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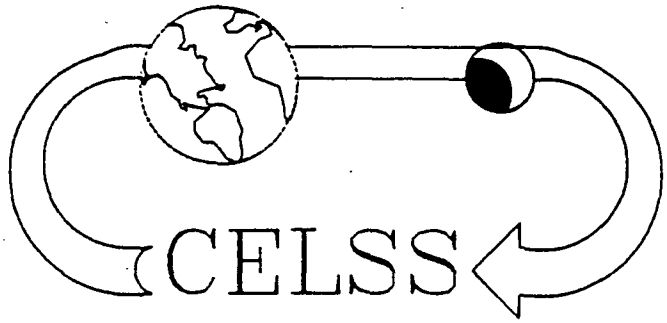
EARTH TO LUNAR



EVOLUTION

UNIVERSITY OF COLORADO
DEPARTMENT OF AEROSPACE ENGINEERING SCIENCES

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June 18, 1991

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Abstract

A Lunar Base Reference Mission for the Phased Implementation of Bioregenerative Life Support System Components

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The need for a new generation of cost-effective and reliable regenerative life support systems has been emphasized for all future space missions requiring long-term presence of humans. Increasing mass closure through recycling and *in situ* production of life support consumables will increase safety and self-reliance , reduce resupply and storage requirements and thereby reduce mission cost. Our previous design efforts provided the foundation for the characterization of organisms or 'biological processors' in engineering terms and developed a methodology for their integration into an engineered ecological life support system in order to minimize the mass flow imbalances between consumers and producers. These techniques for the design and the evaluation of bioregenerative life support systems have now been integrated into a Lunar Base reference mission, emphasizing the phased implementation of components of such a biological life support system. In parallel, a designer's handbook has been compiled from knowledge and experience gained during past design projects to aid in the design and planning of future space missions requiring advanced regenerative life support system technologies. The Lunar Base reference mission addresses in particular the phased implementation and integration of biological life support components and includes the resulting infrastructure burdens and needs such as mass, power, volume and structural requirements of the life support system. In addition, operational aspects such as manpower requirements and the possible need and application of 'robotics' have been addressed.

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TABLE OF CONTENTS

	EXECUTIVE SUMMARY	I
1.0	INTRODUCTION	1
1.1	MISSION DESCRIPTION	5
1.2	METHODOLOGY	6
1.3	MISSION SCENARIO	7
2.0	CELSS	13
2.1	INTRODUCTION	13
2.2	PHASED IMPLEMENTATION	16
2.3	SPIN-OFFS/EARTH APPLICATIONS	24
2.4	PHYSIOCHEMICAL/BIOREGENERATIVE INTEGRATION	24
2.4.1	OXYGEN GENERATION TECHNOLOGIES	25
2.4.2	CARBON DIOXIDE REMOVAL TECHNOLOGIES	26
2.4.3	CARBON DIOXIDE REDUCTION	27
2.4.4	WATER SYSTEM REVITALIZATION	27
2.5	CRITICAL TECHNOLOGIES	31
2.5.1	HYDROPONIC PLANT PRODUCTION	31
2.5.2	PLANT LIGHTING	35
2.6	SUPPORT AND MAINTENANCE REQUIREMENTS	43
2.7	CELSS RECOMMENDATIONS AND CONCLUSION	44
3.0	INFRASTRUCTURE	58
3.1	STRUCTURE	58
3.2	NODES	61
3.3	POWER	64
3.4	HEAT REJECTION	69
3.5	SAFETY	76
3.6	LUNAR SITE	79
3.7	COMMUNICATIONS	83
3.8	TRANSPORTATION	89
3.9	NAVIGATION	96
3.10	LANDING SITE	100
3.11	INFRASTRUCTURE RECOMMENDATIONS AND CONCLUSION	102
4.0	ROBOTICS	113
4.1	INTRODUCTION	113
4.2	RATIONALE	113
4.3	HISTORY	115
4.4	BASELINE REQUIREMENTS AND ASSUMPTIONS	116
4.5	ROBOTICS TASK DESCRIPTION	117
4.6	REQUIRED TECHNOLOGIES	120
4.7	TECHNOLOGICAL ADVANCES	122
4.8	RECOMMENDATIONS	129
4.9	TEN YEAR PLAN	129
4.10	ROBOTICS GROUP CONCLUSION	130
5.0	OVERALL CONCLUSION	140
	REFERENCES	142

TABLE OF FIGURES

1-1 SPACE PROGRAM CHEMISTRY....10
1-2 SPACE HABITATION FILTER BOX....10
1-3 SPACE EXPLORATION RATIONALE....11
1-4 MISSION SCENARIO....12

2-1 HUMAN REQUIREMENTS....45
2-2 AVERAGE PLANT PERFORMANCE....45
2-3 CELSS SCALING....46
2-4 IMPACTS FOR A CREW OF FOUR....46
2-5 P/C CANDIDATE TRADE STUDY....47
2-6 SOILD POLYMER WATER ELECTROLYSIS SUBSYSTEM....47
2-7 STATIC FEED WATER ELECTROLYSIS SUBSYSTEM....48
2-8 ELECTROCHEMICAL DEPOLARIZED CARBON DIOXIDE CONCENTRATOR SUBSYSTEM....48
2-9 BOSCH CO2 REDUCTION SUBSYSTEM....49
2-10 SABATIER CO2 REDUCTION SUBSYSTEM....49
2-11 VAPOR COMPRESSION DISTILLATION WATER RECLAMATION SUBSYSTEM....50
2-12 THERMOELECTRIC INTEGRATED MEMBRANE EVAPORATION SUBSYSTEM....50
2-13 VAPOR PHASE CATALYTIC AMMONIA REMOVAL SUBSYSTEM....51
2-14 REVERSE OSMOSIS SUBSYSTEM....51
2-15 AEROBIC TREATMENT....52
2-16 ANAEROBIC TREATMENT....52
2-17 OPEN LOOP SCHEMATIC....53
2-18 PHYSICAL/CHEMICAL LIFE SUPPORT SCHEMATIC....53
2-19 BACTERIA PHYSICAL/CHEMICAL HYBRID....54
2-20 SYSTEM CLOSURE COMPARISIONS....54
2-21 VOLUME REQUIREMENTS FOR PLANT GROWTH UNIT....55
2-22 HYDROPONIC UNIT FOR 2 M2 OF PLANT GROWTH....55
2-23 LIGHT AND PLANT FUNCTIONS....56
2-24 LIGHTING DEVICE PARAMETERS....56
2-25 LUNAR CELSS LIGHTING DESIGN QUALITIES....57
2-26 LIGHTING DESIGN TRADE STUDY....57
2-27 L.E.D. PRIMARY LIGHTING W/SECONDARY OPTIONS....58

3-1 RADIATOR FIN TYPES....104
3-2 CARNOT CYCLE....104
3-3 REFRIGERATION CYCLES....105
3-4 HEAT PIPE....105
3-5 WET AND DRY HEAT EXCHANGERS....106
3-6 MOVING BELT RADIATOR....106
3-7 LIQUID DROPLET RADIATOR CONFIGURATIONS....107
3-8 RADIATOR MASS COMPARISON....108
3-9 PERMANENTLY SHADOWED POLAR SITE....108
3-10 LUNAR SITE TRADE STUDY....109
3-11 LUNAR SITE COMPARISON....109
3-12 EARTH TO LUNAR TRANSPORTATION....110
3-13 LUNAR LANDER MASS COMPARISON....110
3-14 LANDER MASS BREAKDOWN....110
3-15 NAVIGATION SYSTEM TRADE STUDY....111

TABLE OF FIGURES - CONTINUED

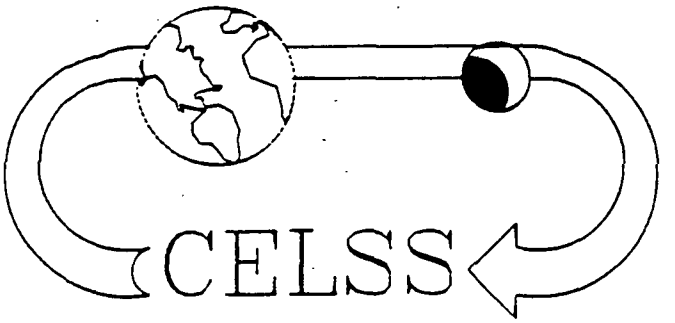
3-16 NAVIGATION SYSTEM COMPARISON 111
3-17 LANDING SITE BLAST BARRIER 112
3-18 LANDING SITE DIAGRAM 112

4-1 LUNAR BASE DESIGN 131
4-2 OFFLOAD, TRANSPORT, AND POSITION TRADES 131
4-3 OFFLOAD SCORE TABLE 132
4-4 TRANSPORT SCORE TABLE 132
4-5 TRANSPORTATION VEHICLE TRADES 133
4-6 USER SURVEY OF DESIRED IMPROVEMENTS IN 133
4-7 THREE-DEGREES-OF-FREEDOM WRIST TABLE 134
4-8 THREE-DEGREES-OF-FREEDOM WRIST VARIATIONS 134
4-9 TRIPLE-AXIS COMMON-PIVOT ARM WRIST (TACPAW) 135
4-10 REMOTE MANIPULATOR SYSTEM WRIST 135
4-11 SENSOR VARIATIONS 136
4-12 THERMAL FLOW CHART 136
4-13 DECISION MATRIX CRITERIA WEIGHTING FACTORS TABLE 137
4-14 TRANSPORT MEDIA DECISION MATRIX TABLE 137
4-15 TECHNOLOGY PROGRESSION TIMELINE 138
4-16 PROPOSED LUNAR ROBOT DESIGNS 138
4-17 PROPOSED LUNAR ROBOT DESIGNS 139

5-1 CONCLUSION 142

EXECUTIVE SUMMARY

EARTH TO LUNAR



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June 18, 1991

Earth to Lunar CELSS Evolution

Executive Summary

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Introduction Three decades ago, human-kind first glimpsed the Earth from space. Since that day, the space programs of a growing number of nations have served not only as the means by which our universe may be explored, but also as a platforms from which to view the complex planet we call home. Undoubtedly, the U.S. Space Program under the direction of the National Aeronautics and Space Administration (NASA) has provided key leadership in this odyssey. NASA has completed close observations of seven of the planets, including robotic landers on Mars and has launched, retrieved and repaired satellites with the world's first reusable space vehicle. Perhaps NASA's most difficult and best known challenge was landing the first humans on the moon. As space author Joshua Stoff stated, "The Apollo program was a bargain. It cost the taxpayers a sum amounting to only one-third of one percent of the Gross National Product in 1970, yet the technical and scientific knowledge gained from it was immeasurable. The Apollo flights gave man a new sense of who he was and where he was, and the views of Earth from space dramatically portrayed the planet's fragility." In addition, the height of the U.S. Space Program coincided with the height of the United States' industrial prowess, and served as a catalyst for the enrollment of students in the fields of math and science.

