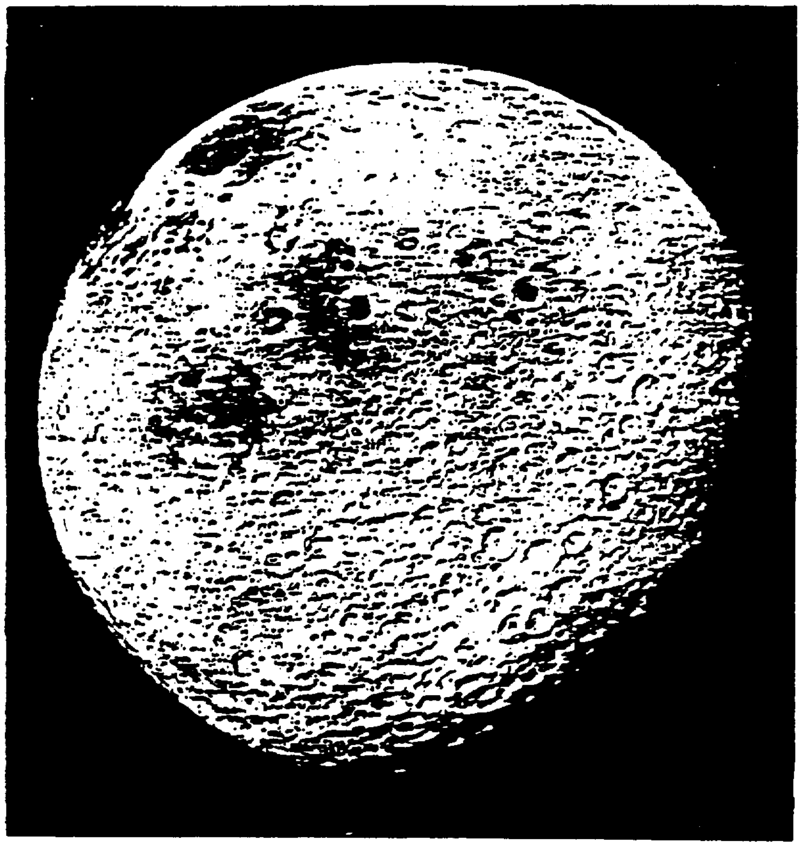


Figure 3.3.3.b. Apollo 16 view of part of the Moon's east limb and farside. The prominent dark mare at top left is Crisium, with dark patches of Mare Marginis (near middle) and Mare Smythii (middle left). The densely cratered nature of the farside highlands shows well along the terminator where the sun angles are low. [232]

THE LUNAR INTERIOR

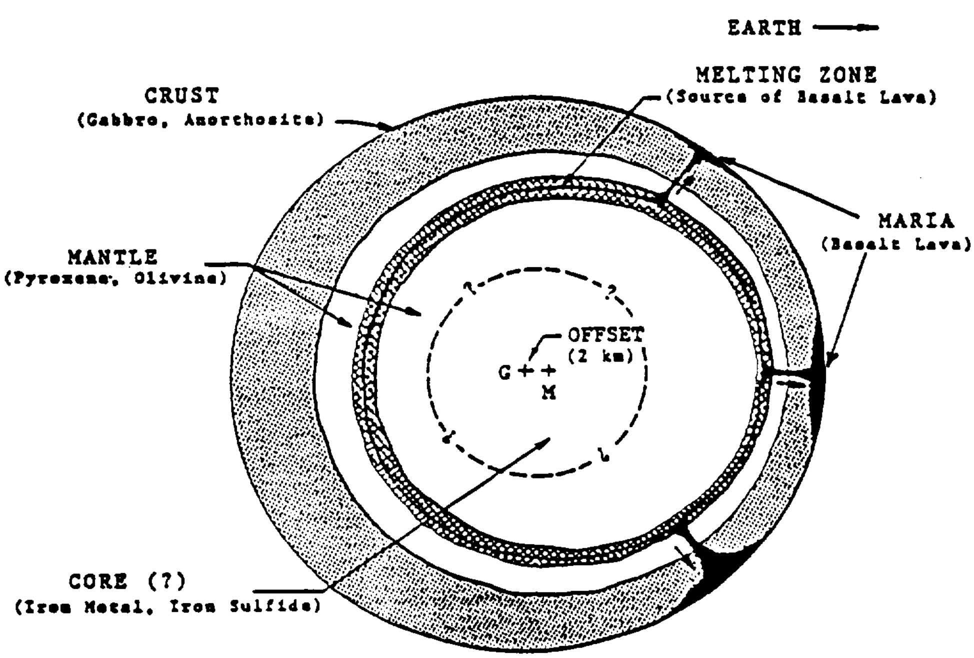


Figure 3.3.3.c. A Slice through the Moon. The internal structure of the moon, as determined by the Apollo Program, is shown in this cross section. The moon's diameter is about 3,500 kilometers, and the different layers are not drawn to scale. The outer crust (dotted) is thicker on the far side of the moon (about 100 kilometers) than it is on the near side (about 60 kilometers). This crust is rich in calcium and aluminum and is composed of such rocks as gabbro and anorthosite. Beneath the crust is a denser mantle (white), rich in magnesium and probably composed mostly of the minerals pyroxene and olivine. A small iron-rich core (dashed boundary) may exist at the center of the moon. The moon's center of mass (M) is offset about two kilometers toward the earth from its geometric center (G). The maria (black) on the near side are filled with basalt that formed in a deep zone of melting within the moon's mantle and then rose to the surface (arrows). [32]

Mare Areas

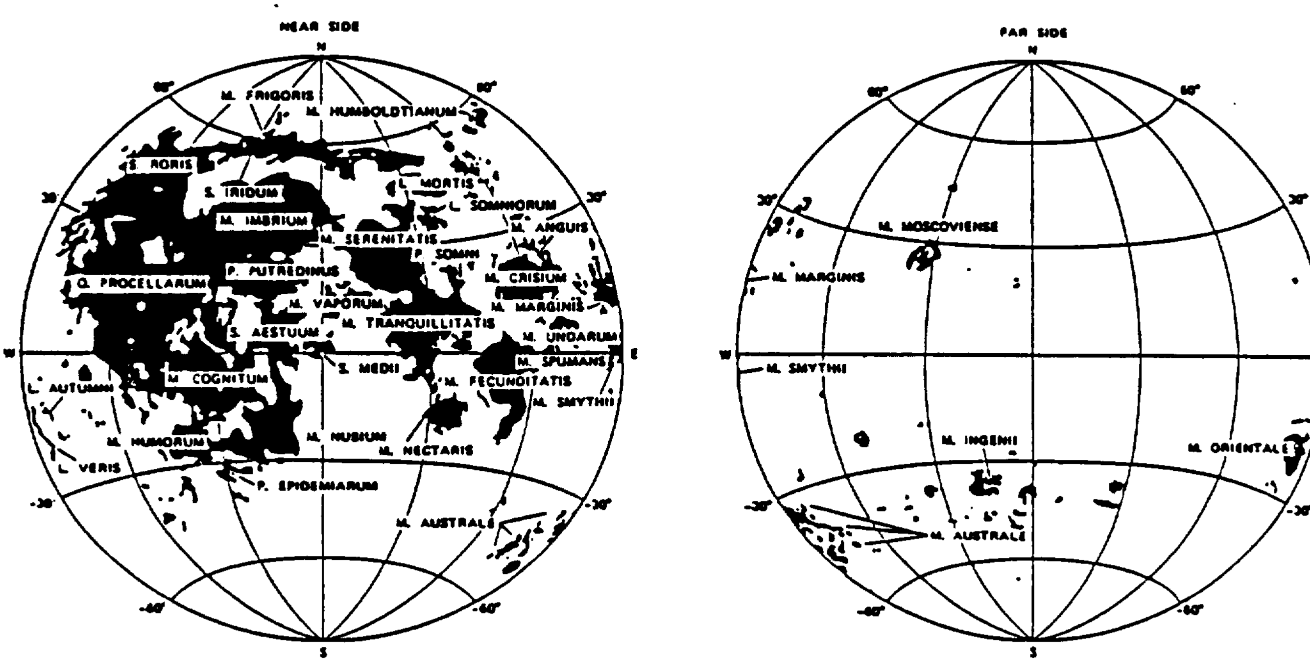


Figure 3.3.3.d. Distribution of mare materials. (*After Head*, 1976). [232]

TYPICAL ANALYSES OF MARIAL ROCKS

	Green glass Apollo 15	Olivine basalt Apollo 12	Olivine basalt Apollo 15	Quartz basalt Apollo 15	Quartz basalt Apollo 12	High K basalt Apollo 11	Low K basalt Apollo 11	High Ti basalt Apollo 17	Aluminous mare basalts Apollo 12	Luna 16
SiO_2	45.6	45.0	44.2	48.8	46.1	40.5	40.5	37.6	46.6	45.5
TiO_2	0.29	2.90	2.26	1.46	3.35	11.8	10.5	12.1	3.31	4.1
Al_2O_3	7.64	8.59	8.48	9.30	9.95	8.7	10.4	8.74	12.5	13.9
FeO	19.7	21.0	22.5	18.6	20.7	19.0	18.5	21.5	18.0	17.8
MnO	0.21	0.28	0.29	0.27	0.28	0.25	0.28	0.22	0.27	0.26
MgO	16.6	11.6	11.2	9.46	8.1	7.6	7.0	8.21	6.71	5.95
CaO	8.72	9.42	9.45	10.8	10.9	10.2	11.6	10.3	11.82	12.0
Na_2O	0.12	0.23	0.24	0.26	0.26	0.50	0.41	0.39	0.66	0.63
K_2O	0.02	0.064	0.03	0.03	0.071	0.29	0.096	0.08	0.07	0.21
P_2O_5	-	0.07	0.06	0.03	0.08	0.18	0.11	0.05	0.14	0.15
S	-	0.06	0.05	0.03	0.07	-	-	0.15	0.06	-
Cr_2O_3	0.41	0.55	0.70	0.66	0.46	0.37	0.25	0.42	0.37	-
Total	99.4	99.77	99.46	99.08	100.23	99.67	99.85	99.58	100.2	100.42

Figure 3.3.3.e. [232]

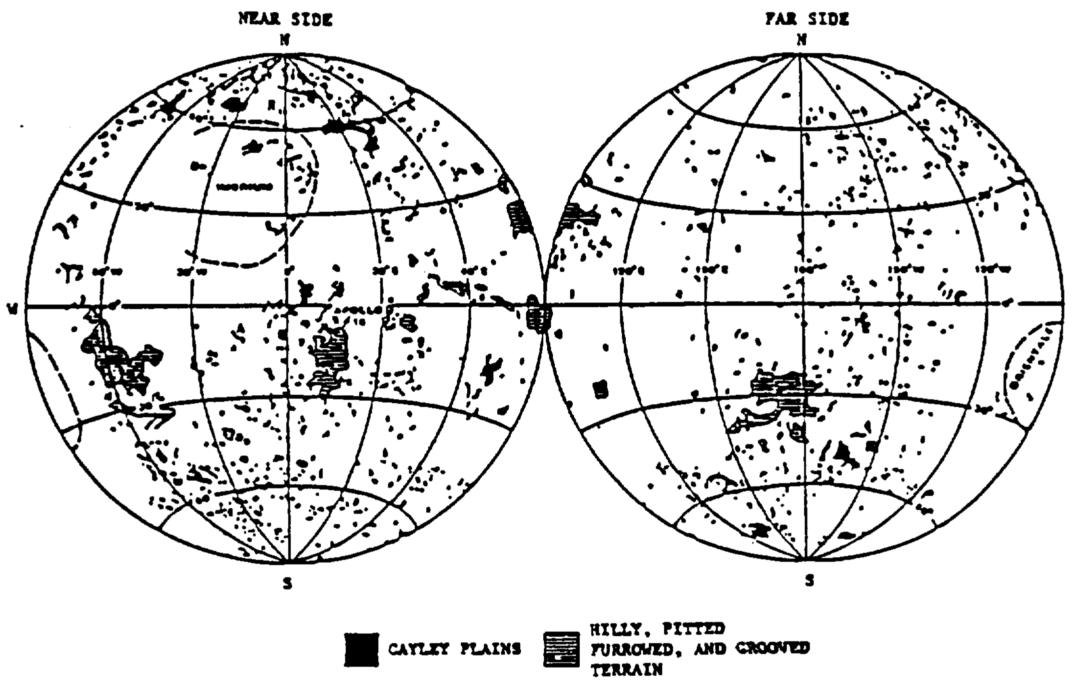


Figure 3.3.3.f. Distribution of Cayley plains and other units associated with impact basins. (*After Howard et al.*, 1974). [232]

TYPICAL ANALYSIS OF IGNEOUS ROCKS FOUND AS CLASTS IN HIGHLAND BRECCIA

	Anorthosite	Gabbroic anorthosite	Anorthositic gabbro	Troctolite	Low-K Fra Mauro basalt	Medium-K Fra Mauro basalt
SiO_2	44.3	44.5	44.5	43.7	46.6	48.0
TiO_2	0.06	0.35	0.39	0.17	1.25	2.1
Al_2O_3	35.1	31.0	26.0	22.7	18.8	17.6
FeO	0.67	3.46	5.77	4.9	9.7	10.9
MnO	-	-	-	0.07	-	-
MgO	0.80	3.38	8.05	14.7	11.0	8.70
CaO	18.7	17.3	14.9	13.1	11.6	10.7
Na_2O	0.80	0.12	0.25	0.39	0.37	0.70
K_2O	-	-	-	-	0.12	0.54
Cr_2O_3	0.02	0.04	0.06	0.09	0.26	0.18
Total	100.5	100.2	99.9	99.9	99.6	99.4

Figure 3.3.3.g. (from *Taylor*, 1975) [232].

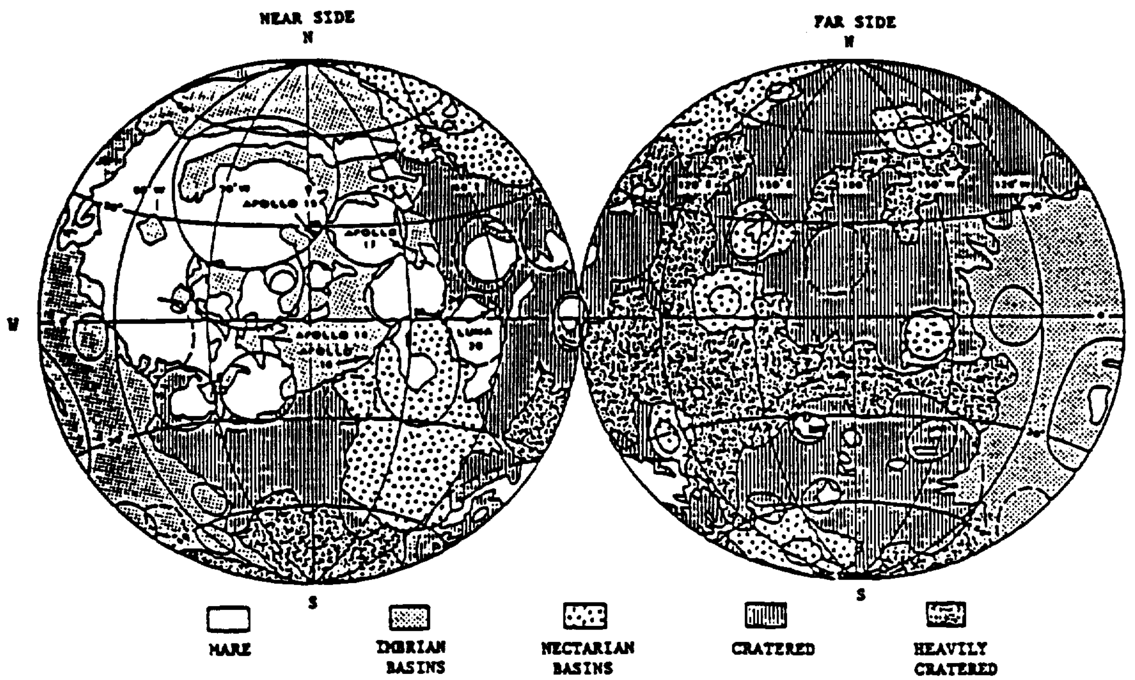


Figure 3.3.3.h. The Imbrium and Nectaris Basin Provinces. (*From Howard et al.*, 1974) [232]

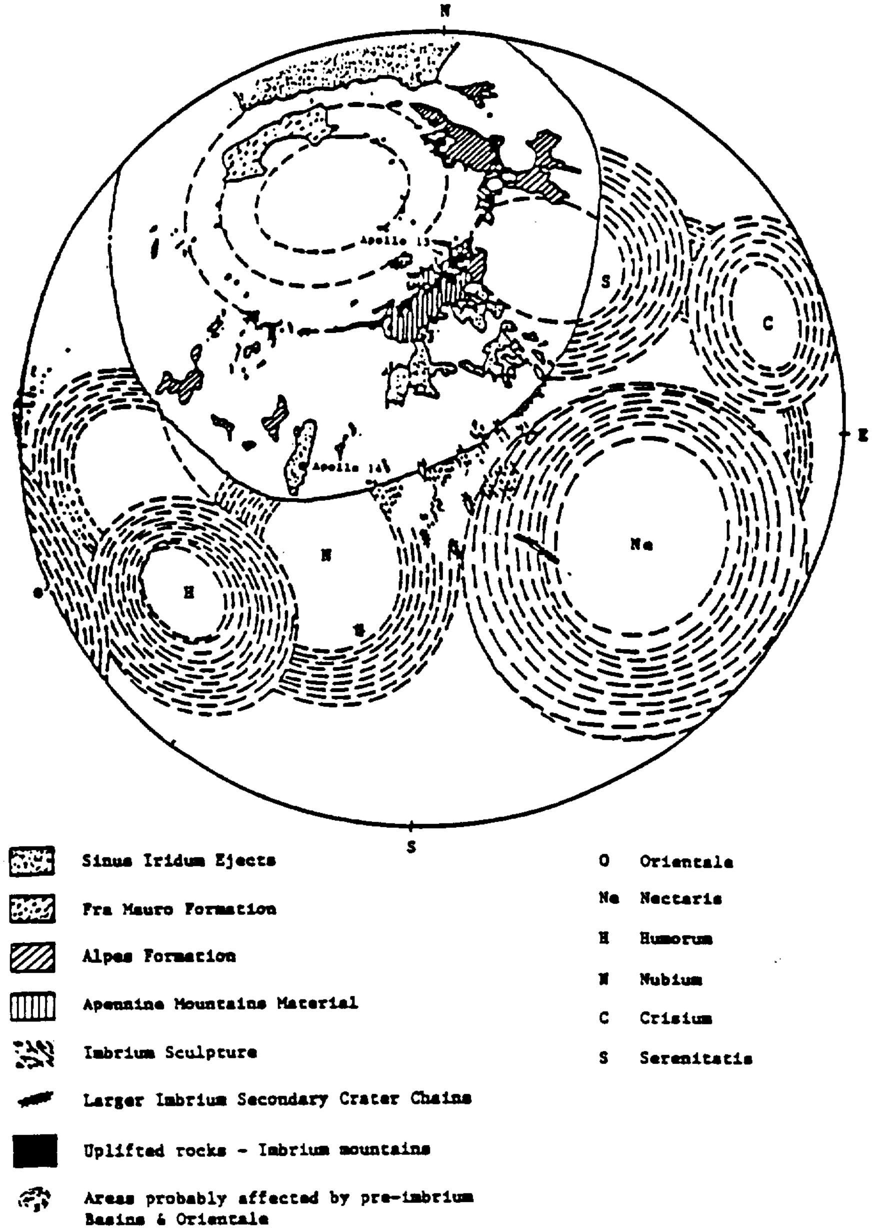


Figure 3.3.3.i. Distribution of materials associated with the Imbrium basin on the nearside of the Moon. The approximate extent of materials from other basins is indicated and possible relative ages are shown by overlapping relations. [232]

4. Lunar Processing of Local Resources:

4.1. IMPACT OF LOW GRAVITY ON LUNAR PROCESSING

LUNAR VERSUS TERRESTRIAL ENVIRONMENT – EFFECTS ON PROCESSING

Environmental Feature	Comparison to Earth	Processing Consequences
Gravity	Moon: 1/6 g Earth: 1 g	Major effects on fluidized beds, gas-solids transport systems, gravity flow of liquid and particulate solids
Surface Temp. Range	Moon: about 290 °C (-140 °C - +150 °C) Earth: 30 °C	Widely fluctuating as-mined feed-solids temperature
Atmosphere/ Coolants	Moon: Air/Water Absent Earth: Air/Water Abundant	Only closed-loop fluid systems usable; final heat rejection by radiation or heat pipe; unlimited hard vacuum available
Conventional Fuels	Moon: Absent Earth: Plentiful	Process heating by electricity or direct solar; power generation by nuclear or solar
Human Access	Moon: Difficult/Minimal Earth: Easy/Frequent	Extreme emphasis on minimum maintenance, modular replacement

Table 4.1.a. [222]

OTHER LUNAR ENVIRONMENT/DESIGN EFFECTS

Environmental Feature	Design Response
Fluctuating Surface (Feed Solids) Temperature	Provide agitated holding bins to average out Overdesign preheat capacity
Lack of Coolants/Conventional Fuels	Use heat integration to reduce energy demand, heat rejection duties High heater-to-process coefficients desirable for make-up heat supply; Efficient, low-weight radiators desirable
Difficult Human Access	Redundancy/automated change-out for high-maintenance items: Pumps and Blowers Solids feeders Electric resistance heaters Overdesign/minimize use of high-wear items Shaft seals Rotating surfaces in dusty or gritty service

Table 4.1.b. [222]

4. Lunar Processing of Local Resources:

4.1. IMPACT OF LOW GRAVITY ON LUNAR PROCESSING (CONT.)

REDUCED GRAVITY EFFECTS ON EQUIPMENT DESIGN

Parameter	Approximate Dependence on g	Lunar vs. Terrestrial Design
	Fluidized Bed Reactors, Solids Standpipes	
Minimum Fluidization Velocity, U_{mf}	$g^{1.0}$	Operable gas velocity range is from U_{mf} to U_t; must use larger particles or lower velocities
Particle Terminal Velocity, U_t	$g^{2/3}$ - $g^{1.0}$	Larger particles: larger bubbles mean poorer contacting efficiency
Bubble Diameter	$g^{0.4-1.0}$	Smaller bubbles mean better contacting efficiency; gravity effect counters particle size effect on bubble size
Bed Expansion	$1/(g^{0.7-1.0})$	Taller bed required for same inventory
Standpipe Throughput	$g^{0.5}$	Taller standpipes for same throughput
	Fixed Bed Reactors	
		No major effects
	Liquid Pumps	
Suction Head	$g^{1.0}$	Taller suction legs or low NPSH pumps required

Table 4.1.c. [222]

4.2. Resources available at a lunar base

(see also sec. 3.3.)

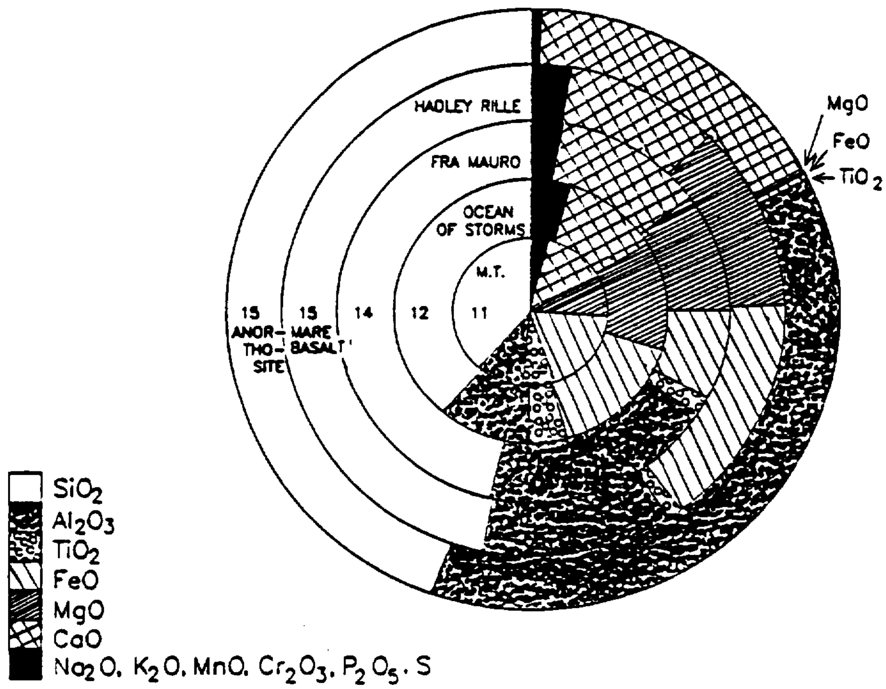


Figure 4.2.a. Typical abundance of major oxides for the different Apollo landing sites 11 through 15. [225]

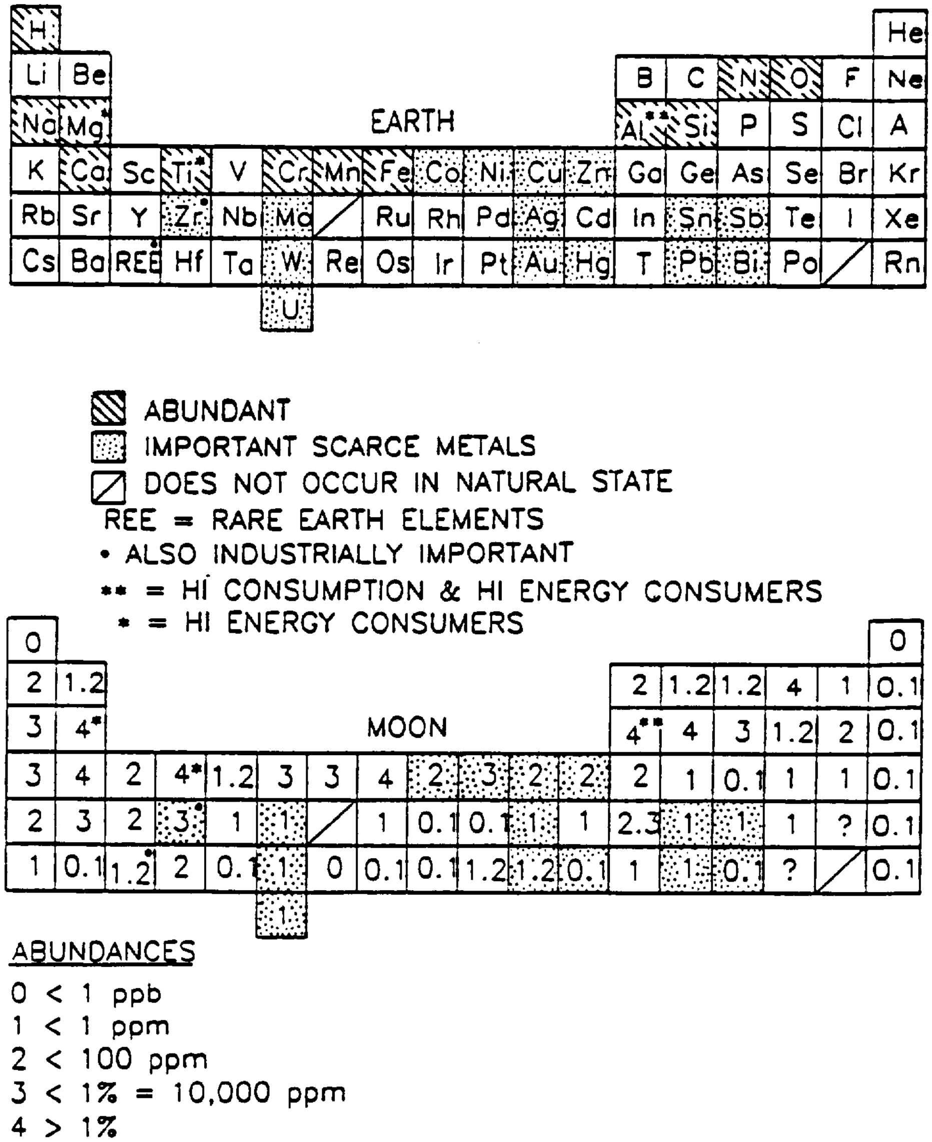


Figure 4.2.b. Comparison of industrial raw materials. [225]

ELEMENTAL CONSTITUENTS OF LUNAR VOLCANIC GAS

MINIMAL AMOUNTS

B	Ar	Ag	Xe
C	Cu	Cd	Au
F	Zn	In	Hg
Na	Ga	Sb	Tl
S	Ge	Te	Pb
Cl	Br	I	Bi

Table 4.2.c. [230]

4.3. Feasibility of Lunar Resources Utilization

4.3.1. Lunar Soil Processing Technology Options and Products

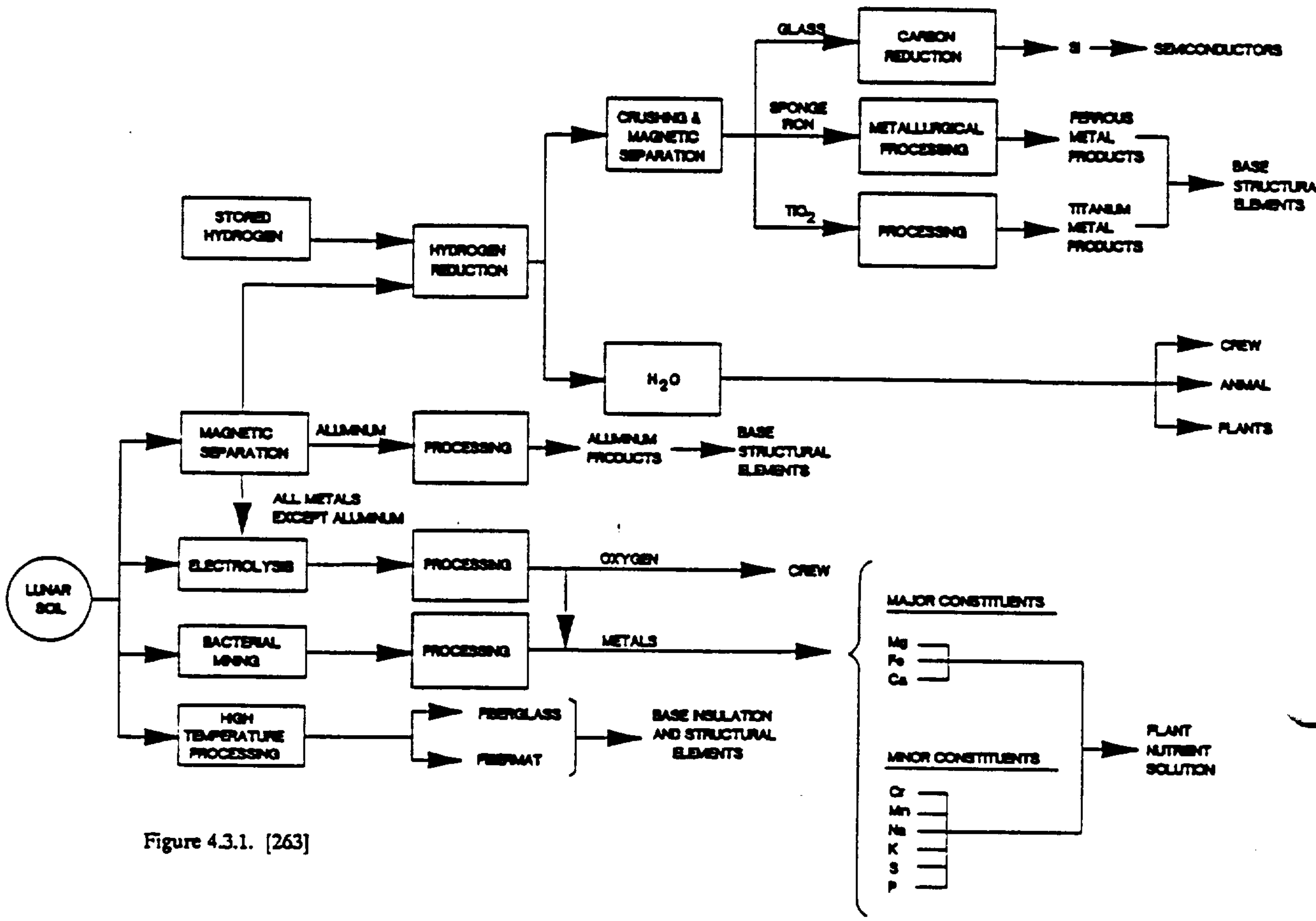


Figure 4.3.1. [263]

4.3.2. Theoretically attainable materials

1. Water - from hydrogen reduction of ilmenite
2. Cements - $CaO:SiO_2:Al_2O_3$
3. Glass Products
4. Metals - Al, Cr, Fe, Mg, Ni, Ti
5. Elements / Trace Materials - Ar, C, Ca, Cl_2, H_2, He, N_2, O_2, S, Si

4.3.3. Potentially Utilizable Resources

1. Regolith - radiation shielding, thermal insulation
2. Metals - iron
3. Ilmenite reduction - H_2O, titanium, iron, CO_2 (external carbon source)

- $FeTiO_3 + H_2 = Fe + TiO_2 + H_2O$ or

- $4\,FeTiO_3 + CH_4 = 4\,Fe + TiO_2 + 2\,H_2O + CO_2$

for more details, see sec. 4.4.

Potential output materials derived solely from Lunar sources (derived from R.D. Waldron; more detailed material description in R.D. Waldron [29]).

1. Structural Elements:

1.1 Alloys:

High capacity:	Al-, Mg-, Fe-. Ti-alloys
Limited capacity:	Cr (high Cr-Steel), Ni, Co, Mn

1.2 Reinforced Metals:

High capacity:	Al_2O_3 in Al, Mg; Fe-glass in Mg; Ti_5Si_3 in Ti
Limited capacity:	Al_2O_3 in Ni; SiO_2 in Ni

1.3 Structural Non-Metals:

High capacity:	cast basalt; dark glass; foamed glass
Limited capacity:	

2. Thermal Materials (refractories, insulation, fibers):

High capacity:	Al_2O_3; CaO; MgO; TiO_2; SiO_2; spinels; mixed ceramics; "S"-fibers; Ti_5Si_3
Limited capacity:	Cr_2O_3; K_2TiO_3;

3. Electric / Magnetic Materials:

3.1 Conductors:

High capacity:	Fe; Al; Mg

3.2 Resistance Alloys:

High capacity:	Kanthal A-1
Limited capacity:	Ni-Cr;

3.3 Semi-Conductors:

High capacity:	Si
Limited capacity:	AlP; FeS_2; NiO; CaO

3.4 Dielectrics / Insulators:

High capacity:	see thermal materials (except Ti_5Si_3) + titanates;

3.5 Magnetics:

High capacity:	Fe; Si-steel; Fe_3O_4; $MeFe_2O_4$; sendust
Limited capacity:	CrO_2

3.6 Electrodes:

High capacity:	FeO; TiO

4. Abrasives:

High capacity:	see refractories (except CaO) + garnets;

5. Volatiles:

High capacity:	O_2; O_3
Limited capacity:	SO_2, SO_3, CrO_3
Very low:	C (30-115 ppm); N_2 (1-82 ppm); S (1000 ppm).

6. Chemicals / Reagents:

High capacity:	CaO, CaO_2, MgO_2; P_2O_5; MnO_2
Low capacity:	Ca; Mg; Al; Fe; sufaltes; Phosphates; Chromates; Na;

Compositions of Whole Soils and Mineral Fractions

AVERAGE COMPOSITIONS OF APOLLO AND LUNA SOILS

Component (Wt.%)	A-11	A-12	A-14	A-15	A-16	A-17	L16	L20
SiO_2	42.47	46.17	48.08	46.20	45.09	39.87	43.96	44.95
Al_2O_3	13.78	13.71	17.41	10.32	27.18	10.97	15.51	23.07
TiO_2	7.67	3.07	1.70	2.16	.56	9.42	3.53	.49
Cr_2O_3	.30	.35	.22	.53	.11	.46	.29	.15
FeO	15.76	15.41	10.36	19.75	5.18	17.53	16.41	7.35
MnO	.21	.22	.14	.25	.07	.24	.21	.11
MgO	8.17	9.91	9.47	11.29	5.84	9.62	8.79	9.26
CaO	12.12	10.55	10.79	9.74	15.79	10.62	12.07	14.07
Na_2O	.44	.48	.70	.31	.47	.35	.36	.35
K_2O	.15	.27	.58	.10	.11	.08	.10	.08
P_2O_5	.12	.31	.50	.11	.12	.07	.14	.11
S	.12	.10	.09	.06	.06	.13	.21	.08
H	51.0	45.0	79.6	63.6	56.0	59.6		(ppm)
He	60	10	8	8	6	36		
C	135	104	130	95	106.5	82		
N	119	84	92	80	89	60	134	107
Ni	206	189	321	146	345	131	174	208
Co	32	43	35.8	54.4	25.3	35	37	40.5

Figure 4.3.3.a. [29]

COMPOSTIONS OF WHOLE SOILS AND MINERAL FRACTIONS

Modal Abundance	Pyroxene	Olivine	Plagioclase	Opaques (mostly Ilmenite)
	High-titanium basalts			
Vol.%	42-60%	0-10%	15-33%	10-34%
Component		Wt. %		
SiO_2	44.1-53.8	29.2-38.6	46.9-53.3	< 1.0
Al_2O_3	0.6-6.0	-	28.9-34.5	0-2.0
TiO_2	0.7-6.0	-	-	52.1-74.0
Cr_2O_3	0-0.7	0.1-0.2	-	0.4-2.2
FeO	8.1-45.8	25.4-28.8	0.3-1.4	14.9-45.7
MnO	0-0.7	0.2-0.3	-	< 1.0
MgO	1.7-22.8	33.5-36.5	0-0.3	0.7-8.6
CaO	3.7-20.7	0.2-0.3	14.3-18.6	< 1.0
Na_2O	0-0.2	-	0.7-2.7	-
K_2O	-	-	0-0.4	-
	Low-titanium basalts			
Vol. %	42-60%	0-36%	17-33%	1-11%
Component		Wt. %		
SiO_2	41.2-54.0	33.5-38.1	44.4-48.2	< 1.0
Al_2O_3	0.6-11.9	-	32.0-35.2	0.1-1.2
TiO_2	0.2-3.0	-	-	50.7-53.9
Cr_2O_3	0-1.5	0.3-0.7	-	0.2-0.8
FeO	13.1-45.5	21.1-47.2	0.4-2.6	44.1-46.8
MnO	0-0.6	0.1-0.4	-	0.3-0.5
MgO	0.3-26.3	18.5-39.2	0.1-1.2	0.1-2.3
CaO	2.0-16.9	0-0.3	16.9-19.2	< 1.0
Na_2O	0-0.1	-	0.4-1.3	-
K_2O	-	-	0.03	-
	Highland Rocks			
Vol.%	5-35%	0-35%	45-95%	0-5%
Component		Wt. %		
SiO_2	51.10-55.4	37.70-39.9	44.00-48.0	0-0.1
Al_2O_3	1.00-2.5	0-0.1	32.00-36.0	0.80-65.0
TiO_2	0.45-1.3	0-0.1	0.02-0.03	0.40-53.0
Cr_2O_3	0.30-0.7	0-0.1	0-0.02	0.40-4.0
FeO	8.20-24.0	13.40-27.3	0.18-0.34	11.60-36.0
MgO	16.70-30.9	33.40-45.5	0-0.18	7.70-20.0
CaO	1.90-16.7	0.20-0.3	19.00-20.0	0-0.6
Na_2O	-	-	0.20-0.6	-
K_2O	-	-	0.03-0.15	-

Figure 4.3.3.b. [29]

4.4. More details on important resources processing options

Location of resources given in ch. 3.3.