The Current State of the Space Program NASA has begun several new space initiatives since the Apollo era, despite the tragic loss of the Challenger. The fourth shuttle and 41st shuttle mission in ten years have just been completed. This accounts for 249 days in space, 128 days more than the total of the three Skylab missions [Garret, conversation 1991]. Two scientific observatories, the Hubble and the Gamma Ray Observatory, have begun making observations, and the Magellan spacecraft is completing it's mapping of Venus. The Galileo and Ulysses spacecraft are currently enroute to their planetary and solar destinations. However, over the years, the technical base from which these initiatives were spawned has experienced incohesive growth. Some areas, such as launch systems and communications, have seen massive strides over the past 30 years. The payload of the Saturn V was 120 tons, 60 times greater than the payload of the first Mercury Redstone only eight years earlier, and the Shuttle has the best reliability record of any man-rated vehicle (97.6%). In contrast, life support system technologies have been nearly stagnant, with early space shuttle food packages being basically identical to those used in Apollo and the Gemini missions [Sauer, R. 1984]. Therefore, underdeveloped areas such as life support, provide great potential for rapid technical advance with little initial cost. For NASA to meet these technical challenges, it must have an efficient personnel and consistent funding base.

In 1970, NASA had a total of 31,223 employees , a number that had dropped to 22,613 in 1980, and currently stands at 23,625. The percentages of scientists and engineers to other NASA employees has risen and fallen with the same dynamics, beginning with 58.4% in 1970, 49.6% in 1980, and currently 55.6%. Both of these patterns are indicative of the space program's funding (funding peaked at .8% of the GNP in 1969, and fell to .2% of the GNP in 1975, where it has levelled off since), which is creating an unbalanced personnel base. Therefore, the passage of knowledge from the more senior engineers to the newer employees is imperative to the ongoing synthesis of space technology. Although NASA still enjoys general public support, recent events in the budget process show that this support is not a guarantee of consistent funding, and publications such as the Augustine report have not only recognized these situations, but have also expressed concern over NASA's goal setting and scientific base.

It is worth noting that many of the above problems can be remedied utilizing a "phased" design approach. Phasing allows new technology and personnel bases to be built upon the reliable foundation of past experience, while providing returns at each step. This allows more flexibility to political and financial discontinuities, and shows a visible track record of accomplishments. Lastly, for each step in the design process, spin-off technologies can be easily identified, amounting to wider support for space initiatives because their global benefits are showcased. The research effort outlined in this paper was designed to be reflective of these conclusions, categorized as cost effective, safe and credible.

Definition of CELSS and its Benefits The comprehensive results of human activities on the environment, such as deforestation and ozone depletion, and the natural laws that govern the global environment have yet to be determined. Closed Ecological Life Support Systems (CELSS) research can play an instrumental role in distilling these mysteries, as well as have the ability to support life in hostile environments, which the Earth one day may become. CELSS conclusions, such as the time scales in which plants fix carbon dioxide (CO_2), will

be the key to understanding each component and how it affects the ecological balance between plants and animals, the environment, and the biological engines that drive the Earth's system. However, in order to understand how CELSS can be used as an investigative tool, the concept of a CELSS must be clearly defined.

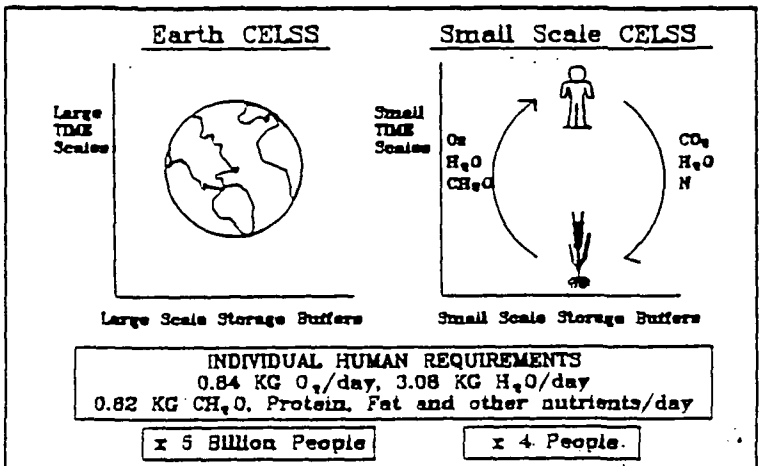

Figure 1: Artificial Ecosystems for space travel would operate on much shorter time scales and with much smaller buffer volumes than the only true closed ecological life support system, our planet Earth.

The best example of a CELSS is the one in which we live, Earth. The Earth, however, is not a true closed system because it receives inputs via energy from the sun, and mass from contact with stellar and interstellar space materials. However, for the most part, the Earth is an isolated system, where the requirements for its many life forms are met by the ecological "balance" between all terrestrial organisms. This balance is formed by the natural matching of net products of some life forms to the consumption needs inherent in other life forms, and vice versa (Figure 1). The "inputs" and "outputs" of these life forms can be broken down very simply into gas, liquid, and solid loops. They are called loops because the matching of consumptions (inputs) to productions (outputs) initiates a recycling of the initial foundation of resources, allowing the system to be closed, and thus self-sufficient. Plants and animals affect all three loops simultaneously. For example, animals consume oxygen and carbohydrates (food), breathe out carbon dioxide, and have nitrogenous compounds present in their feces. Through photosynthesis, plants utilize the carbon dioxide and nitrogen compounds to produce oxygen and carbohydrates. All CELSS have balances composed of these reactions, although the Earth enjoys the advantage of tremendous time scales and large available storage buffers.

Humans share the same life enabling environment with plants, but the baseline means of supporting life in hostile environments like space have utilized storage or Physical/Chemical (P/C) systems. P/C systems use non-biological processes to support human life. The Lithium Hydroxide Scrubber is an example of how P/C systems are used on the Space Shuttle to store excess CO_2. However, this system is neither "regenerative," nor "recycling", as it uses up the LiOH and the carbon dioxide is lost. An example of a regenerative system is the molecular sieve, which was used on Skylab to remove the CO_2 from the atmosphere. If biological elements are implemented into a system to initiate recycling, the system is termed "Bioregenerative."

Understanding the interactions in Bioregenerative recycling systems leads to numerous benefits: improved recycling of water can be provided through advances in water treatment with bacteria or plants; longer lasting light sources, such as LED's, will be pioneered to decrease the cost of running greenhouses; high yield agricultural techniques increase the net production of biomass; and higher yields for starving nations can be obtained just by better utilizing available resources. It is also conspicuous that such a system would benefit the human habitation of space in the ways categorized as important earlier. This system is cost effective because resupply mass can be reduced (Lunar base: 453 kg/person/2 weeks in resupply mode; only 61 kg/person/week with biological waste water treatment). In addition, a CELSS doesn't involve many of the safety problems that are currently inherent in some baseline P/C systems. Both the Bosch and Sabatier process have the potential to release harmful gases such as carbon monoxide, hydrogen or methane and have high operating temperatures. For example, the Sabatier process releases 9152 kJ of heat for every kilogram of CO_2 reduced. Lastly, CELSS technology has an innate credibility in that it is building on the oldest, most proven life support system ever, the Earth's own ecological balance.

CELSS: An Engineering Perspective The working composition of a CELSS may be characterized by how it makes use of the "functions" involved in each of the Gas, Liquid and Solid loops (Figure 2). These functions can be defined as Storage, Monitoring, Treatment, Transport, Collection and Use. For example, to maintain a chicken in CELSS, it's Gas, Liquid and Solid inputs must be "transported" to it for "use" in consumption. Then the outputs from the use function, such as feces, can be "collected" and transported to "storage." In storage, the nitrogen compounds in the feces can be extracted through a "treatment" function, and then be used as fertilizer for the plants. Together, these functions perform all the tasks needed for the operation of a CELSS.

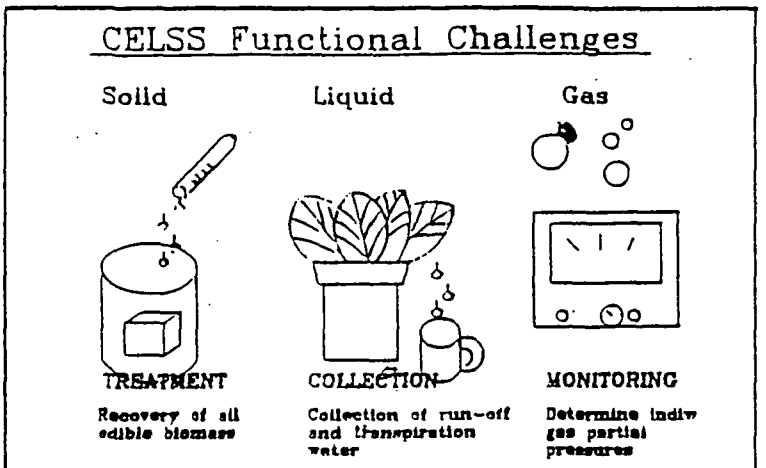

Figure 2: Mass flows in a CELSS may be broken down into gaseous, liquid and solid matter. For each loop, forcing functions move the matter between storage, treatment, collection, use and monitoring locations.

Certainly, challenges remain before biological elements can be implemented with the same level of integration experience characteristic of P/C systems. Problems such as water recycling, contamination control and conversion of all biomass into edible form must be overcome. But it is obvious that CELSS research has a tremendously positive potential to impact both how life is lived on Earth and in space.