4.4.1. Ilmenite Processing

Location: Found in mare regions; approximately 10% usable ilmenite content.

Processing Methods:

4.4.1.1. Hydrogen reduction:

- Regolith passed through beneficiator (removes oversize material and separates remainder into tailings and feed material; (90% ilmenite, 10% flux).
- Simplest method.
- Preheated ilmenite combined with hydrogen to produce water.
- Water is separated , oxygen stored, hydrogen recycled.
- Only FeO oxygen liberated (1/3 available oxygen).
- Cold-trap technology could be applied to system.
- May be problem with fluidized beds in 1/6g.

4.4.1.2. Carbomethyl reduction

- Regolith passed through beneficiator.
- Feed material mixed with carbonaceous reductant- carbon can be from garbage or recycled off gas.
- Lunar steel formed.
- Earth based research on system.

4.4.1.3. Plasma processing

- Regolith passed through beneficiator.
- Uses high temperature plasma torch for reduction.
- Two-thirds or more of the oxygen available could be reduced (TiO could be partially reduced).
- Catalyst would need to be added so titanium doesn't back react with oxygen (hopefully recyclable).
- Can not be modeled well on Earth due to fast gas cooling times.

4.4.2. Lunar Soil Extraction:

4.4.2.1. Hydrogen Extraction:

- Microwave Techniques:
  High frequency microwaves might potentially be utilized for the extraction of solar hydrogen as water. The main draw back of this technique is likely to be the large power requirements.

- Microbial Extraction:
  Bacteria might potentially be capable of utilizing the hydrogen in the Lunar fines via hydrogenases. This methodology is dependent on the molecular hydrogen being accessible to the hydrogenases, or the Lunar fines might prove toxic to the bacteria.

- Benefaction/Thermal Release of Gases:
  The Lunar fines which comprise the hydrogen rich component of ilmenite can potentially be separated using vibratory screens and electrostatics. The main disadvantage of this system is the large quantities of regolith that are required to produce relatively small amounts of the surface bound hydrogen. Potentially the easiest way to relase trapped gases is by heating the Lunar fines. The main disadvantage of this system is the potential power requirements.

4.4.2.2. Oxygen Extraction:

- Carbothermal Processing:
  Carbon in theory can be used instead of hydrogren in the reduction of ilmenite to produce water and Lunar steel. The main disadvantage of this system is likely to be the large power requirements and high pressures required (100-150 atmospheres.)

- Electrolysis of Silicate:
  Molten silicates might be used to produce oxygen gas via electrolysis. This system is likely to be power dependent.

- Destructive Distillation:
  Very high temperature distillation of the Lunar soil might yield useful substances other than oxygen. The main draw back is likely to be the extreme temperatures involved.

4.4.2.3. Water Extraction:

- Hydrogen Reduction of Ilmenite:
  Ilmenite can be reduced by hydrogen at temperatures on the order of 700-1000 degrees C, and can be used to process Lunar regolith for water. The water can be split by electrolysis to yield hydrogen and oxygen. The main disadvantages of this system are a limited endogeneous hydrogen supply, and potentially large power requirements. This is currently the most likely method to be utilized in processing Lunar soil for water (hydrogen/oxygen).

- Ilmenite Benefication:
  1) Particles > 100 microns removed by vibratory screen
  2) Particles < 20 microns separated by turboscreening

- Ilmenite Reduction:
  One proposed reaction is ilmenite with hydrogen to produce water:
  $$FeTiO_3 + H_2 = Fe + TiO_2 + H_2O$$
  A more practical reaction may be methane with ilmenite (CH_4 supplied from earth or from biological waste processing; see Figure 4.4.2.):
  $$4FeTiO_3 + CH_4 = 4Fe + 4TiO_2 + 2H_2O + CO_2$$

- Considerations:
  1) Soil is approximately 10% ilmenite (47 Wt. %FeO, 53 Wt. % TiO_2)
  2) Soil Density = 1800 Kg/m^3
  3) Per-pass H_2 conversion approximately 5%
  4) Shipping Costs of O_2 - $10,000/Kg

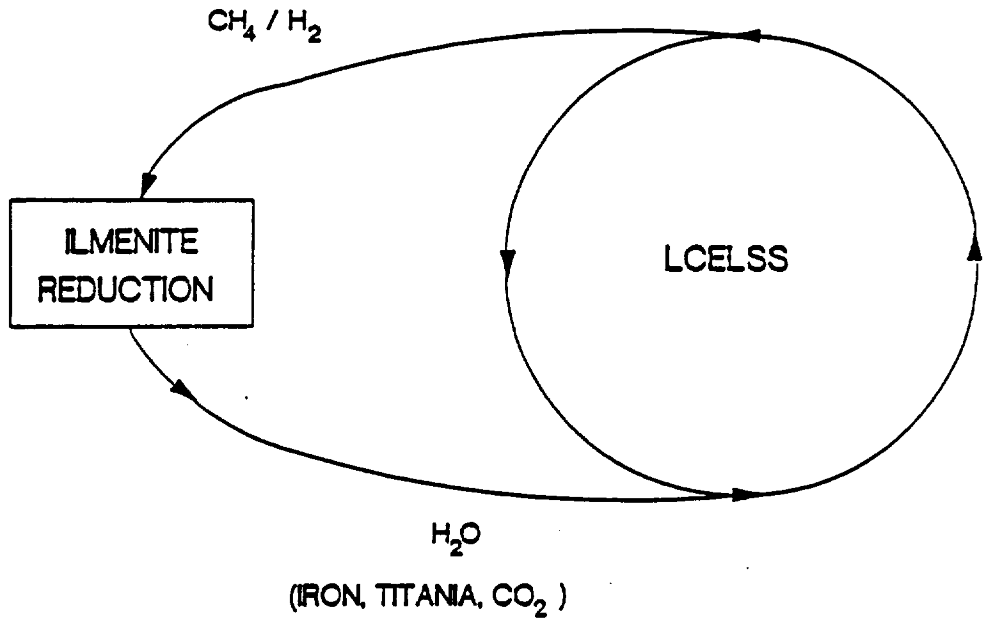


Figure 4.4.2. Methane produced by bioprocessing of waste in the lunar life support system LCELSS may be used for ilmenite reduction rather than hydrogen. The carbon would be recycled as carbon dioxide for further biomass-production.

5. Siting of a Lunar Base

SITING OF A LUNAR BASE

Design Driver		Polar North/South	Equator Far/Near	Earth Terminator
Mission:	*Resource:He^3*	little/no	yes	yes
	Resource:Ilmenite	maybe	Far:little Near:yes	little
	Resource:Hydrogen	little/no	solar wind	solar wind
	Resource:Volatiles	trapped in shade	unlikely	unlikely
	Tech.Demonstrator			
	Commercial Potential			
Mission:	*Science*			
	Exploration	very little known	F:little known N:more known	little known
	Astrophysic/Sky	S:little known N:more explored	F:EM Shielding N:Earth EM noise	Earth noise
	IR-astronomy	cryogenic in shade	artificial cooling	artificial cooling
Power:	*Solar Power Avail.*	0.5 year day/night	14 day day/night	14 day day/night
	Solar Tracking	360 Degree tracking	180 Degree tracking	180 Degree tracking
	Heat Sink	high Delta T/crater	no shade at full sun	lattitude dependent
	Energy Storage	for 0.5 years	for 14 days	for 14 days
Safety:	*Solar Wind*	craters for shielding	no natural shielding	no natural shielding
	Solar Flares	craters for shielding	no natural shielding	no natural shielding
	Cosmic Radiation	no benefits	no benefits	no benefits
	Meteroids	no benefits	N:Earth shielding	no benefits
	Communication	14d Earth visible	N:Earth always F:earth not visible	mostly visible
	Accessibility	always from polar orbit	always from equatorial	limited to certain launch window
	Corrosion		H_2-embrittlement? temperature variation	H_2-embrittlement temperature variation
	Operation		F:disturbing EM-silence	
Environment:	*Visibility*	shade/dark	long twilight	long twilight
	Temperature Var.	little	high (14d)	high (14d)
	dust	same	same	same
	illumination	constant, long shade	changing	changing
Flexibility: Expandability:	*small area on moon (limited to 80km diam.)*	ample space	ample space	

6. Glossary:

Albedo:	Efficiency at which a body reflects light.
Apogee:	nearest point on orbit to Earth.
Basalt:	fine-grained volcanic rock; containing plagioclase and pyroxene as main material.
Basin:	large crater with multiple rings.
Breccia:	rock with large angular grains cemented together by a finer grained matrix.
Clinopyroxene :	a monoclinic iron / magnesia / calcium silicate
Cosmic Radiation:	lower flux but higher energy than solar radiation; 85% H, 13%, He, 2% heavier atoms
Ecliptic:	Plane of Earth's orbit around the Sun.
far side:	lunar hemisphere turned away from Earth.
Feldspar:	aluminosilicate mineral
Fines:	Lunar soil finer than 1 millimeter
Granite:	rock rich in silica and K-feldspar
Highlands:	pale colored regions on the Moon. Terra / terrae. Cover approximately 4/5 of the lunar surface.
Ilmenite:	iron-titanium-oxide mineral; FeTiO3.
KREEP:	rock type rich in potassium, rare Earth elements and phosphorous.
Light plains:	highland light plains; pale, level areas in the lunar highlands.
Mantle:	zone between core and crust.
Maria/mare:	dark, level plains (floors of basins); dark areas of iron-rich basalt. Basalt filled the older basins, created by impact around 3.8-4.3 Bio. years ago.
Mare-basalt:	basalt from maria; rich in iron and titanium.
Meteorite:	solid object in space.
micrometeorite :	very small meteorite.
near side:	lunar hemisphere turned towards Earth.
Olivine:	ferromagnesia silicate mineral; $((K=Mg,Fe)_2SiO_4)$
Orthopyroxene:	ferromagnesian silicate mineral
Perigee:	nearest point on orbit around Earth.
Plagioclase:	calcium feldspar mineral
Pyroxene:	calcium/iron/magnesium silicate mineral; general formula is XYZ_2O_6 with X = Ca, Y = Mg, Ti, Al, Mn, CR; Z = Si, Al.
Pyroxferroite:	uniquely lunar silicate mineral
Regolith:	fine-grained lunar surface layer; result of erosion (meteor impact); 1-20m deep (5-6 m in mare areas, more in highlands). Debris layer with particle size between micrometers and up to 10 meter. Consists out of fragments of bedrock, glass droplets and meteoritic material.
Regolith Breccia:	breccia formed by sintering of soil.
Sidereal month:	time taken by the Moon to return to the same celestial longitude; 27.32 Earth days.
Spinel:	a hard, crystalline mineral composed chiefly of oxide of aluminum, magnesium, and iron.
Synodic Month:	lunar day; time between same alignment of Sun, Earth and Moon; 29.53 days.
Silicate:	mineral with lattice of silicon and oxygen.
Solar Flares:	short time peaks of solar activity; high energy in MeV to GeV-range; 90%H, 9% He, 1% others.
Solar Cosmic Rays:	energetic ions from the Sun.
Solar Wind:	low energy ions from the Sun in keV-range; typically 99% H, 1% He, 1% others.
Terminator:	boundary of illuminated hemisphere.
Terra/terrae:	highlands; pale colored regions on the Moon; densely cratered.
Troctolite:	rock containing plagioclase and olivine

Bibliography

[240] (1977 Nov) Space and Planetary Environment: Criteria Guidelines for use in Space Vehicle Development. In G.S. West, J.J.Wright, and H.C. Euler (eds): NASA-TM-78119. :.

[314] Burke, J.D., (1984 Oct) Merits of a Lunar Base Location. In W.W. Mendell, LPI, and NASA (eds): Lunar Bases and Space Activities of the 21st Century. Washington:, pp. 77-84.

[230] Delano, J.W., (1982 Oct) Volatiles Within the Earth's Moon. In (ed): NASA-CR-170063, Conference on Planetary Volatiles (Lunar and Planetary Institute, N83-20881). :, pp. 27-28.

[225] Ehricke, K.A., (1981 May) A Socio-Economic Evaluation of the Lunar Environment and Resources I. Principles and overall system strategy. Acta Astronautica, (Pergamon Press Ltd., Great Britain) 8: 1389-1405.

[32] French, B.M., (1977) The Moon Book: Chapter 6: Anatomy of a Moon Rock. Chapter 7: The Lunar Soil. Chapter 10: The Lunar Interior: Mapping with Echoes. Chapter 9: The Lunar Surface: The Billion-Year Sunburn. New York, NY 10022: Penguin Books.

[222] Gibson, M.A., C.W. Knudsen, (1985) Lunar Oxygen Production From Ilmenite. In W. Mendell (ed): Lunar Bases and Space Activities for the 21st Century. Houston: Lunar and Planetary Institute, pp.543-550.

[232] Guest, J.E., R. Greeley, (1977) Geology on the Moon. New York:.

[242] Langseth, M.G., S.J. Keihm, K. Peters, (1976) Revised Lunar Heat-Flow Values. In (ed): Proceedings of the 7th Lunar Sciences Conference.:, pp. 3143-3171.

[233] Munch, T.A., (1970) Geology of the Moon - A Stratigraphic View. :.

[315] Nealy, John E., Wilson, John W., Townsend, Lawrence W., (1988, Dec) Solar-Flare Shielding with Regolith at a Lunar-Base Site. NASA Technical Paper 2869, Langley Research Center.

[243] Robie, R.A., B.S. Hemingway, W.H. Wilson, (1970) Specific heats of Lunar Surface Materials from 90 to 350 K. In (ed): Proceedings of the Apollo 11 Lunar Sciences Conference. :, pp. 2361-2367.

[263] Schwartzkopf, S.H., D.G. Kane, R.L. Stempson, Lockheed-Missiles, (1988 July) Greenhouses and Green Cheese: Use of Lunar resources in CELSS Development. In (ed): SAE-88-1057, 18th Intersociety Conference on Environmental Systems San Francisco. :.

[241] Silberberg, R., et. al.,(1985) Radiation Transport of Cosmic Ray Nuclei in Lunar Material and Radiation Doses. In W. Mendell (ed.): Lunar Bases and Space Activities of the 21st Century. Washington:, pp.663-669.

[29] Waldron, R.D., (1988) Lunar Manufacturing: A Survey of Products and Processes. Acta Astronautica Pergamon Press 17 NO 7: 691-708.

[175] Woodcock, G.R., (1986) Space Stations and Platforms. Malabar, Fla: Orbit Books.

Note: References are taken from the Lunar Life Support Systems Database at Bioserve Space Technologies, Boulder, Colorado; for full database see Appendix.

Appendix: Database on Lunar CELSS

References used for a feasibility study of a Lunar Base and a Lunar Controlled Ecolological Life Support System are listed in the following paragraphs: 1) Lunar Environment, 2) Power Systems, 3) Air Regeneration, 4) Water Recycling, 5) Waste Management, 6) Food Production. The [db-id]-number refers to the identification number of a reference within the database and has been used in this document as a reference number within the text.

1) Lunar Environment and Resource Utilization:

[1] Humphries, W.R., J.L. Reuter, R.G. Schunk. (1986). Space Station Environmental Control and Life Support System Distribution and Loop Closure Studies. In: SAE-86-0942. pp. 285-296. [db-id.: 2]. [Topics: CELSS; Life Sciences; Air; Water; Oxygen; Environment control].

[2] Bagotzy, V.S., A.M. Skundila. (1980). Chemical Power Sources. London: Academic Press. [db-id.: 3]. [Topics: CELSS; Environment; Electrolysis; Fuel cells].

[3] Bugbee, B., F.B. Salisbury. (1988). Space Farming in the 21st Century. 21st Century : 32-40. [db-id.: 5]. [Topics: CELSS; Food production; LCELSS; Artificial environment; Plant; Diversity; Yield; Crop physiology].

[4] Arnold, J.R.. (1979 Sept). Ice in the Lunar Polar Regions. Journal of Geophysical Research, Paper Number 9B0581 84: 5659-5668. [db-id.: 10]. [Topics: CELSS; Lunar Base; Resources; Water; Ice].

[5] Ray, C.D., W.R. Humphries. (1986). Status of the Space Station Environmental Control and Life Support Systems Design Concept. In: SAE-86-0943. pp. 297-308. [db-id.: 23]. [Topics: CELSS; Physiochemical; Control; Environment; Power; Air; Water].

[6] Waldron, R.D.. (1988). Lunar Manufacturing: A Survey of Products and Processes. Acta Astronautica Pergamon Press 17 NO 7: 691-708. [db-id.: 29]. [Topics: CELSS; Lunar resources; Chemical Elements; Lunar Soils].

[7] French, B.M.. (1977). The Moon Book: Chapter 6: Anatomy of a Moon Rock. Chapter 7: The Lunar Soil. Chapter 10: The Lunar Interior: Mapping with Echoes. Chapter 9: The Lunar Surface: The Billion-Year Sunburn. New York, NY 10022: Penguin Books. [db-id.: 32]. [Topics: CELSS; Lunar Resources].

[8] Alviolz, L.. (1979). Space Science Board National Academy of Science. [db-id.: 92]. [Topics: CELSS; Radiation; Habitability].

[9] Calvin, E.M.. (1975). Foundations of Space Biology and Space Medicine. NASA :. [db-id.: 93]. [Topics: CELSS; Radiation; Habitability].

[10] Cox, Ainsworth. (1983). Advances in Space Research. [db-id.: 94]. [Topics: CELSS; Radiation; Habitability].

[11] Davidson, D.E.. (1980). Radiation Sensitizers - Use in Management of Cancer. [db-id.: 95]. [Topics: CELSS; radiation; Habitability].

[12] Glasstone, S., P.J. Dolan. (1977). The Effects of Nuclear Weapons United States Department of Defense and Energy Research and Development Administration. [db-id.: 97]. [Topics: CELSS; radiation; Habitability].

[13] Grahn, D... Space Radiation Effects Workshop. [db-id.: 98]. [Topics: CELSS; Radiation; Habitability].

[14] Graul, E.H., W. Ruther. (1987). Effects of Heavy Ions on Egg-Developing Systems. In: ESA-SP-271. Proceedings of the Third European Symposium on Life Sciences Research in Space. pp. 215-218. [db-id.: 99]. [Topics: CELSS; Radiation; Habitability].

[15] Graze, P.R.. (1979). Transplantation. [db-id.: 100]. [Topics: CELSS; Radiation; habitability].

[16] Hardy, A.. (1983). Proceedings, Space Radiation Effects Workshop. [db-id.: 101]. [Topics: CELSS; Radiation; Habitability].

[17] Janni, J.F.. (1969 Dec). Aerospace Medicine :. [db-id.: 102]. [Topics: CELSS; Radiation; habitability].

[18] Johnson, R.S.. (1977). Biomedical Results From Skylab. NASA :. [db-id.: 103]. [Topics: CELSS; Radiation; Habitability].

[19] Kiefer, J., E. Schneider. (1987). Cellular Effects of Heavy Ions: Experimental Results and Theoretical Approaches. In: ESA-SP-271. Proceedings of the third symposium on Life Sciences Research in Space. pp. 205-208. [db-id.: 104]. [Topics: CELSS; biophysics; Radiation].

[20] Kranz, A.R.. (1987). Effects of Cosmic Heavy Ion Radiation And Space Microgravity on Plant Systems. In: ESA-SP-271. Proceedings of the Third European Symposium on Life Sciences Research in Space. pp. 219-226. [db-id.: 105]. [Topics: CELSS; Radiation; Biophysics].

[21] Langham, W.. (1967). Radio-biological Factors in Manned Space Flight. [db-id.: 106]. [Topics: CELSS; Radiation; Biophysics; Habitability].

[22] Lett, J.T.. (1987). Advances in Radiation Biology. New York: Academic Press. [db-id.: 107]. [Topics: CELSS; Radiation; Habitability].

[23] Lindberg, C.. (1987). Ultraviolet (180-300 nm) Action Spectra For Inactivation and DNA Photoproduct Formation of Bacillus Subtilis Spores Under Ultrahigh Vacuum. In: ESA-SP-271. Proceedings of the Third European Symposium on Life Sciences Research in Space. pp. 197-200. [db-id.: 108]. [Topics: CELSS; radiation; biophysics].

[24] Reitz, G.. (1987). Radiation Problems in MAnned Spaceflight With A View Towards The Space Station. In: ESA-SP-271. Proceedings of the Third European Symposium on Life Sciences Research in Space. pp. 209-214. [db-id.: 109]. [Topics: CELSS; biophysics; radiation].

[25] Schenk, K., J. Kiefer. (1987). Survival and Mutation Induction of Dehydrated Yeast Cells After UV Exposure. In: ESA-SP- 271. Proceedings of the Third European Symposium on Life Sciences Research in Space. pp. 201-204. [db-id.: 110]. [Topics: CELSS; Radiation; Biophysics].

[26] Stauber, N.C.. (1982-83). AAS Proceedings Space Safety and Rescue. In:. [db-id.: 111]. [Topics: CELSS; Radiation; Habitability].

[27] Tobits, C.A., P. Todd. (1974). Space Radiation Biology and Related Topics. [db-id.: 112]. [Topics: CELSS; Radiation; Habitability].

[28] Todd, P.. (1983). Advances in Space Research. [db-id.: 113]. [Topics: CELSS; Radiation; Habitability].

[29] Yuhas, J.. (1970). Radiation Research. [db-id.: 114]. [Topics: CELSS; Habitability; Environment; Radiation].

[30] Guerra, L., Large-Scale-Programs-Ins. (1988 Aug). A Commonalty Assessment of Lunar Surface Habitation. In: Engineering, Construction and Space. Proceedings of Space 1988. pp. 274-286. [db-id.: 153]. [Topics: CELSS; Lunar base; Environment; Habitation].

[31] Vaniman, D.. (1988 Aug). Extraction of Light Gases. In: Engineering, Construction and Operations in Space. Proceedings of Space 88. Albuquerque, New Mex:, pp. 78-89. [db-id.: 165]. [Topics: CELSS; Lunar-base; Atmosphere; Local-Resources; Surface; Properties:].

[32] Woodcock, G.R., Boeing-Aerospace. (1988 Aug). Basing Options for Lunar Oxygen for Manned Mars Missions. In: Engineering, Construction and Operations in Space. Proceedings of Space 88. Albuquerque, New Mex:, pp. 421-434. [db-id.: 166]. [Topics: CELSS; Lunar-base; Local-Resources; Oxygen].

[33] Ho, D., L.E. Sobon. (1979). Extraterrestrial Fiberglass Production using Solar Energy N79- 32237. In: NASA-SP- 428. Space resources and Space Settlements. : NASA, pp. 225-232. [db- id.: 171]. [Topics: CELSS; Resources; Environment; Lunar resources; Sun].

[34] Bhogeswara, R.D., U.V. Choudary, T.E. Erstfeld, R.J. Williams, Y.A. Chang. (1979). Extraction Processes for the Production of Aluminum, Titanium, Iron, Magnesium, and Oxygen From Non-terrestrial Sources. In: NASA-SP-428. Space Resources and Space Settlements. : NASA, pp. 257-274. [db-id.: 172]. [Topics: CELSS; Resources; Environment; Lunar resources; Oxygen].

[35] Chang, S., J.F. Kerridge. (1982 Oct). Accretion Of Volatiles. In: NASA-CR-170063, Conference on Planetary Volatiles, N83-20881. Houston, Texas: Lunar and Planetary Institute/NASA, pp. 21- 22. [db-id.: 173]. [Topics: CELSS; Resources; Environment; Lunar resources; Carbon; Hydrogen; Nitrogen].

[36] Lewis, J.S., R.A. Lewis. (1987). Space Resources - Breaking the Bonds of Earth. : Columbia University Press, pp. 172-211. [db-id.: 174]. [Topics: CELSS; Lunar Base; Lunar Resources].

[37] Woodcock, G.R.. (1986). Space Stations and Platforms. Malabar, Fla: Orbit Books. [db-id.: 175]. [Topics: CELSS; Lunar Base; Radiation; Sun; Space; Physiochemical].

[38] Taylor, L.A.. (1988). Rocks and Minerals of the Moon: Materials for a Lunar Base. In: Second Symposium on Lunar Base and Space Activities of the 21st Century, Houston April 5-7 1988. [db-id.: 179]. [Topics: CELSS; Lunar base; environment; Lunar Soil].

[39] Averner, M.M., R.D. MacElroy, D.T. Smernoff. (1987 Sep). Development of a Plant Growth Module. In (ed): NASA, Moffett Field, CA. Ames Rese. [db-id.: 186]. [Topics: CELSS; Air flow; Carbon dioxide; Crop growth; Humidity; Irradiation; Nutrition; Oxygen].

[40] Tremor, J.W., R.D. MacElroy. (1987 Sep). CELSS Program Meeting. In (ed): NASA, Moffett Field, CA. Ames Rese. [db- id.: 187]. [Topics: CELSS; Plant Growth; Irradiation; Illumination; Microorganism; Nutrition; Organic Material; Plant Diseases].

[41] Thompson, B.G., B.H. Lake. (1987 Sep). Effect of Radiation on the Long Term Productivity of a Plant Based CELSS. In NASA (ed):. Washington: Alberta Research Council, Edmonton. [db-id.: 188]. [Topics: CELSS; Productivity; Radiation dosage; Radiation effects; Vegetation growth; Extraterrestrial radiation; Mutations; Solar flares].

[42] MacElroy, R.D., J. Tremor, D.T. Smernoff, W. Knott, R.P. Prince. (1987 Sep). Review of Recent Activities in the NASA CELSS Program. In (ed):. : NASA, Moffett Field, CA. Ames Rese. [db-id.: 195]. [Topics: CELSS; Food Production; Oxygen production; Photosynthesis; Waste; Utilization; Cellulose; Extraterrestrial radiation; Gravitational Effects].

[43] Venketeswaran, S.. (1987 Aug). Growth of Plant Tissue Cultures in Simulated Lunar Soil: Implications for a Lunar Base CELSS. Semiannual Report February 1-July 31, 1987. Status rept. In NASA (ed): NASA-CR-181131. NAS 1.26:181131. : Houston Univ., TX. [db-id.: 205]. [Topics: CELSS; Environment simulation; Lunar base; Lunar environment;; Lunar soil; Rice; Seeds; Plant Growth].

[44] Babcock, P.S.. (1986 Mar). Nonlinear System Controller Design Based on Domain of Attraction: An Application to CELSS (Closed Ecological Life Support Systems) Analysis and Control. In NASA (ed): NASA-CR-177401, NAS 1.26:177401, T-4081. : California Univ., Berkeley. [db-id.: 207]. [Topics: CELSS; Models; Simulation; Spacecraft environments].

[45] Ehricke, K.A.. (1981 May). A Socio-Economic Evaluation of the Lunar Environment and Resources I. Principles and overall system strategy. Acta Astronautica, (Pergamon Press Ltd., Great Britain) 8: 1389-1405. [db-id.: 225]. [Topics: CELSS; Lunar Base; Environment; Lunar resources].

[46] Johenning, B., H.H. Koelle. (1986 Jan). Evolution and Logistics of an Early Lunar Base. Acta Astronautica (Pergamon Journals ltd., Great Britain) 13 no 9: 527-536. [db-id.: 227]. [Topics: CELSS; Resources; Environment].

[47] Williams, R.J.. (1985). Oxygen Extraction From Lunar Materials: An Experimental Test of an Ilmenite Reduction Process. In W.W. Mendell (ed): Lunar Bases and Space Activities of the 21st Century. Houston, TX: Lunar and Planetary Institute, pp. 551-558. [db- id.: 229]. [Topics: CELSS; Resources; Air; Oxygen].

[48] Delano, J.W.. (1982 Oct). Volatiles Within the Earth's Moon. In (ed): NASA-CR-170063, Conference on Planetary Volatiles (Lunar and Planetary Institute, N83-20881). pp. 27-28. [db- id.: 230]. [Topics: CELSS; Resources; Environment; Lunar resources].

[49] System-Development-Corp. (1986 Dec). Lunar Power Systems, Final report. In: NASA-CR-171956, N87-17398, NAS1.26: 171956. p. 324. [db-id.: 231]. [Topics: CELSS; Lunar base; Environment; Power].

[50] Guest, J.E., R. Greeley. (1977). Geology on the Moon. New York:. [db-id.: 232]. [Topics: CELSS; Lunar base; Environment; Geology; Resources; Lunar Soil].

[51] Munch, T.A.. (1970). Geology of the Moon - A Stratigraphic View. [db-id.: 233]. [Topics: CELSS; Lunar Base; Environment; Geophysics; Geology].

[52] Fiedler, G.. (1971). Geology and Physics of the Moon - A study of some fundamental problems. [db-id.: 234]. [Topics: CELSS; Lunar base; Environment; Thermal Properties; Physical; properties].

[53] NASA-Johnson. (1977 July). Lunar Sample Studies. In: NASA-SP-148, NAS 1.21:418. [db-id.: 235]. [Topics: CELSS; Lunar Base; Environment; Geology; Lunar Soil].

[54] French, B.U.. (1982). The Moon / Chapter 7. In J.K. Beatty, B. O'Leary, and A. Chailleu (eds): The New Solar System. Cambridge, Ma.: Sky Publishing Corporation, pp. 71-82. [db-id.: 236]. [Topics: CELSS; Lunar base; Environment; Geology].

[55] Cadogan, P.H.. (1981). The Moon - Our Sister Planet. Cambridge, MA: Cambridge University Press, p. 391. [db-id.: 237]. [Topics: CELSS; Lunar base; Environment; Geology].

[56] (1979). Lunar Remote Sensing and Measurements Professional Paper 1046-B. In H.J. Moore, J.M. Boyce, G.G. Schetser, and D.H. Scott (eds):. : US Geological Survey, p. 78. [db-id.: 238]. [Topics: CELSS; Lunar Base; Geology; Environment; Magnetism; Geochemistry].

[57] (1987). The Geologic History of the Moon. In D.E. Wilhelms (ed): Prof. Paper 1348. GovDoc 1916:1348. : US Geological Survey, p. 326. [db-id.: 239]. [Topics: CELSS; Environment; Geology; Resources].

[58] (1977 Nov). Space and Planetary Environment: Criteria Guidelines for use in Space Vehicle Development. In G.S. West, J.J. Wright, and H.C. Euler (eds): NASA-TM-78119. [db-id.: 240]. [Topics: CELSS; Lunar Base; Environment; Space].

[59] Silberberg, R., C.H. Tsao, J.H. Adams. Radiation Transport of Cosmic ray Nuclei in Lunar Material and Radiation Doses. In W.W. Mendell (ed): Lunar Bases and Space Activities of the 21st Century. [db-id.: 241]. [Topics: CELSS; Lunar base; Environment; Radiation].

[60] Langseth, M.G., S.J. Keihm, K. Peters. (1976). Revised Lunar Heat-Flow Values. In: Proceedings of the 7th Lunar Sciences Conference. pp. 3143-3171. [db-id.: 242]. [Topics: CELSS; Lunar base; Environment; Geology; Thermal properties].

[61] Robie, R.A., B.S. Hemingway, W.H. Wilson. (1970). Specific heats of Lunar Surface Materials from 90 to 350 K. In: Proceedings of the Apollo 11 Lunar Sciences Conference. pp. 2361- 2367. [db-id.: 243]. [Topics: CELSS; Lunar base; Environment; Geology; Thermal Properties].

[62] Cremers, C.J.. (1972). Thermal Conductivity of Apollo 14 Fines. In: Proceedings of the 3rd Lunar Sciences Conference. Cambridge, MA.: The MIT Press, pp. 2611-2617. [db-id.: 244]. [Topics: CELSS; Lunar base; Geology; Environment; Thermal properties].

[63] Schwartzkopf, S.H., D.G. Kane, R.L. Stempson, (Lockheed-Missiles). (1988 July). Greenhouses and Green Cheese: Use of Lunar resources in CELSS Development. In: SAE-88-1057, 18th Intersociety Conference on Environmental Systems San Francisco. [db- id.: 263]. [Topics: CELSS; Lunar Base; Bioregenerative; Food; Environment; Lunar; Resources; Illumination].

[64] Hypes, W.D., J.B.J.r. Hall. (1988). The Environmental Control and Life Support System for a Lunar Base - What Drives its Design. In: LBS-88-253. [db-id.: 281]. [Topics: CELSS; Lunar Base; Air; Water; Environment].

[65] French, J.R.. (1984 Oct). Nuclear Power Plants for Lunar Bases JPL. In W.W. Mendell (ed): Lunar bases and Space Activities of the 21st Century. Houston: LPI, pp. 99-110. [db-id.: 311]. [Topics: CELSS; Lunar base; Power; Environment].

[66] Burke, J.D.. (1984 Oct). Merits of a Lunar Base Location. In W.W. Mendell, LPI, and NASA (eds): Lunar Bases and Space Activities of the 21st Century. Washington:, pp. 77-84. [db-id.: 314]. [Topics: CELSS; Lunar Base; Environment].

[67] NEALY, J.E., J.W. WILSON, and L.W. TOWNSEND (1988). SOLAR-FLARE SHIELDING WITH REGOLITH AT A LUNAR BASE SITE. NASA TECHNICAL PAPER 2869 2869: 1-18. [db-id.: 315]. [Topics: ENVIRONMENT; RADIATION; SHIELDING; SOLAR FLARES].

<u>2) Power System:</u>

[1] Ray, C.D., W.R. Humphries. (1986). Status of the Space Station Environmental Control and Life Support Systems Design Concept. In: SAE-86-0943. :, pp. 297-308. [db-id.: 23]. [Topics: CELSS; Physiochemical; Control; Environment; Power; Air; Water].

[2] Oniciu, L.. (1976). Fuel Cells. Kent: Abacus Press. [db-id.: 43]. [Topics: CELSS; Physiochemical; Power; Electrolysis; Fuel cells].

[3] Criswell, D.R., R.D. Waldron. (1988 July). Lunar based power systems. Acta Astronautica 17 NO7: 709-716. [db-id.: 177]. [Topics: CELSS; LUNAR BASE; POWER].

[4] System-Development-Corp. (1986 Dec). Lunar Power Systems, Final report. In (ed): NASA-CR-171956, N87-17398, NAS1.26: 171956. p. 324. [db-id.: 231]. [Topics: CELSS; Lunar base; Environment; Power].

[5] Panchyshyn, M., R. Pressentin, B. Trueblood. (1986 Oct). Multimegawatt Nuclear Power System for Lunar Base Application. In: AAS-86-308. 33rd Annual meeting. Aerospace: Century XX1. Boulder, Colorado:. [db-id.: 310]. [Topics: CELSS; Lunar base; Power].

[6] French, J.R.. (1984 Oct). Nuclear Power Plants for Lunar Bases JPL. In W.W. Mendell (ed): Lunar bases and Space Activities of the 21st Century. Houston: LPI, pp. 99-110. [db-id.: 311]. [Topics: CELSS; Lunar base; Power; Environment].

[7] Brandhorst, H.W.. (1987). Space power - Emerging Opportunities. Acta Astronautica 16: 335-342. [db-id.: 312]. [Topics: CELSS; Lunar Base; Power].

[8] Angelo, J.A., D. Buden. (1985). Space Nuclear Power. Malabar, Florida: Orbit Book Company. [db-id.: 313]. [Topics: CELSS; Power; Lunar Base].

<u>3) Atmosphere Management and Regeneration:</u>

[1] Larkins, J.T., R.C. Wagner, M.L. Gopikanth. (1986). A Space Station Utility - Static Feed Electrolyzer. In: SAE-86-0920. pp. 97-107. [db-id.: 1]. [Topics: CELSS; Physiochemical; Air; Water; Carbon Dioxide; Oxygen].

[2] Humphries, W.R., J.L. Reuter, R.G. Schunk. (1986). Space Station Environmental Control and Life Support System Distribution and Loop Closure Studies. In: SAE-86-0942. pp. 285-296. [db-id.: 2]. [Topics: CELSS; Life Sciences; Air; Water; Oxygen; Environment control].

[3] Ray, C.D., W.R. Humphries. (1986). Status of the Space Station Environmental Control and Life Support Systems Design Concept. In: SAE-86-0943. pp. 297-308. [db-id.: 23]. [Topics: CELSS; Physiochemical; Control; Environment; Power; Air; Water].

[4] Boyda, R.B., C.W. Miller, M.R. Schwartz. (1986). Integrated Air Revitalization System for Space Station. In: SAE- 86-0946. pp. 331-343. [db-id.: 46]. [Topics: CELSS; Physiochemical; Air; Carbon Dioxide; Oxygen].

[5] Smernoff, D.T.. (1986). Atmosphere Stabilization and Element Recycle in an Experimental Mouse-Algal System. In: NASA-CR-177402. [db-id.: 54]. [Topics: CELSS; Bioregenerative; Air].

[6] Erickson, A.C., J.F. McElroy. (1986). Space Station Life Support Oxygen Generation by SPE Water Electrolyzer Systems. In: SAE-86-0949. pp. 367-373. [db-id.: 67]. [Topics: CELSS; Physiochemical; Air; Oxygen].

[7] Nitta, K., K. Otsubo. (1986). Gas and Water Recycling System for IOC Vivarium Experiments. In: NASA-TM-88215. CELSS '85 Workshop July 16-19 1985 Moffett Field, CA. NASA-Ames.: NASA, pp. 185-200. [db-id.: 152]. [Topics: CELSS; water; Air; Recycling].

[8] So, K.T., J.B. Hall, C.D. Thompson. (1987,July). Environmental Control and Life Support Systems Analysis for a Space Station Life Sciences Animal Experiment. In: SAE-87-1417, 17th Intersociety Conference, Environmental Systems. Seattle, Washington:. [db-id.: 169]. [Topics: CELSS; Physiochemical; Life Sciences; Air; Water].

[9] Skoog, A.I., A.O. Brouillet. (1981). Trends In Space Life Support. Acta Astronautica, (Pergamon Press Ltd., Great Britain) 8: 1135-1146. [db-id.: 170]. [Topics: CELSS; Bioregenerative; Air; Water; Waste].