Mission Statement and Rationale The evolutionary establishment of a Lunar Base with a Bioregenerative Life Support System in a Space Station Freedom (SSF) module to support a crew of four for two week durations was chosen as the design topic. Not only is the base the first step in the development of a proving ground for enabling technologies for the long duration stay of humans in space, but the CELSS research will have an immediate and positive impact over a broad scope of Earth needs. In the United States, it will also serve as a catalyst for the nation's economy and education. Advances in "space technology" such as robotics and CELSS can provide increased manufacturing competitiveness or "smarter" environmentally controlled homes. Currently the United States ranks behind other industrial nations in the average capacity citizens have for mathematics and sciences. If similar results occur as those following the Apollo program, this new initiative can serve to inspire students to take an interest in these critical foundations of American education. Through the development of a Lunar Base, a number of returns will be experienced here on Earth long before a single piece of equipment is transported to the surface, or a single byte of scientific information is transmitted back to Earth.

Since the transport of mass is the primary cost driver for a Lunar initiative, the integration of a CELSS into the base is a prudent decision because eventually the initial cost of the initial CELSS mass will be paid for in resupply cost savings. This "break-even point" has been estimated by Lockheed for a very similar Lunar CELSS (LCELSS) scenario as ours at 2.6 years for a crew of four. By using an average Earth to Low Earth Orbit (LEO) cost of $10,000/kg and multiplying by a factor of five for the cost from LEO to the Lunar surface, the cost per kg to the moon can be estimated. Implementing a biological waste water treatment into an existing P/C resupply system alone reduces the cost from $22.6 M to $3M for one person for two weeks.

Because of the merits of phasing described earlier, a phased implementation of biological elements was utilized, and a CELSS design group examined the strategy of phasing organisms into a baseline P/C system. All of the design groups followed the same methodology for solving their design problems: Identify requirements and the options to meet them; Perform a trade study and pick the best option; Examine critical technologies and their spin-off applications. For the CELSS group, reducing resupply mass and optimizing the rate of movement towards a closed, balanced system were the primary objectives. A phasing strategy that concentrated on the most mass intensive loop, Liquid, was employed, and critical technologies such as hydroponics and lighting were investigated. An Infrastructure group examined implications of such a CELSS system and performed sanity checks on the Power, Mass and Volume requirements that such a system would have. The extent to which these would impact site location, transportation, power, navigation, communications, thermal regulation and safety were also determined. Based on the results of these two groups, a list of labor requirements was made. Since robotics can be employed to alleviate these tasks from astronauts' duties while increasing safety and decreasing mission cost, a Robotics group was formed. Referencing the labor requirements, the Robotics group was able to make recommendations for a robot with a power source as its design foundation, and work-packages for different tasks. The results of these design groups provide a believable, cost-effective and safe bioregenerative life support system design inclusive of the robotic and infrastructure needs to shelter and maintain it on the Lunar surface. The first step is a CELSS initiative based on Earth and Space based needs like recycling and regeneration of resources.

CELSS

As the population of the world continues to increase, the conservation of our vital resources becomes ever more important. For example, California, the state with the largest population growth, has suffered a major water shortage due to the recent droughts, leaving its water reserve at less than 20% of its capacity. California's need for water is further compounded by a large agricultural industry that uses 90% of its fresh water for irrigation. The need for additional water is currently being met by "mining" groundwater, but most of the underground supply is a one-time usage that will eventually run dry. Therefore, because of the limited supply of potable "drinking" water, there is an urgency to find a way to conserve or replenish it. In Irvine, California this problem is already being addressed by a system that reuses all of the towns wastewater for municipal irrigation (Englebert, 1984). Currently, this critical area is being studied at Stennis Space Center: plants are utilized to recycle water and to remove air pollutants in the 'BioHome' research project (in: Nelson, 1990). A company in Boulder, Colorado, has already marketed and installed biological wastewater treatment systems that recycle water in people's homes and have proven that the technology is achievable (Purecycle). These are just some of the benefits that can be derived from further CELSS research.

The major stumbling block for attaining a CELSS is closure. It is essential to CELSS research to have the ability to perform experiments without any outside influences in order to exactly quantify all the parameters governing plant and animal growth. The current baseline in closed experiments consists of closed growth chambers at Kennedy and Johnson Space Centers, as well as initial research and breadboard testing being performed at Ames and Marshall Space Centers, respectively. Ninety days for a wheat experiment is the longest amount of time that closed experiments have been run. Other experiments such as Biosphere II may provide only limited data because the multiple variables present in the experiment prevent a specific understanding of any particular component. When one considers the large number of organisms that need to be investigated, as well as the required iterations for each experiment, current facilities fall short of the ones required.

Currently, physical/chemical systems are the technology used for total resupply missions such as on the space shuttle. Regenerative systems have been examined on Earth but have not been widely used in space except, for example, the molecular sieve used for CO_2 removal on Skylab. System selections are generally based on trade studies between system mass, resupply requirements and mission duration. These physical/chemical systems fall short when considering safety and compatibility issues. For instance, the Sabatier CO_2 reduction process creates .33 kg of methane, a hazardous byproducts for plants and animals, per person/per day . Physical/chemical systems also become expensive in the long term because they require periodic replacement and repair. Operating parameters, such as high temperatures up to 1500 K for a Sabatier with methane cracking, and pressures up to 1.2 MPa for a Static Feed Water Electrolysis System for O_2 and H_2 generation require massive containment vessels to avoid potentially dangerous conditions. Therefore, even though physical/chemical systems have the advantage of being predictable and autonomous, their disadvantages outweigh their effectiveness for long duration stays. Hence, they become only a building block on which a CELSS can be implemented and provide an eventual buffer for the working CELSS.

On Earth, bioregenerative technology is already being utilized to reduce wastes in sewage treatment. For example, municipal sewage plants utilize bacteria to consume waterborne wastes and purify water, but they produce large amounts of sludge. In open systems like these, however, the efficiencies are hard to calculate. It is imperative to a CELSS that bacteria, micro-organism food chains, and advanced anaerobic treatment be better understood to prevent mass from being locked up within the system. The spin-offs attained can be directly applied to increasing the turn-around of recycled water from sewage treatment plants in addition to closing the water loop for a Lunar Base.

A major stumbling block associated with a CELSS is the basic lack of understanding of bioregenerative systems. The previous classes (USRA Advanced Mission Design) have addressed this issue and determined a way to depict organisms using a systems engineering approach. The first step of this "characterization" was to simply consider each organism as a "black box", in which all the complexities inherent to an organism occur, allowing simple handling of its inputs and outputs. This black box can then be broken down into three levels: functional, process, and operational (Figure 3). The functional level considers the inputs and outputs over an organisms lifespan in terms of mass. This allows a proper mass balance to be determined by correctly matching the inputs and outputs of the organisms. The process level allows one to consider the temporal aspect associated with these inputs and outputs derived from the organisms growth curve, enabling one to determine the correct phasing/harvesting of the organisms. In addition the operational level considers the power, mass, and volume support requirements attributed to each organism.

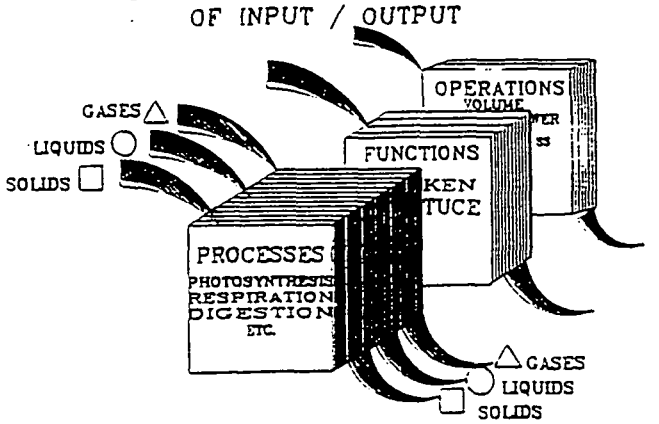

Figure 3: A systems engineering approach, treating each organism as a 'black box', has been chosen to describe and characterize possible candidates for a controlled ecological life support system.

Utilizing this systems approach, a mass balance was arrived at by writing a computer program, which then provided us with numerous possible combinations of organisms for a closed system. However, to verify this mass balance, an accurate characterization of organisms in closed growth chambers remains a stumbling block that needs to be overcome. In order to further understand these biological systems, research into critical technologies and bioregenerative performance depends on metric characterization.

There is an immediate market for the spin-offs gained form CELSS research. Greenhouses for example would directly benefit from any work done in reducing their staggering energy requirements. As a rule of thumb a greenhouses uses 100 times more fuel than field crops for producing plants like tomatoes. Furthermore, research into lighting systems such as LED that last five times longer than current lighting systems would significantly decrease the replacement costs and directly benefit the greenhouse industry. Therefore, any research into improving energy and maintenance efficiencies has direct applications to greenhouses. In addition to plant lighting there are many options for current critical technologies such as hydroponics, monitor and control, harvesting, and processing. Therefore, trade studies need to be performed in these areas in order to Figures out the best candidate; based on parameters like mass, power, volume, safety, cost, and reliability.

In order to achieve the goal of a Lunar base with a Closed Ecological Life Support System there must be a realistic and flexible plan to implement it. The Apollo program for example, had a phased plan to put man on the moon. They did not just jump into the unknown but instead they developed the technology in progression with such programs as unmanned Vanguard, Redstone, Atlas, and Saturn. In manned space flight they also implemented proven technologies as well as used a phased approach with the Mercury, and Gemini programs before the actual Apollo capsule was used. This evolutionary approach not only builds on previous technological steps but also is flexible to variable economic and political support. The approach that was determined for a Lunar base by the spring Space Habitation class was also a phased approach which broke the research down into three phases: a ground based phase, a space based testing phase, and an operational phase. The basic rationale behind this particular phased approach is that CELSS research is so important to the understanding of the Earth as an ecosystem and contains so many industrial applications, that if the mission is scrapped after the ground based phase, numerous benefits would still be attained. Similarly, the space based and operational implementation phases have direct and immediate returns that make each step worthwhile regardless if the entire mission is realized or not.