[10] Schwartzkopf, S.H., D. Rasmussen. (1987 Sep). Plant Growth Module (PGM) Conceptual Design. In (ed): NASA, Moffett Field, CA. Ames Rese. [db-id.: 185]. [Topics: CELSS; Air; Crop growth; Illumination; Nutrition; Microorganisms].

[11] Averner, M.M., R.D. MacElroy, D.T. Smernoff. (1987 Sep). Development of a Plant Growth Module. In (ed): NASA, Moffett Field, CA. Ames Rese. [db-id.: 186]. [Topics: CELSS; Air flow; Carbon dioxide; Crop growth; Humidity; Irradiation; Nutrition; Oxygen].

[12] Nitta, K.. (1987 Sep). Overview of Japanese CELSS Research Activities. In NASA (ed):. : National Aerospace Lab., Tokyo (Ja. [db-id.: 190]. [Topics: CELSS; Air; Gas recovery; Materials Recovery; Recycling; Water; Treatment; Gravitational Effects].

[13] Otsuji, K., T. Sawada, S. Satoh, S. Kanda, H. Matsumura. (1987 Sep). Preliminary Experimental Results of Gas Recycling Subsystems Except Carbon Dioxide Concentration. In NASA (ed):. : Mitsubishi Heavy Industries Ltd. [db-id.: 194]. [Topics: CELSS; Air purification; Atmospheric composition; Gas exchange; Recycling; Waste Utilization; Bioreactor; Carbon dioxide; concentrati].

[14] Nakhost, Z., M. Karel, V.J. Krukonis. (1987 Sep). Non- Conventional Approaches to Food Processing in CELSS, 1. Algal Proteins: Characterization and Process Optimization. In NASA (ed):. : Massachusetts Inst. of Tech., Camb. [db-id.: 197]. [Topics: CELSS; Air purification; Algae; Food Production; Proteins; Amino; Acids; Biomass; Carbon Dioxide].

[15] Smernoff, D.T., R.A. Wharton, M.M. Averner. (1987 Sep). Operation of an Experimental Algal Gas Exchanger for Use in a CELSS. In (ed): NASA, Moffett Field, CA. Ames Rese. [db-id.: 198]. [Topics: CELSS; Air purification; Algae; Gas exchange; Photosynthesis; Waste Utilization; Atmospheric Composition; Carbon dioxide; removal].

[16] Otsuji, K., M. Hirao, S. Satoh. (1987 June). A Regenerable Carbon Dioxide Removal and oxygen recovery system for the Japanese Experiment Module. Acta Astronautica, (Pergamon Journals Ltd., Great Britain) 15 No 1: 45-54. [db-id.: 226]. [Topics: CELSS; Physiochemical; Air; Carbon Dioxide; Oxygen; Contaminants].

[17] Williams, R.J.. (1985). Oxygen Extraction From Lunar Materials: An Experimental Test of an Ilmenite Reduction Process. In W.W. Mendell (ed): Lunar Bases and Space Activities of the 21st Century. Houston, TX: Lunar and Planetary Institute, pp. 551-558. [db- id.: 229]. [Topics: CELSS; Resources; Air; Oxygen].

[18] (1984 July). CELSS: Life Support Systems in Space Travel. In R.D. MacElroy, D.T. Smernoff, and H.P. Klein (eds): NASA-CR-2378. Topical Session of the XXV Cospar meeting in Graz, Austria. Graz. [db-id.: 247]. [Topics: CELSS; Air; Water; Bioregenerative; Control; Modeling].

[19] Huttenbach, R.C., M.L. Pratt, C. Bucke. (1986). An Evolutionary Approach to the Development of A CELSS Based Air Revitalization System. In: SAE-86-0968. 16th Interdiscip. Conference Environmental Sciences. San Diego, Cal.:, p. 515. [db-id.: 251]. [Topics: CELSS; Bioregenerative; Air; Water; Waste].

[20] Grote, M.G., J.A. Stark, E.C. Tefft III. (1986). Enhanced Evaporative Surface for Two-Phase Mounting Plates. In: SAE-86-0979. SAE Technial Papers Series. pp. 617-626. [db-id.: 252]. [Topics: CELSS; Physiochemical; Air; Dehumidification].

[21] Wydeven, T., NASA-Ames. (1988 Nov). A Survey of Some Regenerative Physio-Chemical Life Support Technology. In: NASA-TM-101004. Moffet Field: NASA-Ames Research Center. [db-id.: 255]. [Topics: CELSS; Physiochemical; Air; Water; Waste; Regeneration; Reclamation; Purification; Contaminants].

[22] Boyda, R.B., S.P. Hendrix. (1986). EDC Development and Testing for the Space Station Program. In: SAE-86-0918. :, pp. 75-86. [db-id.: 256]. [Topics: CELSS; Physiochemical; Air; Carbon Dioxide; Oxygen; Electrochemical].

[23] Noyes, G.P., R.J. Cusick. (1986). An Advanced Carbon Reactor Subsystem for Carbon Dioxide Reduction. In: SAE-86-0995. pp. 761-768. [db-id.: 261]. [Topics: CELSS; Physiochemical; Air; Carbon Dioxide].

[24] Friesen, D.T., J.K. Gienger, D.M. Low, D.D. Newbold, W.A. Pledger, and R.J. Ray (1988 Jan). Investigation of Humidity Control via Membrane Separation Final report to NASA JSC contract no. NAS 9-17641. [db-id.: 265]. [Topics: CELSS; Physiochemical; Water; Membrane; Air; Humidity].

[25] Leiseifer, H.P., A.I. Skoog, H. Preiss, (Dornier-System). (1986). Columbus Life Support System and its Technology Development. In: SAE-86-0966. [db-id.: 274]. [Topics: CELSS; Physiochemical; Air; Water; Waste; Control; Contaminants].

[26] Otsuji, K., O. Hanabusa, T. Sawada, S. Satoh, M. Minemoto, and Mitsubishi-Heavy-Ind (1987). An Experimental Study of the Bosch and the Sabatier CO2 Reduction Processes. In: SAE-87-1517. Warrendale, PA: SAE. [db-id.: 275]. [Topics: CELLS; Physiochemical; Air; Carbon Dioxide; Oxygen Regeneration].

[27] Etoh, T., T. Nihei, K. Otsuji, S. Satoh, S. Hatano. (1987). Experimental Study for a Carbon Dioxide Removal System in Space Station. In: SAE-87-1516. Warrendale, PA: SAE. [db-id.: 276]. [Topics: CELLS; Physiochemical; Air; Carbon Dioxide; Purification].

[28] Preiss, H., W. Breitling, H. Funke, Dornier-System. (1987). Regenerative CO2-Control - A Technology Demand for European Manned Space Programs. In: SAE-87-1515. Warrendale, PA: SAE. [db-id.: 277]. [Topics: CELLS; Physiochemical; Air; Carbon Dioxide; Regeneration].

[29] Yanosy, J.L., L.F. Rowell. (1987). Simulation and Control of a Space Station Air Revitalization System. In: SAE-87- 1425. Warrendale, PA: SAE. [db-id.: 278]. [Topics: CELLS; Physiochemical; Air; Carbon Dioxide; Oxygen; Pressure].

[30] Davis, R.G., J.L. Reuter. (1987). Intermodule Ventilation Studies for the Space Station. In: SAE-87-1428. : SAE. [db-id.: 279]. [Topics: CELSS; Air; Carbon Dioxide; Oxygen].

[31] Lemaignen, L., C. Fagot, M. Weibel. (1986). Physiological Requirements and Pressure Control of a Spaceplane. In: SAE-86-0965. : SAE. [db-id.: 280]. [Topics: CELSS; Air; Pressure; Carbon Dioxide; Oxygen; Nitrogen].

[32] Hypes, W.D., J.B.J.r. Hall. (1988). The Environmental Control and Life Support System for a Lunar Base - What Drives its Design. In: LBS-88-253. [db-id.: 281]. [Topics: CELSS; Lunar Base; Air; Water; Environment].

[33] Colombo, G.V., E.S. Mills. (in 60's?). Regenerative Separation of Carbon Dioxide via Metallic Oxides. In: Chemical Engineering Progress Symposium Series,No. 63, Vol. 62. [db-id.: 282]. [Topics: CELSS; Physiochemical; Air; Carbon Dioxide; Purification; Regeneration].

[34] Sauer, R.L., NASA-Johnson. (1985). Metabolic Support for a Lunar Base. In W.W. Mendell (ed): Lunar Bases and Space Activities for the 21st Century. Houston: Lunar and Planetary Institute, pp. 647-651. [db-id.: 283]. [Topics: CELSS; Lunar base; Air; Waste; Food; Water; Nutrients].

[35] Powell, F.T., M. Sedej, C. Lin. (1987). Environmental Control and Life Support System Requirements and Technology Needs for Advanced Manned Space Missions. In: SAE-87-1433: 17th Intersociety Conference on Environmental Systems. Seattle, Washington:. [db-id.: 284]. [Topics: CELSS; Transportation; Cost; Mission Analysis; Water; Waste; Air; Food].

[36] Fujimori, H., A. Hattori, K. Shiraki. (1987). Environmental Control and Life Support System for Japanese Experiment Module. In: SAE-87-1429, 17th Intersociety Conference on Environmental Systems. Seattle, Washington:. [db-id.: 285]. [Topics: CELSS; Physiochemical; Air; Control; Carbon Dioxide; Oxygen].

[37] Foth, W.P., H. Loeser, MBB-ERNO. (1987). Design and Development of the Life Support Subsystem of a Laboratory Model of the Botany Facility. In: SAE-87-1519: 17 Intersociety Conference Environmental systems. Seattle, Washington:. [db-id.: 288]. [Topics: CELSS; Plant Growth; Air; Physiochemical].

[38] Nitta, K., M. Oguchi, S. Kanda. (1985). CELSS Experiment Model and design Concept of Gas Recycle System. In: SAE-85-1393. [db-id.: 301]. [Topics: CELSS; Bioregenerative; Physiochemical; Air; lunar base].

[39] Miller, C.W., L.S. Kovach, Life-Systems. (). Environmental Control Life Support for the Space Station. In: SAE- 86-0944. [db-id.: 302]. [Topics: CELSS; Physiochemical; Requirements; Air; Water; Waste; Food].

[40] Spina, L., M.C. Lee. (1985). Comparison of CO2 Reduction Process: Bosch and Sabatier. In: SAE-85-1343. [db- id.: 303]. [Topics: CELSS; Physiochemical; Air; Regeneration; Carbon Dioxide].

[41] Boyda, R.B., N. Lance, M. Schwartz. (1985). Electrochemical CO2 Concentration for the Space Station Program. In: SAE-85-1341. [db-id.: 304]. [Topics: CELSS; Physiochemical; Air; Regeneration; Carbon Dioxide].

[42] Colling, A.K., R.J. Cusick, R.P. Reysa. (1985). Development Status of Regenerable Solid Amine CO2 Control Systems. In: SAE-85-1340. [db-id.: 305]. [Topics: CELSS; Physiochemical; Air; Regeneration; Carbon Dioxide].

[43] Larkins, J.T., A.J. Kovach. (1985). Static feed Water Electrolysis System for Space Station O2 and O2 Generation. In: SAE-85-1339. [db-id.: 306]. [Topics: CELSS; Physiochemical; Air; Regeneration; Oxygen; Hydrogen].

[44] Kutschker, A., R.M. Taylor, R.J. Cusick. (1986). Design of an Oxygen Sensor with Automatic Self-Testing and Calibration Capability. In: SAE-86-0919. [db-id.: 307]. [Topics: CELSS; Physiochemical; Air; Control].

[45] Schwartz, M.R., S.I. Oldmark. (1986). Analysis and Composition of a Model Trace Gaseous Mixture for a Spacecraft. In: SAE-86-0917. [db-id.: 308]. [Topics: CELSS; Physiochemical; Air; Contaminants].

[46] Brewer, D.A., J.B. Hall. (1986). Effects of Varying Environmental Parameters on Trace Contaminant Concentrations in the NASA Space Station Reference Configuration. In: SAE-86-0916. [db- id.: 309]. [Topics: CELSS; Physiochemical; Air].

4) Water Recycling:

[1] Larkins, J.T., R.C. Wagner, M.L. Gopikanth. (1986). A Space Station Utility - Static Feed Electrolyzer. In: SAE-86-0920. pp. 97-107. [db-id.: 1]. [Topics: CELSS; Physiochemical; Air; Water; Carbon Dioxide; Oxygen].

[2] Humphries, W.R., J.L. Reuter, R.G. Schunk. (1986). Space Station Environmental Control and Life Support System Distribution and Loop Closure Studies. In: SAE-86-0942. pp. 285-296. [db-id.: 2]. [Topics: CELSS; Life Sciences; Air; Water; Oxygen; Environment control].

[3] Arnold, J.R.. (1979 Sept). Ice in the Lunar Polar Regions. Journal of Geophysical Research, Paper Number 9B0581 84: 5659-5668. [db-id.: 10]. [Topics: CELSS; Lunar Base; Resources; Water; Ice].

[4] Nitta, K., A. Ashida, K. Mitani, K. Ebara, A. Yamada. (1986). Water Recycling System Using Thermo-evaporation Method. In: NASA- TM-88215, CELSS '85 Workshop July 16-19 Moffett Field, CA. : NASA, pp. 201-225. [db-id.: 12]. [Topics: CELSS; Physiochemical; water; recycling; thermo-evaporation].

[5] Ray, C.D., W.R. Humphries. (1986). Status of the Space Station Environmental Control and Life Support Systems Design Concept. In: SAE-86-0943. pp. 297-308. [db-id.: 23]. [Topics: CELSS; Physiochemical; Control; Environment; Power; Air; Water].

[6] Modell, M.. (1986). Supercritical Waste Oxidation of Aqueous Wastes. In: NASA-TM-88215. CELSS:CELSS 1985 Workshop. pp. 227-251. [db-id.: 36]. [Topics: CELSS; Physiochemical; Waste; Water].

[7] Ray, R.. (1985). Membrane-Based Water- and Energy-Recovery Systems for the Manned Space Station. In: SAE-85- 1345. 15th Intersociety Conference on Environmental Systems. [db-id.: 48]. [Topics: CELSS; Physiochemical; Water; Waste; Membrane; Reverse Osmosis].

[8] McCray, S.B., R.J. Ray, C.A. Thornton, D.D. Newbold, H.H. Peters. (1987). Development of a Non-Phase Change Waste-Water Treatment Subsystem. In: SAE-87-1514: 17th Intersociety Conference on Environmental Systems July 13-15, 1987. [db-id.: 49]. [Topics: CELSS; Water; Waste; Membrane; Filtration; Reverse Osmosis; Ultrafiltration].

[9] Slavin, T., F. Liening, M. Oleson, R.L. Olson. (1986). CELSS - Physiochemical Waste Management Systems Evaluation. In: NASA-CR- 177422. [db-id.: 53]. [Topics: CELSS; Physiochemical; Waste; Water].

[10] Sundstrom, D., H. Klei. (1979). Wastewater Treatment. New Jersey: Prentice-Hall, Inc. [db-id.: 57]. [Topics: CELSS; Physiochemical; Waste; Water].

[11] Eckenfelder, W.W.J.r., D.J. O'Connor. (1961). Biological Waste Treatment. New York: Pergamon Press. [db-id.: 75]. [Topics: CELSS; Waste; Water; Bioreactor; Bacteria].

[12] Forster, C.F.. (1985). Biotechnology and Wastewater Treatment. London: Cambridge University Press. [db-id.: 80]. [Topics: CELSS; Bioregenerative; Waste; Water Treatment].

[13] Richardson, M.. (1976). A Correlation Between Microbial Biomass, Process Parameters, and Compost Objectives. Thesis for the Department of Civil, Environmental, and Architectural Engineering, University of Colorado :. [db-id.: 139]. [Topics: CELSS; wastewater processing; microbiology; bioregenerative].

[14] Pike, E., c. Curds. (). The Microbial Ecology of the Activated Sludge Process. Department of the Environment, Water Pollution Research Laboratory England : 123-147. [db-id.: 144]. [Topics: CELSS; bioregenerative; wastewater processing; microbiology].

[15] Ray, R.J., S.E. Retzlaff, L. Radke-Mitchell, D.D. Newbold, D.F. Price. (1986). A Membrane-Based Subsystem for Very High Recoveries of Spacecraft Waste Waters. In: SAE-86-0940: 16th Intersociety Conference on Environmental Systems, San Diego July 14-16, 1986. [db- id.: 145]. [Topics: CELSS; waste water; membrane; reverse osmosis].

[16] Nitta, K., K. Otsubo. (1986). Gas and Water Recycling System for IOC Vivarium Experiments. In: NASA-TM-88215. CELSS '85 Workshop July 16-19 1985 Moffett Field, CA. NASA-Ames.: NASA, pp. 185-200. [db-id.: 152]. [Topics: CELSS; water; Air; Recycling].

[17] McCray, S.B., Bend-Research-Inc. (1988 Aug). Development of a Two-Stage Membrane-Based Wash-Water Reclamation Subsystem. In: Engineering, Construction and Operations in Space. Proceedings of Space 88. pp. 999-1010. [db-id.: 157]. [Topics: CELSS; Lunar base; Physiochemical; Waste Treatment; Water; Reclamation].

[18] Kovach, L.S., E.M. Zdankiewicz. (Dec. 1987). Vapor compression distillation subsystem (VCDS): Component enhancement, testing and expert fault diagnostics development, Final Report, Volume I. In: NASA-CR-172072, N88-28634. [db-id.: 167]. [Topics: CELSS; Physiochemical; Water; Reclamation; Electrolysis].

[19] Heppner, D.B., M. Sudar, M.C. Lee. (1988 June). Advancements in oxygen generation and humidity control by water vapor electrolysis. In: NASA-CR-172073, N88-28633. [db-id.: 168]. [Topics: CELSS; Physiochemical; Water; Electrolysis; oxygen].

[20] So, K.T., J.B. Hall, C.D. Thompson. (1987,July). Environmental Control and Life Support Systems Analysis for a Space Station Life Sciences Animal Experiment. In: SAE-87-1417, 17th Intersociety Conference, Environmental Systems. Seattle, Washington:. [db-id.: 169]. [Topics: CELSS; Physiochemical; Life Sciences; Air; Water].

[21] Skoog, A.I., A.O. Brouillet. (1981). Trends In Space Life Support. Acta Astronautica, (Pergamon Press Ltd., Great Britain) 8: 1135-1146. [db-id.: 170]. [Topics: CELSS; Bioregenerative; Air; Water; Waste].

[22] Wilson, R.G., J.D. Tromblee. (1987). A Dishwasher for the Space Station. In: SAE-87-1411. 17th Intersociety Conference on Environmental Sciences. Seattle:. [db-id.: 176]. [Topics: CELSS; Physiochemical; Water; Food; Processing].

[23] Oleson, M., T. Slavin, F. Liening, R.L. Olson. (1986 Jun). CELSS Physiochemical Waste Management Systems Evaluation. In NASA-HQ (ed): NASA-CR-177422, NAS 1.26:177422, BAC-

37, NAS2-11806. Washington: Boeing Aerospace Co., Seattle, WA. [db-id.: 183]. [Topics: CELSS; Physiochemical; Waste Treatment; Water Treatment; Evaporation; Incineration].

[24] Nitta, K.. (1987 Sep). Overview of Japanese CELSS Research Activities. In NASA (ed):. : National Aerospace Lab., Tokyo (Ja. [db-id.: 190]. [Topics: CELSS; Air; Gas recovery; Materials Recovery; Recycling; Water; Treatment; Gravitational Effects].

[25] MacElroy, R.D., N.V. Martello, D.T. Smernoff. (1986 Jan). CELSS 1985 Workshop. In: NASA-TM-88215, NAS 1.15:88215, A-86132. : NASA, Moffett Field, CA. Ames Rese. [db-id.: 212]. [Topics: CELSS; Plant; Algae; Bioreactor; Microorganism; Photosynthesis;; Waste Utilization; Water treatment].

[26] Tibbitts, T.W., R.M. Wheeler. (1984 Nov). CELSS Higher Plant Flight Experiments. In NASA (ed): NASA-CR-177323, NAS 1. 26:177323. : Wisconsin Univ.-Madison. [db-id.: 216]. [Topics: CELSS; Crop growth; Plant Growth; Microgravity; Water].

[27] (1986 Apr). CELSS Experiment Concepts of Space Station Missions. In: MS/SS-02-REV-1-CELSS. : CELSS Experiment Concept Study Gro. [db-id.: 218]. [Topics: CELSS; Waste Treatment; Water Treatment; Ecology; Gases;; Recovery; Agriculture].

[28] (1981 Dec). Development of a Prototype Experiment for Treating CELSS and PCELSS Wastes to Produce Nutrients for Plant Growth. Final Report. In NASA (ed): NASA-CR-173167. NAS1.26: 173167. : Massachusetts Inst. of Tech., Camb. [db-id.: 219]. [Topics: CELSS; Waste water; Chemical Treatment; Food Processing; High; Temperature; Mass Transfer; Oxidation; Permittivity].

[29] (1984 July). CELSS: Life Support Systems in Space Travel. In R.D. MacElroy, D.T. Smernoff, and H.P. Klein (eds): NASA-CR-2378. Topical Session of the XXV Cospar meeting in Graz, Austria. Graz:. [db-id.: 247]. [Topics: CELSS; Air; Water; Bioregenerative; Control; Modeling].

[30] Hong, G.T., P.K. Fowler, W.R. Killilea, K.C. Swallow, (MODAR-Inc). (1987 July). Supercritical Water Oxidation: Treatment of Human waste and System Configuration Trade-off Study. In: SAE-87-1444. 17th Intersociety Conference on Environmental Systems. Seattle, Wa.:. [db-id.: 248]. [Topics: CELSS; Physiochemical; Water Treatment; Waste Treatment; Oxidation].

[31] Dehner, G.F., D.F. Price, Hamilton-Standard. (1987 July). Thermoelectric Integrated Membrane Evaporation Subsystem Testing. In: SAE-87-1446. 17th Intersociety Conference on Environmental Systems. Seattle, Wa.:. [db-id.: 249]. [Topics: CELSS; Physiochemical; Water Treatment; Evaporation].

[32] Loser, H.R.. (1986). Life Support Subsystem Concepts for Botanical Experiments of Long Duration. In: SAE-86- 0967. pp. 499-514. [db-id.: 250]. [Topics: CELSS; life sciences; Biophysics; Plants; Carbon Dioxide; Oxygen; Water].

[33] Huttenbach, R.C., M.L. Pratt, C. Bucke. (1986). An Evolutionary Approach to the Development of A CELSS Based Air Revitalization System. In: SAE-86-0968. 16th Interdiscip. Conference Environmental Sciences. San Diego, Cal.:, p. 515. [db-id.: 251]. [Topics: CELSS; Bioregenerative; Air; Water; Waste].

[34] Putnam, D.F., G.V. Colombo. (1986). Pre- and Post- Treatment Techniques for Spacecraft Water Recovery. In: SAE-86- 0982. pp. 627-634. [db-id.: 253]. [Topics: CELSS; Physiochemical; Water; Waste].

[35] Budininkas, P., F. Rasoull, T. Wydeven. (1986). Development of a Water Recovery Subsystem Based on Vapor Phase Catalytic Ammonia Removal (VPCAR). In: SAE-86-0985. pp. 661-667. [db- id.: 254]. [Topics: CELSS; Physiochemical; Water; Waste; Oxidation].

[36] Wydeven, T., NASA-Ames. (1988 Nov). A Survey of Some Regenerative Physio-Chemical Life Support Technology. In: NASA-TM-101004. Moffet Field: NASA-Ames Research Center. [db-id.: 255]. [Topics: CELSS; Physiochemical; Air; Water; Waste; Regeneration; Reclamation; Purification; Contaminants].

[37] Zdankiewicz, E.M., J. Chu. (1986). Phase Change Water Recovery for Space Station-Parametric Testing Analysis. In: SAE-86-0986. pp. 669-679. [db-id.: 257]. [Topics: CELSS; Physiochemical; Water; Phase Change recovery].

[38] Morasko, G., D.F. Putnam, R. Bagdigian. (1986). Air Evaporation Closed Cycle Water Recovery Technology - Advanced Energy Saving Designs. In: SAE-86-0987. pp. 681-690. [db-id.: 258]. [Topics: CELSS; Physiochemical; Water; Evaporation].

[39] Hall Jr, J.B., D.A. Brewer. (1986). Supercritical Water Oxidation: Concept Analysis for Evolutionary Space Station Application. In: SAE-86-0993al Paper Series. pp. 733-745. [db- id.: 259]. [Topics: CELSS; Physiochemical; Water; Oxidation].

[40] Murray, R.W., R.L. Sauer. (1986). Integrated Waste and Water Management System. In: SAE-86-0996. pp. 769-774. [db-id.: 262]. [Topics: CELSS; Physio-chemical; Water; Waste; distillation; Oxidation].

[41] Hong, G.T., P.K. Fowler, W.R. Killilea, K.C. Swallow. (1987). Supercritical Water Oxidation: Treatment of Human Waste and System Configuration Trade-off Study. [db-id.: 264]. [Topics: CELSS; Physiochemical; Water; Oxidation; Waste].

[42] Friesen, D.T., J.K. Gienger, D.M. Low, D.D. Newbold, W.A. Pledger, and R.J. Ray (1988 Jan). Investigation of Humidity Control via Membrane Separation Final report to NASA JSC contract no. NAS 9-17641. [db-id.: 265]. [Topics: CELSS; Physiochemical; Water; Membrane; Air; Humidity].

[43] Clifford, D., T.J. Sorg. (1986). Removing dissolved inorganic contaminants from water. Environmental Science and Technology 20: 1072-1079. [db-id.: 270]. [Topics: CELSS; Physiochemical; Water; Contaminants; Inorganics].

[44] Leiseifer, H.P., A.I. Skoog, H. Preiss, (Dornier-System). (1986). Columbus Life Support System and its Technology Development. In: SAE-86-0966. [db-id.: 274]. [Topics: CELSS; Physiochemical; Air; Water; Waste; Control; Contaminants].

[45] Hypes, W.D., J.B.J.r. Hall. (1988). The Environmental Control and Life Support System for a Lunar Base - What Drives its Design. In: LBS-88-253. [db-id.: 281]. [Topics: CELSS; Lunar Base; Air; Water; Environment].

[46] Sauer, R.L., NASA-Johnson. (1985). Metabolic Support for a Lunar Base. In W.W. Mendell (ed): Lunar Bases and Space Activities for the 21st Century. Houston: Lunar and Planetary Institute, pp. 647-651. [db-id.: 283]. [Topics: CELSS; Lunar base; Air; Waste; Food; Water; Nutrients].

[47] Powell, F.T., M. Sedej, C. Lin. (1987). Environmental Control and Life Support System Requirements and Technology Needs for Advanced Manned Space Missions. In: SAE-87-1433: 17th Intersociety Conference on Environmental Systems. Seattle, Washington:. [db-id.: 284]. [Topics: CELSS; Transportation; Cost; Mission Analysis; Water; Waste; Air; Food].

[48] Small, J.W., A.T. Linden, C.E. Versotko, R. Burchett. (1987). Recent Developments in Water Quality Monitoring for Space Station Reclaimed Wastewaters. In: SAE-87-1447: 17th International Conference on Environmental Systems, Seattle, WA July 13-15 1987. [db- id.: 291]. [Topics: CELSS; Physiochemical; waste water; treatment].

[49] Fortunato, F.A., K.A. Burke, Life-Systems-Inc. (987). Static Feed Electrolyzer Technology Advancement for Space Application. In: SAE-87-1450. 17th Intersociety Conference on Environmental Systems, Seattle WA July 13-15, 1987. [db-id.: 292]. [Topics: CELSS; physiochemical; water treatment; electrolysis].

[50] Erickson, A.C., M.C. Puskar, J.A. Zagaja, P.S. Miller. (1987). Performance Evaluation of SPE Electrolyzer for Space Station Life Support. In: SAE-87-1451. 17th Intersociety Conference on Environmental Systems Seattle WA July 13-15, 1987. [db-id.: 293]. [Topics: CELSS; physiochemical; water; electrolysis].

[51] Johnson, C.C., D. Rasmussen, G. Curran. (1987). Water Management Requirements for Animal and Plant Maintenance on the Space Station. In: SAE-87-1469. 17th Intersociety Conference on Environmental Systems Settle WA July 13-15, 1987. [db-id.: 294]. [Topics: CELSS; water; requirements].

[52] Nason, J.R., P.G. Tremblay. (1987 July). High Pressure Water Electrolysis for the Space Station. In: SAE-87- 1473, 17th Intersociety Conference on Environmental Systems Seattle, WA July 13-15, 1987. [db-id.: 295]. [Topics: CELSS; water; electrolysis].

[53] McFeters, G.A., B.H. Pyle. (1987 July). Consequences of Bacterial Resistance to Disinfection by Iodine in Potable Water. In: SAE-87-1489, 17th Intersociety Conference on Environmental Systems Seattle, WA July 13-15, 1987. [db-id.: 296]. [Topics: CELSS; water; treatment; iodine disinfection].

[54] Sauer, R.L., D.S. Janik, Y.R. Thorstenson. (1987 July). Medical Effects of Iodine Disinfection Products in Spacecraft Water. In: SAE-87-1490, 17th Intersociety Conference in Environmental Systems Seattle, WA July 13-15, 1987. [db-id.: 297]. [Topics: CELSS; water; iodine treatment].

[55] Bull, R.J.. (1987 July). Toxicological Aspects of Water Recycle and Disinfection. In: SAE-87-1491, 17th Intersociety Conference on Environmental Systems Seattle, WA July 13-15, 1987. [db-id.: 298]. [Topics: CELSS; water; recycle].

[56] Janauer, G.E., T.W. Fitzpatrick, M.B. Krill, G.A. Wilber, R.L. Sauer. (1987 July). Treatment Bed Microbiological Control. In: SAE-87-1492, 17th Intersociety Conference on Environmental Systems Seattle, WA July 13-15, 1987. [db-id.: 299]. [Topics: CELSS; Water; Treatment; Microbiological control].

[57] Wachinski, A.M.. (1988 Aug). Waste Management: Project Mercury to the Space Station. In: Engineering, Construction and Operations in Space. Proceedings of Space 1988. Albuquerque, New Mex., pp. 1011-1021. [db-id.: 300]. [Topics: CELSS; Physiochemical; Waste; Water].

[58] Miller, C.W., L.S. Kovach, Life-Systems. (). Environmental Control Life Support for the Space Station. In: SAE- 86-0944. [db-id.: 302]. [Topics: CELSS; Physiochemical; Requirements; Air; Water; Waste; Food].

5) Waste Processing:

[1] (1982). Microbial Interactions and Communities. New York: Academic Press. [db-id.: 34]. [Topics: CELSS; Bioregenerative; Bioreactor; Waste].

[2] Mitchell, R.. (1974). Introduction to Environmental Microbiology. New Jersey: Prentice-Hall, Inc. [db-id.: 35]. [Topics: CELSS; Bioregenerative; Bacteria; Microorganism; Waste].

[3] Modell, M.. (1986). Supercritical Waste Oxidation of Aqueous Wastes. In: NASA-TM-88215. CELSS:CELSS 1985 Workshop. pp. 227-251. [db-id.: 36]. [Topics: CELSS; Physiochemical; Waste; Water].

[4] Moo-Young, M., H. Blanch. (1981). Design for Biochemical Reactors - Mass Transfer Criteria for Simple and Complex Systems. Advances in Biochemical Engineering 19: 1-70. [db-id.: 37]. [Topics: CELSS; Bioregenerative; Waste; Bioreactor].

[5] Ray, R.. (1985). Membrane-Based Water- and Energy-Recovery Systems for the Manned Space Station. In: SAE-85- 1345. 15th Intersociety Conference on Environmental Systems. [db-id.: 48]. [Topics: CELSS; Physiochemical; Water; Waste; Membrane; Reverse Osmosis].

[6] McCray, S.B., R.J. Ray, C.A. Thornton, D.D. Newbold, H.H. Peters. (1987). Development of a Non-Phase Change Waste-Water Treatment Subsystem. In: SAE-87-1514: 17th Intersociety Conference on Environmental Systems July 13-15, 1987. [db-id.: 49]. [Topics: CELSS; Water; Waste; Membrane; Filtration; Reverse Osmosis; Ultrafiltration].

[7] Slavin, T., F. Liening, M. Oleson, R.L. Olson. (1986). CELSS - Physiochemical Waste Management Systems Evaluation. In: NASA-CR- 177422. [db-id.: 53]. [Topics: CELSS; Physiochemical; Waste; Water].

[8] Sundstrom, D., H. Klei. (1979). Wastewater Treatment. New Jersey: Prentice-Hall, Inc. [db-id.: 57]. [Topics: CELSS; Physiochemical; Waste; Water].

[9] Wydeven, T., J. Temor, C. Koo, R. Jacquez. (1988). Sources and Processing of CELSS Wastes. [db-id.: 68]. [Topics: CELSS; LCELSS; waste processing; bioregenerative; physio-chemical; bioreactor].

[10] Aaronson, S.. (1981). Chemical Communication at the Microbial Level CRC Vol. 1 and 2. Florida: CRC Press. [db-id.: 69]. [Topics: CELSS; Bioregenerative; Bioreactor; Waste].

[11] Adler-Nissan, J., B.O. Eggum, L. Munk, H.J. Olsen. (1977). Biochemical Aspects of New Protein Food. Copenhagen: Pergamon Press. [db- id.: 70]. [Topics: CELSS; Bioregenerative; Food; Waste].

[12] Bailey, J., D. Ollis. (1986). Biochemical Engineering Fundamentals. New York: McGraw Hill Book Co. [db-id.: 71]. [Topics: CELSS; Waste; Bioreactor].

[13] Beal, V.. (1980). Nutrition in the Life Span. New York: John Wiley and Sons. [db-id.: 72]. [Topics: CELSS; Food; Waste].

[14] Breed, R.S., E.G.D. Murray, N.R. Smith. (1957). Bergey's Manual of Determinative Bacteriology. Baltimore: The Williams and Wilkins Co. [db-id.: 73]. [Topics: CELSS; Waste; Bacteria; Bioreactor].

[15] Brock, T.. (1966). Principles of Microbial Ecology. New Jersey: Prentice-Hall, Inc. [db-id.: 74]. [Topics: CELSS; Bioregenerative; Waste].

[16] Eckenfelder, W.W.J.r., D.J. O'Connor. (1961). Biological Waste Treatment. New York: Pergamon Press. [db-id.: 75]. [Topics: CELSS; Waste; Water; Bioreactor; Bacteria].

[17] Faust, S., J. Hunter. (1971). Organic Compounds in Aquatic Environments. New York: Marcel Dekker, Inc. [db-id.: 76]. [Topics: CELSS; Waste; Bioregenerative].

[18] Feichter, A.. (1985). Advances in Biochemical Engineering/ Biotechnology vol 6,10,11, 14,17,19,20,27,29,32. New York: Springer-Verlag. [db-id.: 77]. [Topics: CELSS; Waste; Bioregenerative].

[19] Fogg, G.E.. (1975). Algal Cultures and Phytoplankton Ecology 2nd edition. Madison: University of Wisconsin Press. [db-id.: 78]. [Topics: CELSS; Waste; Algae; Bioregenerative].

[20] Fogg, G.E., W.D.P. Stewart, P. Fay, A.E. Walsby. (1973). The Blue-Green Algae. New York: Academic Press. [db-id.: 79]. [Topics: CELSS; Bioregenerative; Waste; Algae].

[21] Forster, C.F.. (1985). Biotechnology and Wastewater Treatment. London: Cambridge University Press. [db-id.: 80]. [Topics: CELSS; Bioregenerative; Waste; Water Treatment].

[22] Ghose, T.K., A. Fiechter, N. Blakebrough. (1974). Advances in Biochemical Engineering. New York: Springer-Verlag. [db-id.: 81]. [Topics: CELSS; Bioregenerative; Waste].

[23] Hills, C., H. Nakamura. (1978). Food From Sunlight, World Hunger Research Project. Boulder Creek,Ca.: University of the Trees Press. [db-id.: 82]. [Topics: CELSS; Bioregenerative; Food; Waste].

[24] (1978). Human Nutrition Readings From Scientific American. San Francisco: W.H. Freeman and Company. [db-id.: 83]. [Topics: CELSS; Bioregenerative; Food; Waste].

[25] Jackson, D.F.. (1967). Algae, Man, and the Environment. New York: Syracuse University Press. [db-id.: 85]. [Topics: CELSS; Bioregenerative; Algae; Waste].

[26] Laskin, A.I., H.A. Lechavelier. (1973). CRC Handbook of Microbiology, Vol 2 Microbial Composition. Cleveland: CRC Press. [db- id.: 86]. [Topics: CELSS; Bioregenerative; Waste].

[27] Levring, T., H.A. Hoppe, O.J. Schmid. (1969). Marine Algae, A Survey of Research and Utilization. Hamburg: Cram,DeGruyter, and Co. [db-id.: 87]. [Topics: CELSS; Bioregenerative; Waste; Algae].

[28] Marshall, K.C.. (1976). Interfaces in Microbial Ecology. London: Harvard University Press. [db-id.: 88]. [Topics: CELSS; Bioregenerative; Waste].

[29] (1982). Microbial Interactions and Communities. New York: Academic Press. [db-id.: 89]. [Topics: CELSS; Bioregenerative; Waste].

[30] Schlegel, H.G., J. Barnea. (1977). Microbial Energy Conversion. New York: Pergamon Press. [db-id.: 90]. [Topics: CELSS; Bioregenerative; Waste].

[31] Spector, W.S.. (1956). Handbook of Biological Data. Philadelphia: W.B. Saunders Company. [db-id.: 91]. [Topics: waste].

[32] Fan, L., H. Lee, D. Beardmore. (1980). Major Chemical and Physical Features of Cellulosic Materials. In A. Fiechter (ed): Advances in Biochemical Engineering. New York: Springer-Verlag, pp. 101- 118. [db-id.: 136]. [Topics: CELSS; Waste; Cellulose].

[33] Hungate, R.. (1966). The Rumen and its Microbes. New York: Academic Press. [db-id.: 137]. [Topics: CELSS; microbiology; Cellulose; Waste].

[34] Doelle, H., K. Ewings, N. Hollywood. (1982). Regulation of Glucose Metabolism in Bacterial Systems. In A. Feichter (ed): Advances in Biochemical Engineering. New York: Springer-Verlag, pp. 1- 36. [db-id.: 138]. [Topics: CELSS; microbiology; Bacteria; WAste].

[35] Richardson, M.. (1976). A Correlation Between Microbial Biomass, Process Parameters, and Compost Objectives. Thesis for the Department of Civil, Environmental, and Architectural Engineering, University of Colorado :. [db-id.: 139]. [Topics: CELSS; wastewater processing; microbiology; bioregenerative].