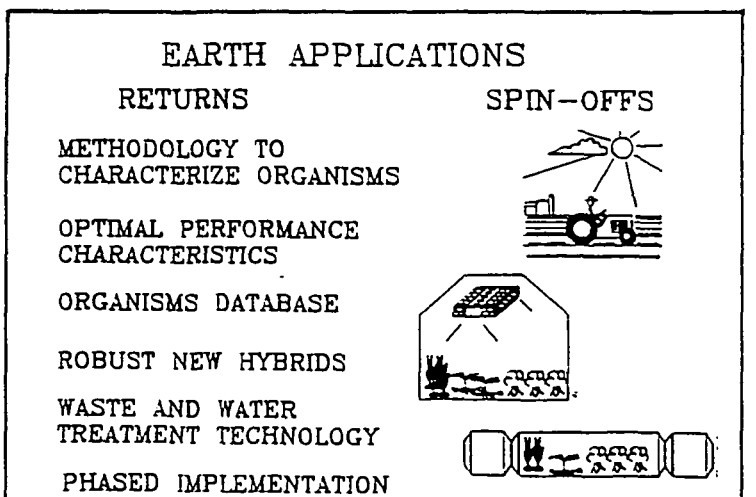

Figure 4: Numerous spin-offs for Earth applications may be derived from CELSS research.

In order to have a successful plan it is necessary to have a step by step method in which spin-offs and Earth applications are realized at each phase (Figure 4). Additional returns from the ground based research of organisms are as follows: methodology to characterize organisms, optimal performance characteristics determined, organism database, robust new hybrids, waste water treatment technology, phased implementation determined. Spin-offs that would be realized are better resource usage, increased crop/livestock production, better yield

predictions, understanding of individual contributions to the ecosystem, benefits from waste water treatment improvements, efficient food production procedures, and a transportable phased ecosystem to reduce resupply to remote terrestrial bases, such as in the Antarctic, desert, or underwater.

The main focus of the CELSS group was to determine the phased implementation of a bioregenerative system for a Lunar base. After examining a number of possible strategies such as establishing a full scale system right from the start, building a system by integrating organism pairs until a full scale system is reached, or introducing one organism into the system at a time, the latter method was chosen. This method has less initial mass costs, has an evolutionary progression, is flexible to programmatic concerns like funding, is less complicated, is easy to implement,and provides returns and benefits at each stage.

The initial Lunar base would use a physical/chemical system with an integrated waste/water treatment system for water recycling. This water loop becomes very important in long term stays because water represents over 90% of the total resupply mass. Plants were chosen to be the next component added to the system because of their impact on resource recycling and because they are less complicated to integrate with existing physical/ chemical systems and other organisms. Lastly, animals will eventually be phased in until a full scale system is achieved. The optimal phased approach that was determined is presented in Figure 5.

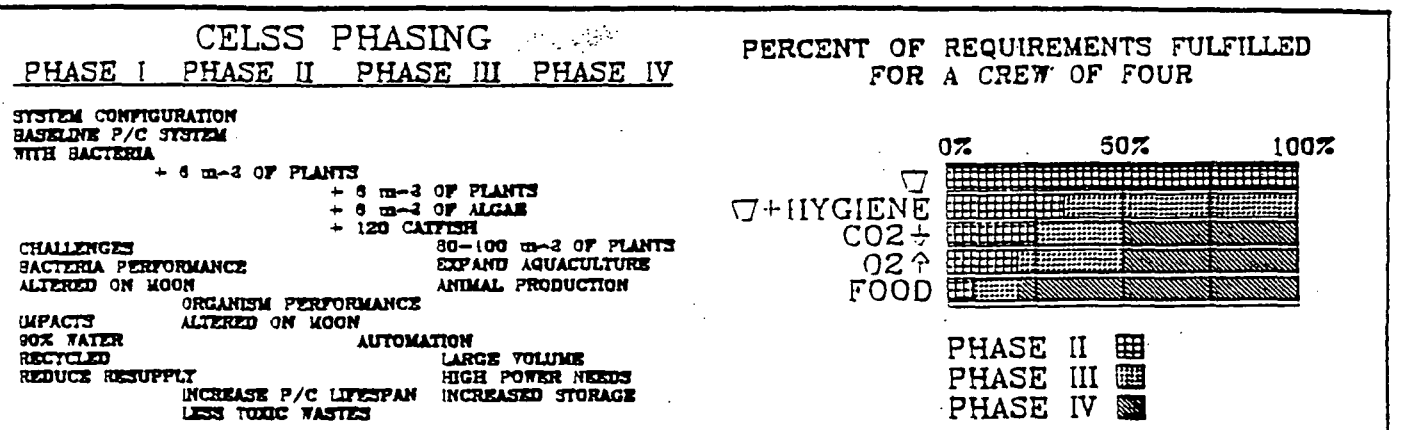

Figure 5: Phased evolution of a balanced bioregenerative life support system. For each integration step, impacts on the existing life support system as well as challenges can be derived. The amount of consumables provided by the bioregenerative part of the life support system are shown for each phase.

In a previous design effort (University of Colorado, 1990), a systems engineering approach successfully characterized organisms. Employing this convention, a balanced bioregenerative life support system was designed with 120 m^2 of plant growth area per person. This compares to the 279 m^2 of intensive agriculture area in Biosphere 2 and the estimated 6 - 25 m^2 from the NASA-CELSS research. A methodology for a phased implementation of such a mass flow balanced system is presented in this paper. Furthermore, returns and spin-offs have been determined, stemming from ground-based research to space-based testing and finally Lunar operation.

Many tasks must be performed daily for CELSS research to bear fruit. For instance, care of plants and efficient volume control ensures the longevity of bioregenerative experiments. Robots must be utilized to partially tend the CELSS, freeing astronauts to further persue CELSS research. Also, a number of support requirements including power, mass, and volume must be met.

Infrastructure An infrastructure is the basic foundation or underlying framework that supports a mission and supplies its fundamental needs. Ideally, once in place, this infrastructure can be taken for granted, like a highway system or a telephone network is in today's society. Also, although the primary mission of the infrastructure is to enable a Lunar base, each element should have specific returns and Earth applications. There are two distinct phases to the development of an initial Lunar base with a Closed Ecological Life Support System, the ground based and space based phases. Since the ground based phase serves as a stepping stone into space, it must be developed first. The ground based elements needed are a closed volume capable of supporting plant and animal life, facilities to allow human integration into the CELSS, a power system, and a thermal control system.

The first segment of the ground based infrastructure to be developed is a life enabling closed volume capable of supporting the CELSS organisms. This support structure must be capable of maintaining the proper

temperature, humidity, and gas concentrations needed for the growth of each organism. It must also provide the proper lighting, nutrient delivery, and waste handling systems, and should be of sufficient volume to allow for a phased implementation. It was estimated that 1 m^3 will be required to support 1 m^2 of growth area for lettuce, and a volume of 3.2 m^3 is sufficient for 120 catfish and an algae system. Therefore, a total volume of 15.2 m^3 will be sufficient to allow expansion through CELSS phase III. Since a Space Station Freedom module is to be utilized for the Lunar structure, it should also be used for the ground based CELSS research, allowing for the development and testing of the same facilities and systems that would be required on the Lunar surface.

There are many Earth based applications of the CELSS infrastructure. For instance, small reliable gas sensors could be utilized by material processing industry and others in which gas purity levels are important. The obtainment of complete closure could also benefit these same industries by improving and lowering the cost of clean room technology, thus facilitating the production of cheap, yet high quality, medical products, computer chips, and aerospace components.

Once the CELSS has been tested using plants and animals, humans will be integrated into the system. While technically humans are animals, they require different, although mostly analogous, support facilities. As was stated earlier, a crew of four was chosen for the initial Lunar base. This allows for a large enough skill base among the crew, redundancy for critical skills, and the ability to complete labor intensive tasks with the initial crew while minimizing the initial Lunar base mass. A list of the required facilities and their volumes for a four person crew is given in Figure 6.

FACILITIES	VOLUME (m^3)
personal quarters	18.8 [1,2]
galley	6.4 [3]
hygiene/waste	4.5 [1]
health maintenance	4.5 [1]
dining/recreation	4.8 [2]
data management/ com.	2.7 [3]
exercise	varies
maintenance	2.7 [3]
EVA storage	12.0 [1]
ECLS	9.5 [3,4]
storage (90 days)	22.6 [3]
CELSS (through phase 3)	15.2

Figure 6: Facilities and approximate volumes for a human habitat on the Lunar surface for a crew of four.
1 (Capps, et al, 1989) 2 (Woodson, 1981)
3 (NASA, 1985) 4 (NASA, 1983)

The third ground based element needed is a small, self contained power supply to generate the electricity for the CELSS and human support systems. The primary requirements for a Lunar power system are that it be safe, reliable, and capable of generating the baseline Lunar power requirement of 100 kW. Several options are available for Lunar implementation, including Radioisotope Thermoelectric Generators (RTG), nuclear reactors, solar dynamic and photovoltaic, and advanced methods such as solar windmills and using thermal gradients. Although RTGs have been used extensively for other purposes, the integration of hundreds of 500 Watt RTGs into a single power system would present a formidable challenge. The advance methods are ruled out because there is insufficient data available on either, although they could be viable options for power system expansion. Consequently, nuclear reactors, solar dynamic, and photovoltaic systems are the choices available needed to provide power for a Lunar base. The current power to mass ratio for a photovoltaic system (without an energy storage system) of 66 W/kg is clearly superior to that for solar dynamic (2.5 W/kg) or nuclear (10—28 W/kg). The main drawback to using photovoltaic systems for most Lunar applications is the mass of energy storage batteries to provide power during the Lunar night. However, if the solar arrays could be placed at a site where continuous or near continuous sunlight is feasible, such as on a mountain near a pole, a high power to mass ratio could be realized while avoiding the safety problems of using nuclear power. If not, then a nuclear reactor, like the SP-100, is the best alternative.

The development of either a nuclear or solar power system would have definite, near-term Earth applications. Currently, nuclear power is viewed as unsafe by the general public, and solar cells are not efficient enough to make solar power commercially attractive. Both of these problems would need to be addressed in the power system development. If solved, then either nuclear or solar would become a viable alternative to using environmentally damaging, and increasingly scarce, fossil fuels as our primary energy source.

Since much of the power supplied to the module's electrical and mechanical systems will be converted into heat, it is necessary to utilize some sort of heat rejection system to maintain an acceptable thermal environment. The system should be sized to handle the maximum power level (100 kW) and be capable of sustaining the optimum temperature range for each individual organism. Several methods are available to accomplish this task, including heat pipes, new techniques like a liquid droplet or moving belt radiator, or by using the moon as a heat sink. The final method is not desirable due to the low heat capacity of regolith.