[36] Pike, E., c. Curds. (). The Microbial Ecology of the Activated Sludge Process. Department of the Environment, Water Pollution Research Laboratory England : 123-147. [db-id.: 144]. [Topics: CELSS; bioregenerative; wastewater processing; microbiology].

[37] Ray, R.J., S.E. Retzlaff, L. Radke-Mitchell, D.D. Newbold, D.F. Price. (1986). A Membrane-Based Subsystem for Very High Recoveries of Spacecraft Waste Waters. In: SAE-86-0940: 16th Intersociety Conference on Environmental Systems, San Diego July 14-16, 1986. [db- id.: 145]. [Topics: CELSS; waste water; membrane; reverse osmosis].

[38] Banks, G., S. Rose, University-of-Colorado. (1988). A Phased Approach to the Evolution of CELSS for Long- Term Space Habitation. [db-id.: 147]. [Topics: CELSS; Lunar-base; Bioregenerative; waste; bacteria; algae].

[39] McCray, S.B., Bend-Research-Inc. (1988 Aug). Development of a Two-Stage Membrane-Based Wash-Water Reclamation Subsystem. In: Engineering, Construction and Operations in Space. Proceedings of Space 88. pp. 999-1010. [db-id.: 157]. [Topics: CELSS; Lunar base; Physiochemical; Waste Treatment; Water; Reclamation].

[40] Meyer-Sedej, M., NASA-JSC. (1988 Aug). Implementing Supercritical Water-Oxidation Technology in a Lunar Base Environmental Life Support System. In: Engineering, Construction and Operations in Space. Proceedings of Space 88. Albuquerque, New Mex., pp. 653-661. [db-id.: 159]. [Topics: CELSS; Lunar-base; Physio-chemical; Waste Treatment].

[41] Skoog, A.I., A.O. Brouillet. (1981). Trends In Space Life Support. Acta Astronautica, (Pergamon Press Ltd., Great Britain) 8: 1135-1146. [db-id.: 170]. [Topics: CELSS; Bioregenerative; Air; Water; Waste].

[42] (1988 Mar). Regenerative Life Support System Research. Progress Report, September 1987-March 1988. In NASA-HQ (ed): NASA-CR-182606, NAS 1.26:182606, SRC-4-5873. Washington: Texas A and M Univ., College Stati. [db-id.: 180]. [Topics: CELSS; Algae; Food Production; Regeneration; Plant Growth; Food; Processing; Lunar base; Waste treatment].

[43] Oleson, M., T. Slavin, F. Liening, R.L. Olson. (1986 Jun). CELSS Physiochemical Waste Management Systems Evaluation. In NASA-HQ (ed): NASA-CR-177422, NAS 1.26:177422, BAC-37, NAS2-11806. Washington: Boeing Aerospace Co., Seattle, WA. [db-id.: 183]. [Topics: CELSS; Physiochemical; Waste Treatment; Water Treatment; Evaporation; Incineration].

[44] Oleson, M., R.L. Olson. (Jun 86). CELSS Conceptual Design Option Study. In NASA (ed): NASA-CR-172421, NAS 1.26:172421, NAS2-11806. Washington: Boeing Aerospace Co., Seattle, WA. [db-id.: 184]. [Topics: CELSS; Contaminants; Plant Growth; Illuminating; Lunar base; Waste treatment].

[45] Takahashi, Y., K. Nitta, H. Ohya, M. Oguchi. (1987 Sep). Applicability of the Catalytic Wet-Oxidation to CELSS. In NASA (ed):. : Niigata Univ. (Japan). Dept. of Ci. [db-id.: 192]. [Topics: CELSS; Waste Treatment; Physiochemical; Oxidation; Biorecator; Nitrogenation; Gasification; Catalysis].

[46] Otsuji, K., T. Sawada, S. Satoh, S. Kanda, H. Matsumura. (1987 Sep). Preliminary Experimental Results of Gas Recycling Subsystems Except Carbon Dioxide Concentration. In NASA (ed):. : Mitsubishi Heavy Industries Ltd. [db-id.: 194]. [Topics: CELSS; Air purification; Atmospheric composition; Gas exchange; Recycling; Waste Utilization; Bioreactor; Carbon dioxide; concentrati].

[47] MacElroy, R.D., J. Tremor, D.T. Smernoff, W. Knott, R.P. Prince. (1987 Sep). Review of Recent Activities in the NASA CELSS Program. In (ed): NASA, Moffett Field, CA. Ames Rese. [db-id.: 195]. [Topics: CELSS; Food Production; Oxygen production; Photosynthesis; Waste; Utilization; Cellulose; Extraterrestrial radiation; Gravitational Effects].

[48] Smernoff, D.T., R.A. Wharton, M.M. Averner. (1987 Sep). Operation of an Experimental Algal Gas Exchanger for Use in a CELSS. In (ed): NASA, Moffett Field, CA. Ames Rese. [db-id.: 198]. [Topics: CELSS; Air purification; Algae; Gas exchange; Photosynthesis; Waste Utilization; Atmospheric Composition; Carbon dioxide; removal].

[49] (1987 June). Publications of the NASA CELSS Program 1984-86. In NASA (ed): NASA-CR-4070. NAS1.26:4070. : George Washington Univ., Washingto. [db-id.: 206]. [Topics: CELSS; Life support systems; Food Processing; Food Production; Nutrition; Waste treatment; Bibliographies].

[50] MacElroy, R.D.. (1986 May). CELSS and Regenerative Life Support for Manned Missions to MARS. In (ed): NASA, Moffett Field, CA. Ames Rese. [db-id.: 209]. [Topics: CELSS; Atmosphere Composition; Biomass; Ecosystem;; Photosynthesis; Waste disposal].

[51] MacElroy, R.D., N.V. Martello, D.T. Smernoff. (1986 Jan). CELSS 1985 Workshop. In (ed): NASA-TM-88215, NAS 1.15:88215, A-86132. : NASA, Moffett Field, CA. Ames Rese. [db-id.: 212]. [Topics: CELSS; Plant; Algae; Bioreactor; Microorganism; Photosynthesis;; Waste Utilization; Water treatment].

[52] Dufour, P.A., J.L. Solberg, J.S. Wallace. (1985 Jul). Publications of the NASA CELSS Program. In NASA (ed): NASA-CR-3911, NAS 1.26:3911. : George Washington Univ., Washingto. [db-id.: 214]. [Topics: CELSS; Bibliographies; Plant Growth; Waste Treatment; Algae; Food; Nutrition; Recycling].

[53] (1986 Apr). CELSS Experiment Concepts of Space Station Missions. In: MS/SS-02-REV-1-CELSS. : CELSS Experiment Concept Study Gro. [db-id.: 218]. [Topics: CELSS; Waste Treatment; Water Treatment; Ecology; Gases;; Recovery; Agriculture].

[54] (1981 Dec). Development of a Prototype Experiment for Treating CELSS and PCELSS Wastes to Produce Nutrients for Plant Growth. Final Report. In NASA (ed): NASA-CR-173167. NAS1.26: 173167. : Massachusetts Inst. of Tech., Camb. [db-id.: 219]. [Topics: CELSS; Waste water; Chemical Treatment; Food Processing; High; Temperature; Mass Transfer; Oxidation; Permittivity].

[55] Wydeven, T.. (1983 Sep). Composition and Analysis of a Model Waste for a Celss. In: NASA-TM-84368, NAS 1. 15:84368, A-9350. : NASA, Moffett Field, CA. Ames Rese. [db-id.: 220]. [Topics: CELSS; Human wastes; Waste Treatment; Chemical Analysis;; Chemical Composition; Vegetables].

[56] Hong, G.T., P.K. Fowler, W.R. Killilea, K.C. Swallow, (MODAR-Inc) (1987 July). Supercritical Water Oxidation: Treatment of Human waste and System Configuration Trade-off Study. In: SAE-87-1444. 17th Intersociety Conference on Environmental Systems. Seattle, Wa.:. [db-id.: 248]. [Topics: CELSS; Physiochemical; Water Treatment; Waste Treatment; Oxidation].

[57] Huttenbach, R.C., M.L. Pratt, C. Bucke. (1986). An Evolutionary Approach to the Development of A CELSS Based Air Revitalization System. In: SAE-86-0968. 16th Interdiscip. Conference

Environmental Sciences. San Diego, Cal.:, p. 515. [db-id.: 251]. [Topics: CELSS; Bioregenerative; Air; Water; Waste].

[58] Putnam, D.F., G.V. Colombo. (1986). Pre- and Post- Treatment Techniques for Spacecraft Water Recovery. In: SAE-86- 0982. pp. 627-634. [db-id.: 253]. [Topics: CELSS; Physiochemical; Water; Waste].

[59] Budininkas, P., F. Rasoull, T. Wydeven. (1986). Development of a Water Recovery Subsystem Based on Vapor Phase Catalytic Ammonia Removal (VPCAR). In: SAE-86-0985. pp. 661-667. [db- id.: 254]. [Topics: CELSS; Physiochemical; Water; Waste; Oxidation].

[60] Wydeven, T., NASA-Ames. (1988 Nov). A Survey of Some Regenerative Physio-Chemical Life Support Technology. In: NASA-TM-101004. Moffet Field: NASA-Ames Research Center. [db-id.: 255]. [Topics: CELSS; Physiochemical; Air; Water; Waste; Regeneration; Reclamation; Purification; Contaminants].

[61] Murray, R.W., R.L. Sauer. (1986). Integrated Waste and Water Management System. In (ed): SAE-86-0996. pp. 769-774. [db-id.: 262]. [Topics: CELSS; Physio-chemical; Water; Waste; distillation; Oxidation].

[62] Hong, G.T., P.K. Fowler, W.R. Killilea, K.C. Swallow. (1987). Supercritical Water Oxidation: Treatment of Human Waste and System Configuration Trade-off Study. [db-id.: 264]. [Topics: CELSS; Physiochemical; Water; Oxidation; Waste].

[63] Schoonover, M.W., R.A. Madsen. (1986 July). Catalytic Processes for Space Station Waste Conversion. In: NASA- CR-177423. [db-id.: 266]. [Topics: CELSS; Physiochemical; Waste; Oxidation].

[64] Lawler, D.F.. (1986). Removing particles in water and wastewater. Environmental Science and Technology 20: 856-861. [db-id.: 268]. [Topics: CELSS; Physiochemical; Waste; Contaminants].

[65] Weber, W.J.. (1986). Removing dissolved organic contaminants from water. Environmental Science and Technology 20: 970- 979. [db-id.: 269]. [Topics: CELSS; Physiochemical; Waste; Organic waste].

[66] McCarty, P.L., D.P. Smith. (1986). Anaerobic wastewater treatment. Environmental Science and Technology 20: 1200-1206. [db-id.: 271]. [Topics: CELSS; Bioregenerative; Waste; Bioreactor; Cellulose; Liquid waste; Solid waste; Waste treatment].

[67] Jewell, W.J.. (1987). Anaerobic sewage treatment. Environmental Science and Technology 21: 14-21. [db-id.: 272]. [Topics: CELSS; Bioregenerative; Waste; Bioreactor; Cellulose; Organic waste; Solid waste; Waste treatment].

[68] Rittmann, B.E.. (1987). Aerobic biological treatment. Environmental Science and Technology 21: 128-136. [db-id.: 273]. [Topics: CELSS; Bioregenerative; Waste; Bacteria; Bioreactor; Waste; treatment].

[69] Leiseifer, H.P., A.I. Skoog, H. Preiss, (Dornier-System). (1986). Columbus Life Support System and its Technology Development. In: SAE-86-0966. [db-id.: 274]. [Topics: CELSS; Physiochemical; Air; Water; Waste; Control; Contaminants].

[70] Sauer, R.L., NASA-Johnson. (1985). Metabolic Support for a Lunar Base. In W.W. Mendell (ed): Lunar Bases and Space Activities for the 21st Century. Houston: Lunar and Planetary Institute, pp. 647-651. [db-id.: 283]. [Topics: CELSS; Lunar base; Air; Waste; Food; Water; Nutrients].

[71] Powell, F.T., M. Sedej, C. Lin. (1987). Environmental Control and Life Support System Requirements and Technology Needs for Advanced Manned Space Missions. In: SAE-87-1433: 17th Intersociety Conference on Environmental Systems. Seattle, Washington:. [db-id.: 284]. [Topics: CELSS; Transportation; Cost; Mission Analysis; Water; Waste; Air; Food].

[72] Small, J.W., A.T. Linden, C.E. Versotko, R. Burchett. (1987). Recent Developments in Water Quality Monitoring for Space Station Reclaimed Wastewaters. In: SAE-87-1447: 17th International Conference on Environmental Systems, Seattle, WA July 13-15 1987. [db- id.: 291]. [Topics: CELSS; Physiochemical; waste water; treatment].

[73] Wachinski, A.M.. (1988 Aug). Waste Management: Project Mercury to the Space Station. In: Engineering, Construction and Operations in Space. Proceedings of Space 1988. Albuquerque, New Mex., pp. 1011-1021. [db-id.: 300]. [Topics: CELSS; Physiochemical; Waste; Water].

[74] Miller, C.W., L.S. Kovach, Life-Systems. Environmental Control Life Support for the Space Station. In: SAE- 86-0944. [db-id.: 302]. [Topics: CELSS; Physiochemical; Requirements; Air; Water; Waste; Food].

6) Food Production in a CELSS:

[1] Ballou, E.V.. (1982 Mar). Mineral Separation and Recycling in a CELSS. In: NASA-CR-166388, NCC 2-53. [db-id.: 4]. [Topics: CELSS; Bioregenerative; Food; Nutrients; Plant Growth].

[2] Bugbee, B., F.B. Salisbury. (1988). Space Farming in the 21st Century. 21st Century : 32-40. [db-id.: 5]. [Topics: CELSS; Food production; LCELSS; Artificial environment; Plant; Diversity; Yield; Crop physiology].

[3] Hoff, J.E., J.M. Howe, C.A. Mitchell. (1982). Nutritional and Cultural Aspects of Plant Species Selection for a Controlled Ecological Life Support System. In: NASA-CR-166324, NASA Grants NSG-2401 and 2404. [db-id.: 17]. [Topics: CELSS; Bioregenerative; Food].

[4] Karel, M.. (1982). Evaluation of Engineering Foods for Controlled Ecological Life Support Systems. In: NASA-CR- 166359. [db-id.: 20]. [Topics: CELSS; Bioregenerative; Food].

[5] Karel, M., A.R. Kamarei. (1984). Feasibility of Producing a Range of Food Products from a Limited Range of Undifferentiated Major Food Components. In: NASA-CR-177329. [db-id.: 21]. [Topics: CELSS; Bioregenerative; Food].

[6] Karel, M., Z. Nakhost. (1986). Utilization of Non- Conventional Systems for Conversion of Biomass To Food Components. In: NASA-CR-177449. [db-id.: 22]. [Topics: CELSS; Bioregenerative; Food].

[7] MacElroy, R., N. Martello, D. Smernoff. (1986). CELSS: CELSS '85 Workshop. In: NASA-TM-88215. [db-id.: 27]. [Topics: CELSS; Bioregenerative; Food; Physiochemical].

[8] MacElroy, R.D., D.T. Smernoff, J.D. Rummel. (1987). CELSS: Design, Development, and Use of a Ground-Based Plant Growth Module. In: NASA-CP-2479. [db-id.: 31]. [Topics: CELSS; Bioregenerative; Food].

[9] Raper, C.. (1982). Plant Growth in Controlled Environments in Response to Characteristics of Nutrient Solutions. In: NASA-CR-166431. [db-id.: 47]. [Topics: CELSS; Bioregenerative; Food].

[10] Tibbitts, T.W.. (1986). CELSS: Calcium-Related leaf Injuries. In: NASA-CR-177399. [db-id.: 60]. [Topics: CELSS; Bioregenerative; Food; Plant Growth].

[11] Tibbitts, T.W., D.K. Alford. (1982). CELSS: Use of Higher Plants. In: NASA-CP-2231. [db-id.: 61]. [Topics: CELSS; Bioregenerative; Plant Growth; Food].

[12] Tibbitts, T.W., R.M. Wheeler. (1986). CELSS: Growth Studies with Potatoes. In: NASA-CR-177400. [db-id.: 62]. [Topics: CELSS; Bioregenerative; Food; Plant Growth].

[13] Wheeler, R.M., T.W. Tibbitts. (1984). Controlled Ecological Life Support System Higher Plant Flight Experiments. In: NASA-CR-177323. [db-id.: 65]. [Topics: CELSS; Bioregenerative; Food; Plants].

[14] Adler-Nissan, J., B.O. Eggum, L. Munk, H.J. Olsen. (1977). Biochemical Aspects of New Protein Food. Copenhagen: Pergamon Press. [db- id.: 70]. [Topics: CELSS; Bioregenerative; Food; Waste].

[15] Beal, V.. (1980). Nutrition in the Life Span. New York: John Wiley and Sons. [db-id.: 72]. [Topics: CELSS; Food; Waste].

[16] Hills, C., H. Nakamura. (1978). Food From Sunlight, World Hunger Research Project. Boulder Creek,Ca.: University of the Trees Press. [db-id.: 82]. [Topics: CELSS; Bioregenerative; Food; Waste].

[17] (1978). Human Nutrition Readings From Scientific American. San Francisco: W.H. Freeman and Company. [db-id.: 83]. [Topics: CELSS; Bioregenerative; Food; Waste].

[18] Jackson, D.. (1964). Algae and Man. New York: Plenum Press. [db-id.: 84]. [Topics: CELSS; Bioregenerative; Food; Algae].

[19] Breigleb, W.. (1987). How Does Physarum Polycephalum Perceive and Use Gravity?. In: ESA-SP-271. Proceedings of the Third European Symposium on Life Sciences Research in Space. pp. 129-134. [db-id.: 123]. [Topics: CELSS; plant biology; cell biology; bioregenerative; Food].

[20] Gerbaud, A., M. Andre. (1987). Closed System Physiology: Role of Oxygen in the Development of Wheat. In: ESA- SP-271. Proceedings of the Third European Symposium on Life Sciences Research in Space. pp. 117-124. [db-id.: 125]. [Topics: CELSS; Bioregenerative; Plant and Cell Biology; Food].

[21] Perbal, G., D. Driss-Ecole. (1987). Gravi-sensing in Lentil Seedling Roots Grown in Space (Spacelab D- 1 Mission). In: ESA-SP-271. Proceedings of the Third European Symposium on Life Sciences Research in Space. pp. 91-97. [db-id.: 128]. [Topics: CELSS; Bioregenerative; Plant; Plant and cell Growth; Food].

[22] Rasmussen, O.. (1987). The Use of Plant Protoplasts in Biotechnological Space Research. In: ESA-SP-271. Proceedings of the Third European Symposium on Life Sciences Research in Space. pp. 107-112. [db-id.: 129]. [Topics: CELSS; Bioregenerative; Food; Plant and Cell Growth].

[23] Howe, J.M., J.E. Hoff, Purdue-University. (1982 June). Plant Diversity to Support Humans in a CELSS Ground-Based Demonstrator. In: NASA-CR-166357, NASA Grant NSG-2401. [db-id.: 140]. [Topics: CELSS; Bioregenerative; Food; Plant Growth; Nutrition].

[24] Eijadi, D.A., BRW-Inc. (1988 Aug). Extraterrestrial Applications of Solar Optics for Interior Illumination. In: Engineering, Construction and Operations in Space. Proceedings of Space 88. Albuquerque, New Mex., pp. 298-309. [db-id.: 150]. [Topics: CELSS; Lunar base; Bioregenerative; Food; Plant Growth; Illumination].