However, either of the advanced methods could realize significant mass savings of up to one-fifth of a comparable heat pipe array.

Many heat rejection systems used today utilize chemicals, such as Freon, that have been proven to damage the environment. Therefore, one benefit of the CELSS heat rejection technology would be to provide a small, lightweight, yet environmentally safe, thermal control system for use on Earth.

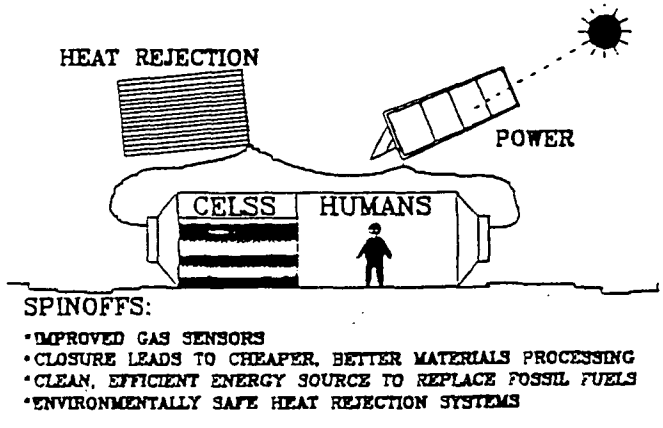

Figure 7: Possible spin-off technologies from the ground-based research in CELSS infrastructure.

Once the ground based phase has been completed (Figure 7), a substantial building block will be in place for the space based phase, the development of a Lunar base. Nevertheless, modifications must be made to adapt the ground based elements to the different thermal, gravity, and radiation constraints of the Lunar surface. Also, several additional elements are needed for the space based phase; a Lunar site, a communication network between the Earth and moon, and a transportation system capable of transporting all of the Lunar base components to the chosen site. During this phase safety also becomes a critical issue for all designs since help is approximately 380,000 km away.

Some of the major threats to crew safety on the Lunar surface include radiation, meteorite strikes, fires, loss of power, and illness/injury. For instance, since radiation doses above 25 rem can have adverse effects on human beings, the module must either have adequate shielding to protect its inhabitants or be placed in an area sheltered from solar radiation. Dual ingress/egress is an extremely important safety feature for the Lunar base. This allows the crew to escape from the module in the event of a catastrophe, such as a major fire, even if one of the exits is blocked. A second important safety feature is an escape vehicle capable of transporting the crew from the Lunar surface back to Earth. This would be necessary if something were to render the module uninhabitable or if a crew member should become critically injured or ill. Also, although the module is to be designed with redundant critical systems, secure storage must be allotted for all important life support elements, such as power, food, water, and air. A ninety day supply of each will be provided to allow the crew to fix the system malfunction, if possible, or sustain them long enough for evacuation or rescue to be possible.

The first Lunar element that will be needed is a site for the base. There are several qualities that are desired of a Lunar site, including a large relatively flat area; good transportation, communication, and solar access; and protection from meteorites and harmful solar radiation. A polar site in the shadow of a large mountain or crater would fulfill all of these requirements plus provide a constant thermal environment for the base, eliminating the expansion and contraction associated with thermal fluctuations. Since approximately 2% of the Lunar surface, or 760,000 km^2 is in permanent shadow, it should be possible to find such a site. Since there is a very limited amount of information available about the polar regions of the moon, detailed remote sensing and mapping will be necessary to identify possible sites. Then, robotic lander/rovers will further investigate each site and provide additional data so a site best meeting the above criteria may be chosen.

A communication network is needed to allow audio/visual data transmittal between the Earth and the Lunar base, enable robotic teleoperation, and provide system housekeeping and evaluation during non man-tended periods. The maximum data rate of 20 Megabits per second (compressed) with a bit error rate of 1×10^{-9} needed for telerobotics is within the capability of current technology, either through the use of spread spectrum millimeter wave technology or optical techniques. A more important consideration is the placement of satellites to ensure near-continuous contact with a polar base. Also, low Lunar orbits are very unstable, requiring smart satellites capable of continuously evaluating their orbital status and making needed corrections. Several of these satellites in a highly eccentric polar orbit would maximize contact time with the base . The signal will then be relayed to a network of geosynchronous satellites which will in turn send the signal to an Earth receiving station.

One spin-off of the communication technology is in the use of the low level expert systems and artificial intelligence employed by the smart satellites. This could be utilized for a number of applications including making buildings more energy efficient by enabling them to use not only the heating system to control temperature, but also drapes, blinds, window tinting, and solar energy.

The final infrastructure element needed for the space based phase is a transportation system capable of transferring all of the base elements to the Lunar surface and placing the communication satellites in orbit. The most efficient method to achieve this is through the use of a three part system, utilizing a heavy lift vehicle (HLV), an orbital transfer vehicle (OTV), and separate cargo and Lunar landers. Since a heavy lift vehicle is not currently in the U.S. launch vehicle inventory, the Lunar lander should be designed first, thus defining the payload requirement for the OTV, and subsequently the HLV. The cargo lander must be capable of landing one module and node, approximately 20,000 kg, while the manned lander must provide transportation to and from the Lunar surface for a crew of four. The payload requirement for the OTV is simply the largest lander, or 48,500 kg for the cargo lander. The heavy lift vehicle to be used is an inline shuttle derived vehicle capable of delivering 95,000 kg to low Earth orbit, allowing an entire Lunar mission to be delivered to LEO with only two HLV launches.

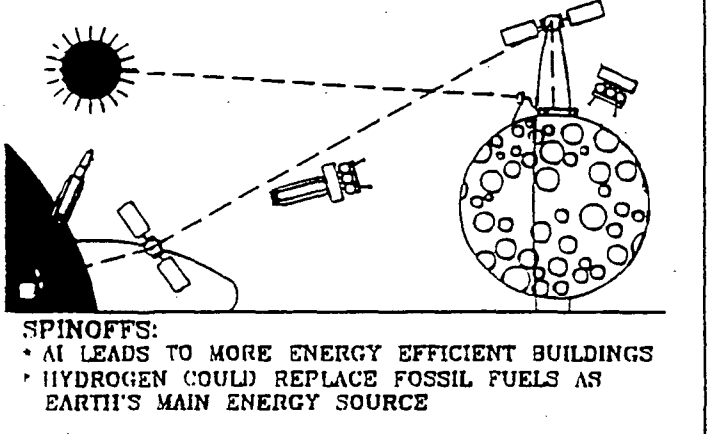

Figure 8: The required Lunar Base infrastructure elements show high potential for Earth-based spin-offs.

One of the critical technologies of the transportation system is the development of cryogenic handling, pumping, and bulk long term storage methods. The resolution of these problems would allow hydrogen to be used in place of fossil fuels for many Earth applications, such as in automobiles. Since hydrogen is a clean, efficient, and abundant source of energy; this would not only benefit the environment, but would provide a cheap source of energy as well. A second critical technology with Earth applications is the terrain following radar navigation system to be employed by the landers. Not only would safe Lunar landings be possible, but the system could also be utilized by the commercial aviation industry to improve landing safety at night and during bad weather.

Once the transportation system and communication network are operational and a Lunar site has been chosen, the ground based elements will be transported to the moon and base construction and assembly begun (Figure 8). Due to workload and safety concerns, robots will be utilized for many of these tasks. Some of the infrastructure support requirements are the ability to clear an area of large obstacles, such as boulders; transport up to 20,000 kg payloads to their proper locations and place them in their desired orientation; and be capable of performing simple construction and assembly tasks. Since robots will also be utilized during the site preparation process and for CELSS maintenance, it is clearly a critical technology requiring more in-depth study.

Robotics Establishing a Lunar infrastructure is vital, but it may require endless hours of labor intensive extravehicular activity (EVA). In space or on the Moon, EVA presents considerable health concerns. For example, the puncture in Jay Apt's glove on Space Shuttle mission STS-37, could have been fatal in the cold vacuum of space. Moreover, harmful solar radiation and meteorite barrages add even greater risk to the hostile environment. The degree of risk is directly proportional to the time spent exposed to it. A major driver for redesigning Space Station Freedom was to decrease astronaut EVA time for assembly from 36 to 6 hours and reduce the thousands of hours required per year for maintenance activities. EVA preparation itself takes 2-4 hours of pre-breathing and gearing. This rescued time can be better utilized to accommodate more experiments at the same launch price. A system of robotics can meet these labor needs to reduce human risks and mission costs. By working with industry to co-develop robotics, costs can be further reduced, and benefits can be brought back to Earth.

Automation and Robotics are a mechanical work-force designed for a wide array of tasks. In the last decade, the robot population has exploded to approximately 350,000 units worldwide (North-Holland, 1990). Machine production industries control the largest share, with some automobile manufacturing corporations employing upwards of 300 robots per plant. A much smaller share find their way into a wide variety of industries ranging from fashion to space.

NASA has historically exploited automation and robotics to ensure safe and cost-effective flight control systems and surface surveying probes. Launch and guidance systems from Vanguard to the Space Shuttle have been automated to enhance flight control performance and free astronauts for orbital tasks. Furthermore,

Apollo Lunar probes , Viking planetary probes, and the Shuttle's remote manipulator arm have all applied robotics. However, these transportation and surveying systems differ greatly from industry's focus on construction.

As the scope of space missions continues to grow, so does the need for larger and more mass intensive structures in space. Current launch systems cannot transport them, and the progression of heavy launch vehicles may never catch up to future space station upgrades and extra-terrestrial outposts. NASA must endeavor to work with industry to improve current robotic construction and design robotic systems for the benefit of both. The time to act is now as Japan owns an overwhelming 63% of the world's robots to America's 12% (North-Holland, 1990).

CELSS	Infrastructure
LED replacement	Cargo Transportation
Crop transportation	Construction/Assembly
Crop harvesting	Lunar surveying
Growth/Volume control	Site raking
Etc...	Etc...

Figure 9 : Establishing a Lunar base and maintaining a Lunar CELSS requires many labor intensive tasks.

The Earth to Lunar CELSS mission elucidates the needs discussed above. Both areas of the mission, CELSS and infrastructure, require a number of labor intensive tasks be completed. A partial general list of requirements is given in Figure 9. Each general task has a set of very specific procedures. For example, one of the most meticulously labor intensive CELSS activities, changing burnt-out LEDs, is detailed in Figures 10. Likewise, a vital infrastructure requirement, retrieving cargo from a Lunar lander, is developed in Figures 11. These two lists represent completely different activities requiring not so different means. Though changing LEDs prescribes precise sensing and hauling cargo requires a stake driver, both activities need a power source, an automated control system, and a system of robotic motors and arms. Beyond the tasks described above, LED heat sensors will detect thermal abnormalities in the module hull, and the stake driver will take core samples of Lunar regolith. In this respect, a small yet complete set of required components is capable of accommodating most of the CELSS and infrastructure needs. For redundancy and cost-effectiveness, the components will be modular with respect to a central power and control unit, much like a tractor. So, in the ideology of Mr. Potatohead, the innovative MPH Lunar robot (Figure 12) was nee.

Scan LED with light sensor for failure
Remove burnt LED
Transport LED to disposal
Transport new LED from storage
Insert new LED

Figure 10: Replacing a failed LED breaks down into specific labor and technology needs.

Locate cargo
Attach cable to cargo
Drive stake into regolith
Position cable around stake
Attach cable to winch
Operate winch

Figure 11: Retrieving cargo sent from the Earth is a very labor intensive, yet simple task.

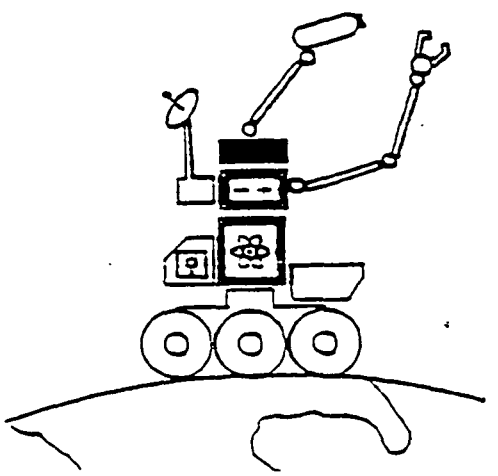

Figure 12: The MPH Lunar Rover (Mr. Potatohead)

The MPH is an autonomous corporal power unit that enables variable component configurations. Electric power is generated by a Dynamic Radio-Isotope Power System (DIPS) and stored by zinc-air batteries. These were chosen primarily for their high specific efficiency and storage capability, respectively (the trades are shown in Figures 13 and 14). Most activities in the vicinity of the module will be powered by an umbilical cable to the main generator, but the power systems give autonomy away from the module and general redundancy. Also in the corporal unit, a computerized neural network controls all robotic actions. The components, listed in Figures 15, will be arranged according to task needs. Current technology, however, is not up to tackling the Lunar environment and other

mission-related limitations. For instance, Lunar dust may inhibit optics, and mass intensive hardware raises launch costs.

Generator Type	Pmax (kWe)	Pspec (We/kg)	Efficiency (We/Wth)	Lifespan (years)
RTG	.5-5	5.2	4.2-6.6%	10
DIPS	1-10	>6.5	18-24%	7
Nuclear Reactor	.5-1	80		

Figure 13: The trade study of nuclear power generators (Faller, et al. 1989) reveals DIPS as the economic technology choice. RTG: =Radio-Isotope Thermal Generator; DIPS = Dynamic Radio-Isotope Thermal Generator; Pmax = peak electric power output.

Storage Type	Pspec (We-hr/kg)	Lifespan (years)
RFC	20-35	
Ni-Cd Batt.	20	15-20
Ni-H2 Batt.	30	10-20
Pb-acid Batt.	25	10-20
S-Na Batt.	100	
Zn-air Batt.	200	

Figure 14: Though lifespans may be roughly the same, zinc-air batteries can store twice as much electric power as the next best battery or regenerative fuel cell (RFC). Sulfur-sodium and zinc-air battery data from Cook, 1991. All other data from Faller, et al. 1989.

Ongoing research and development will not only overcome some of these roadblocks, but accrue benefits stemming from technology improvements. For example, overcoming the problem of Lunar dust on camera lenses may lead to a particle repelling glass. The development of stronger, lighter materials have considerable implications for auto and aerospace industries. Developing titanium-aluminum alloys will reduce the weight of aircraft engines by 60% (Brown, 1991). Beyond industrial spin-offs, medical implications are pacemakers with efficient long-term batteries, durable cybernetics with strong efficient motors, high resolution internal cameras, and teleoperated subdermal probes. Cleaner, more efficient power systems have global economic and environmental impacts. The applications need not stop with the separate MPH components. In Japan, robots have raised industry productivity and improved work safety and health with just a .02% increase in unemployment (Blumenthal, 1990). Currently, teleoperated robots are being employed for nuclear plant maintenance, off-shore mining, underwater dam maintenance, and orange picking to name a few. MPH spin-offs may be prototypes for future life-saving fire fighters, blood-handling sterile nurses, time efficient home constructors and painters, and space station builders. In all cases, the MPH program offers immediate and continual benefits whether it is completed or not.

Remote camera to view tasks and site objects
End effectors for object manipulation, fastening, and sensing
Winch for heavy towing
Pump for fluids handling
Software to enable different tasks
Cable for heavy towing
Bones are mechanical limbs for extension
Teleoperations/Relay to enable camera transmissions and teleoperations
Basket for light storage during transportation
Motors to run all mechanical joints and hardware
Stake driver to embed stakes into regolith
EVA locomotion unit for mobility on Lunar surface
Rail locomotion for mobility and power inside module

Figure 15: The MPH Lunar robot can accomplish a variety of tasks with a small set of utility components.

A comprehensive Earth-based R&D program will help overcome technology roadblocks and provide constant returns. The first stage consolidates the safest and most reliable existing technologies with the most desirable mass, volume, power, and resupply constraints. This primary MPH will be tested both in the Earth-based CELSS module and in reduced gravity KC-135 and space shuttle environments to provide improvements during the second stage. The MPH will aid in the Lunar site selection process, and 3 MPHs will be used for site preparation and construction. The phased robotics mission advances current technology and is a feasible approach that will yield returns both immediately and continually, on the Earth and in space.

Conclusions This paper has compiled both the space and ground based benefits for a Lunar Base with a CELSS, and incorporated them into the overall rationale for a sustained Lunar mission. The necessary steps to achieve this endeavor were outlined, with an emphasis on the phased implementation of biological elements into an initial P/C life support system. The implications of such a system on a Lunar mission infrastructure were also investigated, thereby providing a sanity check for the CELSS requirements. Recommendations of designs were made for shelter, site location, transportation, navigation, power, safety and thermal regulation. Lastly, because a CELSS will increase generic labor demands, there are numerous opportunities for robots to accomplish not only CELSS tasks, but other Lunar base work assignments. This research resulted in several design conclusions for not only a CELSS or Lunar robot, but for many number of Earth based robotic applications.

Although there remain roadblocks in the path of demonstrating that a controlled environment can be optimally designed, closed and maintained, some of these challenges are already being met by innovative solutions. Through a continued and expanded commitment to CELSS research and development, the necessary technologies can be produced for a number of applications including those for a Lunar base. In addition to maintaining the nation's lead in space technology, and increasing our industrial strength with improved robotic capacity, a Lunar mission can benefit the world as a whole. In fact, the most compelling argument for CELSS research is not in decreased resupply for Lunar, deep sea or polar missions, but in providing a comprehensive ecological data base. From this knowledge, we may tackle a variety of other problems, such as utilizing biological means to increase waste treatment in third world countries, thus decreasing the spread of disease. On a global level, satellite observations, combined with ecological models based on CELSS research, can be integrated to observe the biological engines of the Earth. This will allow more accurate conclusions on organisms like plankton's role in affecting the disputed consequences of the Greenhouse Effect and global warming. After all, it is the very result of space research on our planet and others that we are aware of such problems. This vital connection between space exploration and the citizens of the world is the heart of the justification for the space programs' continued existence. It is in this light that we should further pursue space exploration, and the multitude of returns it will continue to deliver to human kind, both on the Earth, and in space.

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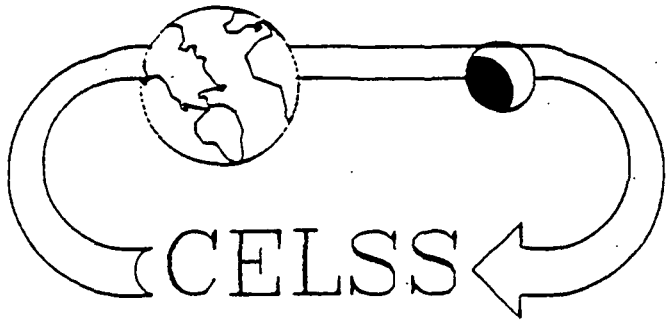
FINAL REPORT

EARTH TO LUNAR



EVOLUTION

UNIVERSITY OF COLORADO
DEPARTMENT OF AEROSPACE ENGINEERING SCIENCES

L.N. Dittmer, M.E. Drews, S.K. Lineaweaver, D.E. Shipley
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Sponsored by NASA/USRA
June 18, 1991

Earth to Lunar CELSS Evolution
Final Report

1.0 INTRODUCTION

This paper summarizes the work of the Spring and Summer1991 Space Habitation class and our recommendations for the design of a first phase implementation of a Lunar Base with a Bioregenerative Life Support System. But before the results of this research is described, it is important to understand the rationale and methodology we used at each step in our design.

Until July of 1969, the structure of the U.S. Space Program could be described as the necessary steps that had to be accomplished to achieve a goal. Even though it was a Herculean and courageous goal, landing the first men on the moon exhibited all the same results that come from the achievement of any goal; for a goal marks the termination point in a race, and the end to which effort is directed. (Webster, 1977) Since the end of the Apollo program, NASA has had to grapple with the problem of directing the space program without a new clear objective. This is evident in the fact that although the public seems to support the space program, the average American would find it difficult to point to the specific goals in the current space agenda, nor a justification for them. In addition, even though risk and accidents have occurred in the space program since its inception, including the loss of three astronauts in the Apollo era, the Challenger accident has severely affected NASA's image as a capable organization. Bureaucracy mounted since 1986 has not solved the problem either. For example, an error in launch processing which involved a work platform being left in the engine compartment of the shuttle, only to be found during launch preparation, shows that NASA is not yet free of serious and avoidable problems. To determine some solution, a more in depth perspective is needed.