[25] Polette, T., Sasakawa-Intern-Center / Space-Architecture. (1988 Aug). A phased Approach to Lunar-Based Agriculture. In: Engineering, Construction and Operations in Space. Proceedings of Space 88. Albuquerque, New Mex:, pp. 287-297. [db-id.: 161]. [Topics: CELSS; Lunar-base; bio-regenerative; food; Lunar agriculture].

[26] Salisbury, F.B., Utah-State-University. (1988 Aug). Wheat Farming in a Lunar Base. In: Engineering, Construction and Operations in Space. Proceedings of Space 88. Albuquerque, New Mex:, pp. 635-646. [db-id.: 163]. [Topics: CELSS; Lunar-base; bio-regenerative; food; plant growth].

[27] Wilson, R.G., J.D. Tromblee. (1987). A Dishwasher for the Space Station. In: SAE-87-1411. 17th Intersociety Conference on Environmental Sciences. Seattle:. [db-id.: 176]. [Topics: CELSS; Physiochemical; Water; Food; Processing].

[28] (1988 Mar). Regenerative Life Support System Research. Progress Report, September 1987-March 1988. In NASA-HQ (ed): NASA-CR-182606, NAS 1.26:182606, SRC-4-5873. Washington: Texas A and M Univ., College Stati. [db-id.: 180]. [Topics: CELSS; Algae; Food Production; Regeneration; Plant Growth; Food; Processing; Lunar base; Waste treatment].

[29] Volk, T.. (1987 Nov). Modeling the Growth Dynamics of Four Candidate Crops for CELSS, Final rept. In NASA-HQ (ed):. Washington: New York Univ., NY. [db-id.: 182]. [Topics: CELSS; Plant Growth; Food Production; Photosynthesis; Potatoes; Soybeans; Wheat].

[30] MacElroy, R.D., J. Tremor, D.T. Smernoff, W. Knott, R.P. Prince. (1987 Sep). Review of Recent Activities in the NASA CELSS Program. In (ed): NASA, Moffett Field, CA. Ames Rese. [db-id.: 195]. [Topics: CELSS; Food Production; Oxygen production; Photosynthesis; Waste; Utilization; Cellulose; Extraterrestrial radiation; Gravitational Effects].

[31] Fry, I.V., J. Hrabeta, J. Dsouza, L. Packer. (1987 Sep). Application of Photosynthetic n(2)-Fixing Cyano-bacteria to the CELSS Program. In NASA (ed):. : Lawrence Berkeley Lab., CA. [db-id.: 196]. [Topics: CELSS; Bacteria; Cyano Compounds; Nitrogenation; Photosynthesis; Biomass; Carbon Dioxide; Food Production].

[32] Nakhost, Z., M. Karel, V.J. Krukonis. (1987 Sep). Non- Conventional Approaches to Food Processing in CELSS, 1. Algal Proteins: Characterization and Process Optimization. In NASA (ed):. : Massachusetts Inst. of Tech., Camb. [db-id.: 197]. [Topics: CELSS; Air purification; Algae; Food Production; Proteins; Amino; Acids; Biomass; Carbon Dioxide].

[33] Radmer, R., J. Cox, D. Lieberman, P. Behrens, K. Arnett. (1987 Sep). Biomass Recycle as a Means to Improve the Energy Efficiency of CELSS Algal Culture Systems. In NASA (ed):. : Martek Corp., Columbia, MD. [db-id.: 199]. [Topics: CELSS; Algae; Biomass energy production; Food Production; Recycling; Atmospheric composition; Carbon Cycle; Photosynthesis].

[34] Oguchi, M., K. Otsubo, K. Nitta, S. Hatayama. (1987 Sep). Food Production and Gas Exchange System Using Blue-Green Alga (Spirulina) for CELSS. In NASA (ed):. : National Aerospace Lab., Tokyo (Ja. [db- id.: 200]. [Topics: CELSS; Blue green algae; Food Production; Gas Exchange; Aqua-culture; Atmospheric Composition; Nutrition; Oxygen; Production].

[35] Knox, J.. (1986 Oct). Method of Variable Spacing for Controlled Plant Growth Systems in Spaceflight and Terrestrial Agriculture Applications. In NASA (ed): NASA-CR-177447 NAS 1.26:177447. : Cooperative Inst. for Research in. [db-id.: 204]. [Topics: CELSS; Plant Growth; Spacing; Greenhouses; Hydroponics; Soybeans;; Food].

[36] (1987 June). Publications of the NASA CELSS Program 1984-86. In NASA (ed): NASA-CR-4070. NAS1.26:4070. : George Washington Univ., Washingto. [db-id.: 206]. [Topics: CELSS; Life support systems; Food Processing; Food Production; Nutrition; Waste treatment; Bibliographies].

[37] Wiltberger, N.L.. (1987 Feb). Growth and Harvesting of Algae in a Micro-Gravity Environment. In NASA (ed):. : Cooperative Inst. for Research in. [db-id.: 208]. [Topics: CELSS; Algae; Food production (In space); Growth; Reduced; gravity].

[38] Dufour, P.A., J.L. Solberg, J.S. Wallace. (1985 Jul). Publications of the NASA CELSS Program. In NASA (ed): NASA-CR-3911, NAS 1.26:3911. : George Washington Univ., Washingto. [db-id.: 214]. [Topics: CELSS; Bibliographies; Plant Growth; Waste Treatment; Algae; Food; Nutrition; Recycling].

[39] (1981 Dec). Development of a Prototype Experiment for Treating CELSS and PCELSS Wastes to Produce Nutrients for Plant Growth. Final Report. In NASA (ed): NASA-CR-173167. NAS1.26: 173167. : Massachusetts Inst. of Tech., Camb. [db-id.: 219]. [Topics: CELSS; Waste water; Chemical Treatment; Food Processing; High; Temperature; Mass Transfer; Oxidation; Permittivity].

[40] Averner, M., M. Karel, R. Radmer. (1984 Nov). Problems Associated with the Utilization of Algae in Bioregenerative Life Support Systems. In: NASA-CR-166615, NCC 2-210. [db-id.: 245]. [Topics: CELSS; Bioregenerative; Food; Plant; Algae].

[41] Schwartzkopf, S.H., D.G. Kane, R.L. Stempson, (Lockheed-Missiles). (1988 July). Greenhouses and Green Cheese: Use of Lunar resources in CELSS Development. In: SAE-88-1057, 18th Intersociety Conference on Environmental Systems San Francisco. [db- id.: 263]. [Topics: CELSS; Lunar Base; Bioregenerative; Food; Environment; Lunar; Resources; Illumination].

[42] Venketeswaran, S.. (1988). Growth of plant tissue cultures in simulated lunar soil - implications for a lunar base CELSS Final report of NASA Grant NAG-9-214 from JSC. Performed by author at University of Houston, Houston, Department of Biology. In: NASA-CR-183233. [db-id.: 267]. [Topics: CELSS; Bioregenerative; Food; Regolith; Plant].

[43] Sauer, R.L., NASA-Johnson. (1985). Metabolic Support for a Lunar Base. In W.W. Mendell (ed): Lunar Bases and Space Activities for the 21st Century. Houston: Lunar and Planetary Institute, pp. 647-651. [db-id.: 283]. [Topics: CELSS; Lunar base; Air; Waste; Food; Water; Nutrients].

[44] Powell, F.T., M. Sedej, C. Lin. (1987). Environmental Control and Life Support System Requirements and Technology Needs for Advanced Manned Space Missions. In: SAE-87-1433: 17th Intersociety Conference on Environmental Systems. Seattle, Washington:. [db-id.: 284]. [Topics: CELSS; Transportation; Cost; Mission Analysis; Water; Waste; Air; Food].

[45] Fielder, J., N. Leggett. (1988). Lunar Agricultural Requirements Definition. In: Engineering, Construction and Operation in Space. Proceedings of Space 1988. Albuquerque, N.Mexic., pp. 344-351. [db-id.: 287]. [Topics: CELSS; Lunar Base; Bioregenerative; Food; Plant].

[46] Miller, C.W., L.S. Kovach, Life-Systems. (). Environmental Control Life Support for the Space Station. In: SAE- 86-0944. [db-id.: 302]. [Topics: CELSS; Physiochemical; Requirements; Air; Water; Waste; Food].

APPENDIX B

ITEMIZED LCELSS DESIGN DATA

Figure 1. Itemized Mass Data for LCELSS SSF Module Plant Growth Unit.

Item	Amount (Units)	Weight/Unit	Total Weight (lb)	Total Mass (kg)
Shell				
Primary Structure	-	-	7,734	3,515
Secondary Structure	-	-	1,932	878
Shell Total			9,666	4,394
Framing				
3" Channel	360 feet	0.597 lb/ft	215	98
3" X 1/4" Angle	1090 feet	0.807 lb/ft	880	400
Floor Grating	120 sq.ft	2.87 lb/sq ft	344	156
Framing Total			1,439	654
Nutrient Delivery System				
1 1/2" PVDF Delivery Pipe	400 feet	0.53 lb/ft	212	96
1 1/2" PVDF Delivery Risers	70 feet	0.53 lb/ft	37	17
3" PVDF Drain Pipe	400 feet	1.38 lb/ft	552	251
3" PVDF Drain Risers	70 feet	1.38 lb/ft	97	44
Nutrient Solution Reservoir (Graphite/Epoxy)	5 each	11 lb/ea	55	25
Nutrient Solution Pump	5 each	42 lb/ea	210	95
Solenoid Valve	110 each	0.7 lb/ea	77	35
Culture Tray (Graphite Epoxy)	100 each	32.5 lb/ea	3,250	1,477
Nutrient Delivery System Total			4,490	2,041
Lighting System (Sunlight)				
Solar Collector	4 each	71.5 lb/ea	285	130
SSF Window	4 each	93.5 lb/ea	374	170
Light Pipe	425 feet	0.673 lb/ft	286	130
Lighting System (Sunlight) Total			945	430

Figure 1. Itemized Mass Data for LCELSS SSF Module Plant Growth Unit (Cont'd).

Item	Amount (Units)	Weight/Unit	Total Weight (lb)	Total Mass (kg)
Lighting System (Artificial)				
Lights	100 sq meters	27 lb/sq meter	2,700	1,227
Lighting System (Artificial) Total			2,700	1,227
Atmosphere Circ. and Temp. Control				
Circulation Fan	10 each	54 lb/ea	540	245
8" Dia. Ducting (H.D. Urethane)	400 feet	1.74 lb/ft	696	316
Heat Exchanger	5 each	80 lb/ea	400	182
Atm. Circ. & Temp. Control Total			1,636	744
Environmental Monitor/Control System				
Environmental Control Computer	2 each	40 lb/ea	80	36
Ion Chromatograph	2 each	55 lb/ea	110	50
Atmosphere Control Subsystem				
CO_2 Concentration Sensor (with Air Pump)	2 each	6.5 lb/ea	13	6
Oxygen Concentration Sensor	2 each	1 lb/ea	2	1
Temperature Sensor	10 each	0.2 lb/ea	2	1
Pressure Sensor	2 each	0.5 lb/ea	1	0
Relative Humidity Sensor	10 each	0.5 lb/ea	5	2
Photosynthetically Active Radiation Sensor	10 each	0.2 lb each	2	1
Atmosphere Subsystem Total			25	11

Figure 1. Itemized Mass Data for LCELSS SSF Module Plant Growth Unit (Cont'd).

Item	Amount (Units)	Weight/Unit	Total Weight (lb)	Total Mass (kg)
Nutrient Solution Control Subsystem				
Dissolved Oxygen Monitor	5 each	8 lb/ea	40	18
pH Monitor	5 each	7 lb/ea	35	16
Electrical Conductivity Monitor	5 each	4 lb/ea	20	9
Solution Addition/Metering Pump	15 each	11.5 lb/ea	172.5	78
High Flow Rate Sub-Micronic Filter (0.22μ)	5 each	4 lb/ea	20	9
Ultraviolet Sterilizer	5 each	7 lb/ea	35	16
Composition Control Reservoirs (with Solns.)	15 each	32.5 lb/ea	487.5	222
Nutrient Solution Subsystem Total			810	368
Environ. Mon/Control System Total			1,025	466
GRAND TOTAL			21,901	9,955

* Primary and Secondary Structure mass values were obtained from Boeing Co.

Figure 2. Itemized Mass Data for LCELSS Hybrid Plant Growth Unit

Item	Amount (Units)	Weight/Unit	Total Weight (lb)	Total Mass (kg)
Shell				
Envelope	1 ea	1,080 lbs	1,080	491
Backbone	1 ea	1,818 lbs	1,818	826
Hatch	1 ea	900 lbs	900	409
Shell Total			3,798	1,726
Framing				
3” Channel	1,040 Feet	0.597 lb/ft	621	282
3” X 1/4” Angle	2,501 feet	0.807 lb/ft	2,018	917
Floor Grating	120 sq.ft	2.87 lb/sq ft	344	156
Framing Total			2,983	1,356
Nutrient Delivery System				
1 1/2” PVDF Delivery Pipe	896 feet	0.53 lb/ft	475	216
1 1/2” PVDF Delivery Risers	158 feet	0.53 lb/ft	84	38
3” PVDF Drain Pipe	896 feet	1.38 lb/ft	1,236	562
3” PVDF Drain Risers	158 feet	1.38 lb/ft	218	99
Nutrient Solution Reservoir (Graphite/Epoxy)	11 each	11 lb/ea	121	55
Nutrient Solution Pump	11 each	42.5 lb/ea	462	213
Solenoid Valve	246 each	0.7 lb/ea	172	78
Culture Tray (Graphite Epoxy)	224 each	32.5 lb/ea	7,280	3,309
Nutrient Delivery System Total			10,048	4,570
Lighting System (Sunlight)				
Solar Collector	0 each	71.5 lb/ea	0	0
SSF Window	0 each	93.5 lb/ea	0	0
Light Pipe	0 feet	0.673 lb/ft	0	0
Lighting System (Sunlight) Total			0	0

Figure 2. Itemized Mass Data for LCELSS Hybrid Plant Growth Unit (Cont'd)

Item	Amount (Units)	Weight/Unit	Total Weight (lb)	Total Mass (kg)
Lighting System (Sunlight)				
Lights	224 sq meters	27 lb/sq meter	6,048	2,750
Lighting System (Sunlight) Total			6,048	2,750
Atmosphere Circ. and Temp. Control				
Circulation Fan	20 each	54 lb/ea	1,080	491
8" Dia. Ducting (H.D. Urethane)	800 feet	1.74 lb/ft	1,392	633
Heat Exchanger	5 each	100 lb/ea	798	363
Atm. Circ. & Temp. Control Total			3,270	1,486
Environmental Monitor/Control System				
Environmental Control Computer	2 each	40 lb/ea	80	36
Ion Chromatograph	2 each	55 lb/ea	110	50
Atmosphere Control Subsystem				
CO_2 Concentration Sensor (with Air Pump)	2 each	6.5 lb/ea	13	6
Oxygen Concentration Sensor	2 each	1 lb/ea	2	1
Temperature Sensor	10 each	0.2 lb/ea	2	1
Pressure Sensor	2 each	0.5 lb/ea	1	0
Relative Humidity Sensor	10 each	0.5 lb/ea	5	2
Photosynthetically Active Radiation Sensor	10 each	0.2 lb ea	2	1
Atmosphere Subsystem Total			25	11

Figure 2. Itemized Mass Data for LCELSS Hybrid Plant Growth Unit (Cont'd)

Item	Amount (Units)	Weight/Unit	Total Weight (lb)	Total Mass (kg)
Nutrient Solution Control Subsystem				
Dissolved Oxygen Monitor	11 each	8 lb/ea	88	40
pH Monitor	11 each	7 lb/ea	77	35
Electrical Conductivity Monitor	11 each	4 lb/ea	44	20
Solution Addition/Metering Pump	33 each	11.5 lb/ea	380	173
High Flow Rate Sub-Micronic Filter (0.22μ)	11 each	4 lb/ea	44	20
Ultraviolet Sterilizer	11 each	7 lb/ea	77	35
Composition Control Reservoirs (with Solns.)	33 each	32.5 lb/ea	1,072.5	488
Nutrient Solution Subsystem Total			1,782.5	810
Environ. Mon/Control System Total			1,998	908
GRAND TOTAL			28,153	12,797

Figure 3. Itemized Mass Data for LCELSS Inflatable Plant Growth Unit

Item	Amount (Units)	Weight/Unit	Total Weight (lb)	Total Mass (kg)
Shell				
Envelope	1,620.5 sq. meters	3.7 lb/sq meter	5,996	2,725
Backbone	-	-	0	0
Hatch	1 ea	900 lbs/ea	900	409
Shell Total			6,896	3,135
Framing				
3" Channel	2,240 feet	0.597 lb/ft	1,337	608
3" X 1/4" Angle	8,975 feet	0.807 lb/ft	7,243	3,292
Floor Grating	1,200 sq.feet	2.87 lb/sq ft	3,444	1,565
Framing Total			12,024	5,465
Nutrient Delivery System				
1 1/2" PVDF Delivery Pipe	2,114 feet	0.53 lb/ft	1,120	509
1 1/2" PVDF Delivery Risers	370 feet	0.53 lb/ft	196	89
3" PVDF Drain Pipe	2,114 feet	1.38 lb/ft	2,917	1,326
3" PVDF Drain Risers	370 feet	1.38 lb/ft	511	232
Nutrient Solution Reservoir (Graphite/Epoxy)	26 each	11 lb/ea	286	130
Nutrient Solution Pump	26 each	42.5 lb/ea	1,105	503
Solenoid Valve	580 each	0.7 lb/ea	406	185
Culture Tray (Graphite Epoxy)	528 each	32.5 lb/ea	17,160	7,800
Nutrient Delivery System Total			23,701	10,774
Lighting System (Sunlight)				
Solar Collector	0 each	71.5 lb/ea	0	0
SSF Window	0 each	93.5 lb/ea	0	0
Light Pipe	0 feet	0.673 lb/ft	0	0
Lighting System (Sunlight) Total			0	0

Figure 3. Itemized Mass Data for LCELSS Inflatable Plant Growth Unit (Cont'd)

Item	Amount (Units)	Weight/Unit	Total Weight (lb)	Total Mass (kg)
Lighting System (Artificial)				
Lights	528 sq meters	27 lb/sq meter	14,256	6,480
Lighting System (Artificial) Total			14,256	6,480
Atmosphere Circ. and Temp. Control				
Circulation Fan	48 each	54 lb/ea	2,592	1,178
8" Dia. Ducting (H.D. Urethane)	1600 feet	1.74 lb/ft	2,784	1,265
Heat Exchanger	48 each	83.3 lb/ea	4,000	1,818
Atm. Circ. & Temp. Control Total			9,376	4,262
Environmental Monitor/Control System				
Environmental Control Computer	2 each	40 lb/ea	80	36
Ion Chromatograph	2 each	55 lb/ea	110	50
Atmosphere Control Subsystem				
CO_2 Concentration Sensor (with Air Pump)	4 each	6.5 lb/ea	26	12
Oxygen Concentration Sensor	4 each	1 lb/ea	4	2
Temperature Sensor	20 each	0.2 lb/ea	4	2
Pressure Sensor	4 each	0.5 lb/ea	2	1
Relative Humidity Sensor	20 each	0.5 lb/ea	10	5
Photosynthetically Active Radiation Sensor	20 each	0.2 lb ea	4	2
Atmosphere Subsystem Total			50	23