NASA'S CHEMISTRY: THE CURRENT AND HISTORICAL SPACE PROGRAM
Not surprisingly, NASA today is the product of a number of influences since its birth in 1958 (see Figure 1-1), 12 months after the launch of Sputnik. The original goals included orbiting a man in space, first accomplished by the Soviets in 1961, and a race to the moon. As mentioned above, after this goal was accomplished in the height of American pride, as Apollo 11 touched down on the Lunar surface in July of 1969, the Space Program itself was left to enter the new decade without a continuous series of objectives.

That same year, when President Nixon appointed Vice President Spiro Agnew to be the chairman of the Space Task Force, his ambitious recommendations for a reusable space vehicle, a space station and a Mars mission, were shot down. At the time, Congress was very concerned with how the $25 billion spent on Apollo could have been used at home on social programs. NASA escaped with the reusable space vehicle idea only. However, NASA still had very high expectations for this vehicle, that we now have come to know as the Space Shuttle.

The Shuttle's primary purpose was to decrease the cost to access to orbit; but there was some dichotomy of thought surrounding just how well it could do this. One NASA associate administrator theorized that launch costs may be as low as $5 dollars per pound, and that profits could eventually be generated. Adversely, an engineer at NASA, A. O. Tischler, pointed out the overhead of NASA salaries imposed at least a $500 dollar per pound cost on all launches. He also stated that before NASA takes a "precipitous, total immersion dive into the future...it would be shrewd to make sure first that we know how to swim."

Observations such as these were drowned away by a pork barrel minded Congress anxious to secure funding projects for their district, and they added their own list of expectations to the Shuttle shopping list too. In fact, the vehicle that ended up as the Shuttle is actually the constrained product of a number of incompatible shopping lists of requirements from not only NASA and Congress, but the Air Force and the Office of Management and Budget as well.

Despite these incongruities in the designed purpose of the Shuttle, both the Shuttle fleet, and the overall Space Program, have enjoyed immense success since 1969. Ten more men have been landed on the moon's surface, satellites, including Voyager and Pioneer, have produced close observations of seven of the planets, the two robotic Viking probes have landed on and investigated the Martian surface, and Skylab has logged months worth of man hours in space. The Space Shuttle alone has proven to be a spectacularly productive and advanced space vessel, including the highest thrust to weight ratio of any engine, and the lightest and most efficient thermal protection. It has launched large scale satellites, and performed the first retrieval and repair of satellites in orbit (Roland, 1985). These accomplishments are especially impressive in light of the fact that funding to NASA has dropped from 0.8% of the GNP in 1969 down to 0.2% in 1975, where it has remained since.

These achievements have been eclipsed, not only by the Challenger accident, but also by other frustrating problems including the aberration on the Hubble Space Telescope lens, and engine pump leaks and umbilical door cracks in the Space Shuttle. NASA's job is agreeably a difficult one; it takes 1.2 million procedures to successfully be completed for each launch the Space Shuttle (Augustine, 1990). In addition, NASA must perform openly in the public eye. But solutions to date, amounting to mostly bureaucracy, have proven that lessons that should have been learned far earlier, have not yet been recognized. In the heart of NASA's next major goal, the construction of a permanently occupied space station, a problem over integrating two incompatible types of research, life sciences and materials processing, has only recently been resolved. This was not, however, accomplished before pushing the program years behind. And the most frustrating aspect is that this is the exact problem that was encountered two decades previously by trying to put everyone's eggs in the same space basket called Shuttle.

NASA REPORTS AND THE SPACE HABITATION FILTER BOX

The successive waves of reports concerning NASA are another sign of ailment with the Space Program (see Figure 1-2). Sensing a lack of objective in the space agenda, even after President Reagan called for the development of a permanently tended space station, Congress directed the formation of the National Commission on Space. Their conclusions, published as Pioneering The Space Frontier, made recommendations on the Space Program's transition into the twenty-first century, and referenced them back to fifteen public forums they held nation-wide on the public's impression of the Space Program. The impact of these ideas was developed in Leadership and America's Future in Space. But in the report, author and former astronaut Sally Ride asked the question: "What does the Space Shuttle or Space Station support in the long term?" She also compared the U.S. and Soviet Space Programs, characterizing ours as revolutionary, whereas the Soviets' is evolutionary. In July of 1990, a 90 day study was completed on the procedural segments to implement Space Station Freedom and the lunar and Mars bases discussed in the earlier reports. This report, referred to as the Space Exploration Initiative, identified critical technologies to achieve these goals, specifically life sciences, reliable and more capable space transportation, robotics, surface nuclear power and radiation shielding.

Yet during all this time, literally billions of dollars have been spent on the design, and redesign after redesign, of the Space Station, and with little tangible results to show the taxpayers for their investment. In this light, last year's Augustine report on The Future of the U.S. Space Program, and

the recently released Stafford Synthesis Report, have been published. These reports say little in the area of new information, but have expanded and reiterated in the areas identified previously. Especially on topics such as the continued lack of national consensus on the Space Program, and the need to synthesize technology in critical areas to meet our objectives.

The Space Habitation class has sifted the chemistry of the space program through the information in these reports, and filtered out a set of conclusions:

CONCLUSIONS AND APPLICATIONS TO DESIGN

1. Each step in the agenda must support the goals of the overall Program. One reason a Lunar Base was chosen for our semester project is, in addition to the intrinsic benefits of returning to the moon, it is also a logical and necessary step as a proving ground for future missions.

2. The merits of phasing include:

A. at each step, there is some return for investment

Our mission scenario was designed so that if the program was cancelled at any point, there would still be some tangible returns for the resources that were invested for each step.

B. and new technology is built from the synthesis of old

To attempt an evolutionary instead revolutionary approach, it is important to utilize and modify technology to meet future technological requirements. By choosing a SSF module, proven technology can be utilized and built upon.

3. Each step must identify and be designed with consideration for the potential of spin-off technologies.

By exploring other uses for technologies needed for the Space Program, a wider spectrum of support is generated because the funding invested in maturing them can be applied for many uses, including many here on earth. For example, technology used in the development of robots that can help in the construction of a Lunar Base, can also be used for construction purposes on Earth.

These conclusions were then applied to four major sections of the Space Program, defined as Mission to Planet Earth (MTPE), Mission from Planet Earth (MFPE), Technology Base and more specifically, Launch Systems. MTPE suffers from the "putting all your eggs in one space basket" syndrome, and we examined ways to change the structure of the Earth Observing System to remedy this problem. Two technologies vital to the

future of space exploration are robotics and life sciences, both of which we identified as being currently under-developed. If NASA wishes to meet many of its goals, new or modified launch systems also need to be developed to meet these objectives. Lastly, the next logical step in the human exploration of space outlined as part of MFPE, is the establishment of a Lunar Base. Armed with the Space Program's historical background and a perspective of how previous difficulties can be minimized, we can now examine how a Lunar Base fits into overall rationale and agenda of the Space Program.

1.1 MISSION DESCRIPTION

RATIONALE

The expense of a Lunar Base would be very large, and in order to have public support this expenditure must be justified. Without public support and specific goals, the government is less supportive of NASA programs. However, the expense for a Lunar Base can be accounted for by showing the direct rationale behind it and proving that the Earth applications and spin-offs far out weigh the cost.

The basic rationale for a Lunar Base consists of three main aspects: human factors, economic opportunities, and scientific discoveries (see Figure1-3). One of the major components of human factors is education. An example of how the space program has already affected education is when the enrollment in engineering and sciences increased 27% after the Apollo expedition in 1969. Other contributing factors are an increase in national pride and the chance for human beings to make new discoveries in a new and different environment, commonly referred to as serendipity. Another important aspect is economic opportunities. The Lunar Base's vital purpose is to be a technological test bed, where technologies such as robotics, automation, miniaturization, communications and others will be developed to new heights. A better understanding of these technologies will enable America to become more competitive in the world market. Finally the last aspect is a chance for scientific discoveries that are not so easily accessible on Earth. For example a Lunar Base would allow a more in depth study of astronomy, astrophysics, and the geology of the moon.

Although there are many different opinions on what the goals of the space program should be, the Lunar Base option would be the best one to implement. There are many reasons for this belief. First of all the Lunar Base would be a great stepping stone to Mars, along with the space station Freedom. Further, the Lunar Base would be realistic because

we've been there before and the technology exists to go back. This goal would also be challenging because there have never been extended stays on the moon. From this basic rationale and the current needs of the space program, our mission was determined.

PURPOSE

The mission is to determined a first phase implementation of a Lunar Base with a bioregenerative life support system, established over a twenty-five year span, in order to support a four person crew. The major emphasis of the base will be a test bed for enabling technologies that facilitate sustained life support in space. The base will also demonstrate the potential for long duration stays independent of Earth resupply. In addition, it can aid in the development of new technologies required for permanent habitation in space.

REQUIREMENTS

In order to develop a Lunar Base it is necessary to have the key elements such as a life support system to sustain the crew, an infrastructure to support the base and robotics to assist in the construction of and maintenance of it. Therefore, we broke our class down into three groups: CELSS, structures, and robotics.

1.2 METHODOLOGY

To accomplish the tasks in a efficient and logical way, a specific methodology was implemented . The methodology is as follows: to identify necessary requirements and options, next perform trade studies, then choose a design to implement, define its critical technologies, and identify the direct Earth applications for each step in the plan. A detailed description of the group's individual goals are as follows:

STRUCTURES

The structures group identified and examined the infrastructure requirements for a Lunar Base, including transportation, communication, shelter, power, as well as many others.

ROBOTICS

The robotics group determined a methodology that identifies the robotic tasks needed for the construction and maintenance of a Lunar Base.

CELSS

The CELSS group examined the ideal phasing of biological organisms into a hybrid physical/chemical regenerative life support system as well as analyzed critical technologies for a CELSS such as hydroponics and plant lighting.

1.3 MISSION SCENARIO

Once a rationale for going to the moon has been established, and the purpose of the Lunar Base has been defined, it is possible to develop a mission scenario for the phased implementation of a Lunar Base with a bioregenerative life support system.

This scenario is divided into five phases, each of which builds upon earlier phases and current technology (Figure 1-4). The scenario is also designed to provide tangible benefits and returns after each phase. This ensures that noticeable progress is being made after each phase and that something can be gained from the program even if it should be canceled.

In phase A preliminary site selection and CELSS experimentation missions are conducted. Remote sensing and mapping of the lunar surface will be conducted to provide information for the site selection process. By the end of this phase, a fully functional CELSS experiment should be also be running on Earth and a one-sixth g experiment should be started in low Earth orbit. The one-sixth g experiment will use the knowledge gained through experimentation of the Earth and determine how low gravity effects the CELSS operation.

During Phase B the data compiled during the remote sensing missions will be analyzed and three preliminary sites will be chosen for further study. Also, a communication network will be established, and a lunar transportation system will be operational. This is important for the transport of and communication with the robotic landers/rovers that will do further site evaluation in the next phase. It also gives the heavy lift vehicle time to prove its reliability so that a manned rating can be obtained before it is necessary to transport humans to the moon. By the end of this phase, modifications should have been made to the one-sixth g CELSS experiment so that it is functioning properly. This will provide needed information about how a CELSS system will behave on the lunar surface.

Phase C involves sending a robotic lander/rover to each of the three preliminary sites chosen in phase B. Not only would these rovers provide

further site selection data, but could also carry small CELSS experiments and conduct robotic exercises. These robots will provide a valuable testbed where problems regarding such things as tele-operation and lunar navigation can be investigated at length.

In phase D the site selection information gathered by the rovers will be integrated with that of the remote sensing and mapping satellites. Using this information, final site determination can be accomplished. Also, providing the distances between the three preliminary sites isn't too great, the rovers from the two sites not chosen will begin to travel to the chosen site. This will provide further information regarding the operation of lunar robots, as well as allowing the rovers to be utilized in different capacities by the Lunar Base.

Once the first four phases have been accomplished, the transport of Lunar Base elements can begin. Therefore, a more detailed launch analysis was developed in phase E. Each launch incorporates the same phased approach used in the overall scenario so that tangible returns are realized after each launch.

During the first launch, the main construction robots and their construction implements will be transported to the lunar surface along with a nuclear power supply. The robots' first task would be to set up the reactor, which would subsequently provide them with power. They would also do preliminary site preparation work such as leveling a landing area and grading preliminary roads. This would provide extensive knowledge about robotic construction on the lunar surface.

The second launch would provide an escape vehicle for the crew that is to follow. During its time on the lunar surface, not only would the escape vehicle be capable of performing self evaluation checks to ensure its readiness, but its communication and data handling capabilities could be utilized to transmit data from the CELSS experiments back to Earth. The hydrogen and oxygen supply, which would converted to water for use in the module, could also be used as an emergency fuel source for the escape vehicle's fuel cells.

The third launch would include the habitation module and a small emergency node. Although a single node only provides one source of pressurized ingress/egress, it is not feasible to deliver two nodes to the lunar surface with the module, nor is practical to land a full-size hard node. The emergency node coupled with an internal module air supply

and power from the nuclear reactor would allow for immediate short-term module access should it be required.

The fourth launch is the final outfitting launch for the initial Lunar Base. A second nuclear reactor would be supplied for redundancy, along with an external auxiliary air supply. Also, the second, full-size node will be shipped during this launch to provide the module with a second point of ingress and egress. Once the components of this launch have been successfully hooked up to module, the capability for longer stays of over two weeks would exist.

The final launch of phase E would also be the first manned mission. The four person crew would stay for approximately two weeks and would perform final construction and assembly tasks, as well as conduct final base verification. Depending upon the accomplishments and/or failures of this first manned mission, final base setup and verification may be extended to a second mission. However, after the completion of these tasks, the Lunar Base will be capable of supporting routine man-tended missions.

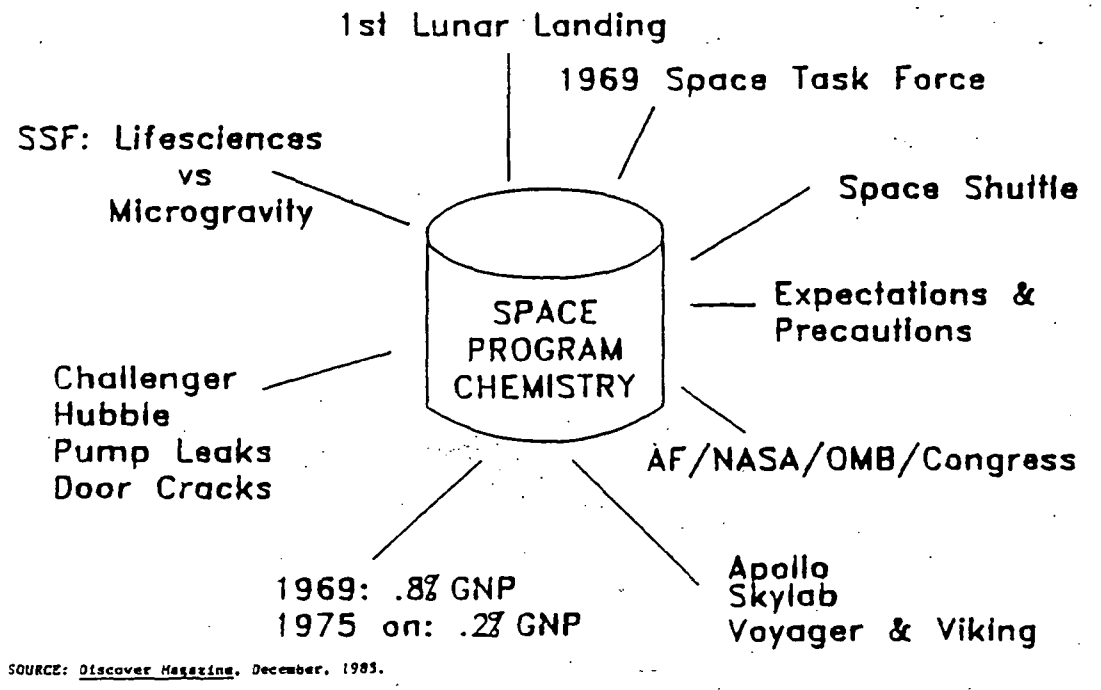


FIGURE 1-1 SPACE PROGRAM CHEMISTRY

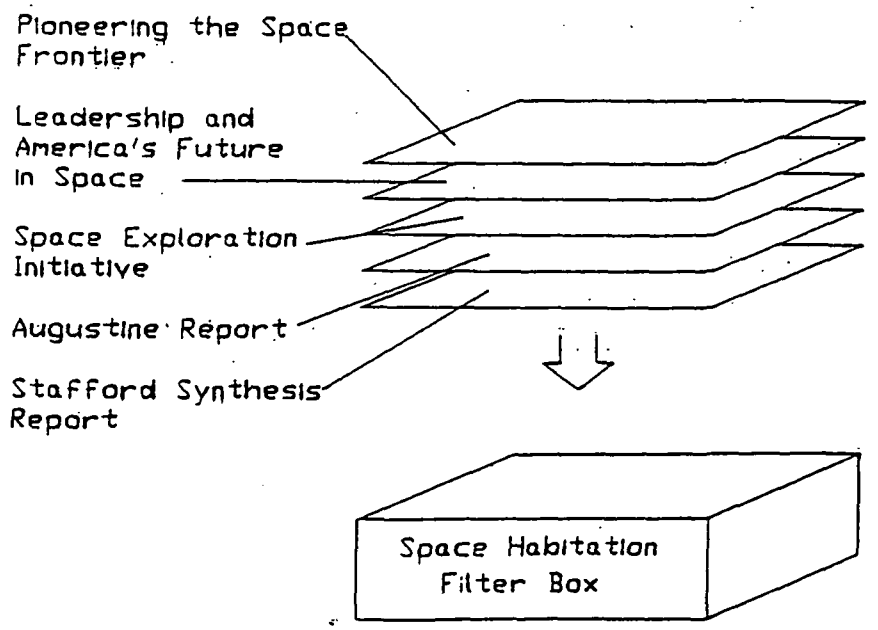


FIGURE 1-2 SPACE HABITATION FILTER BOX

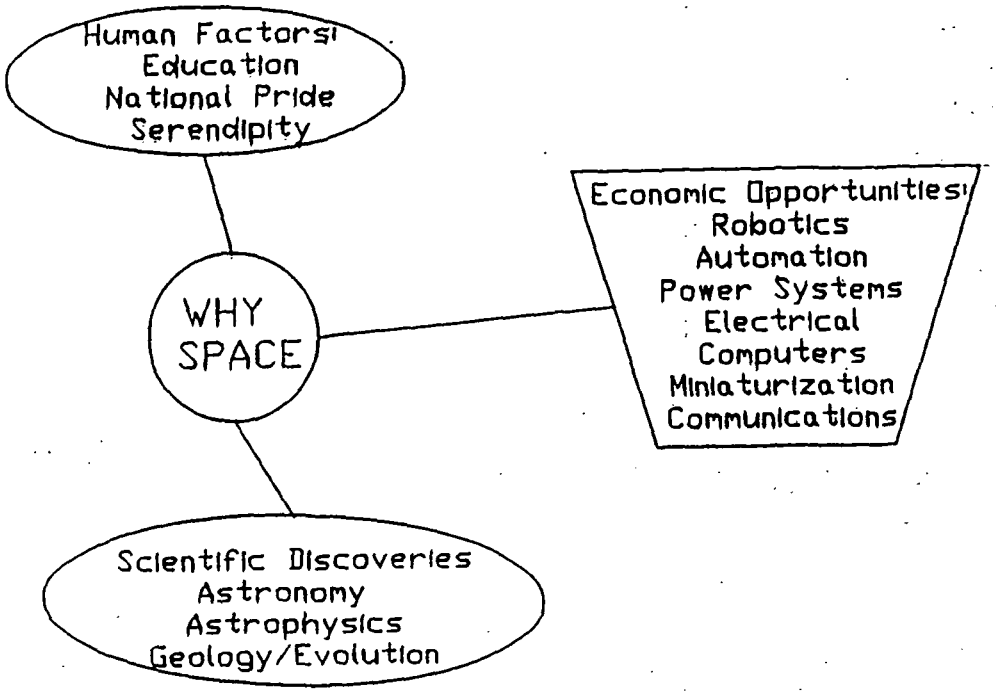


FIGURE 1-3 SPACE EXPLORATION RATIONALE

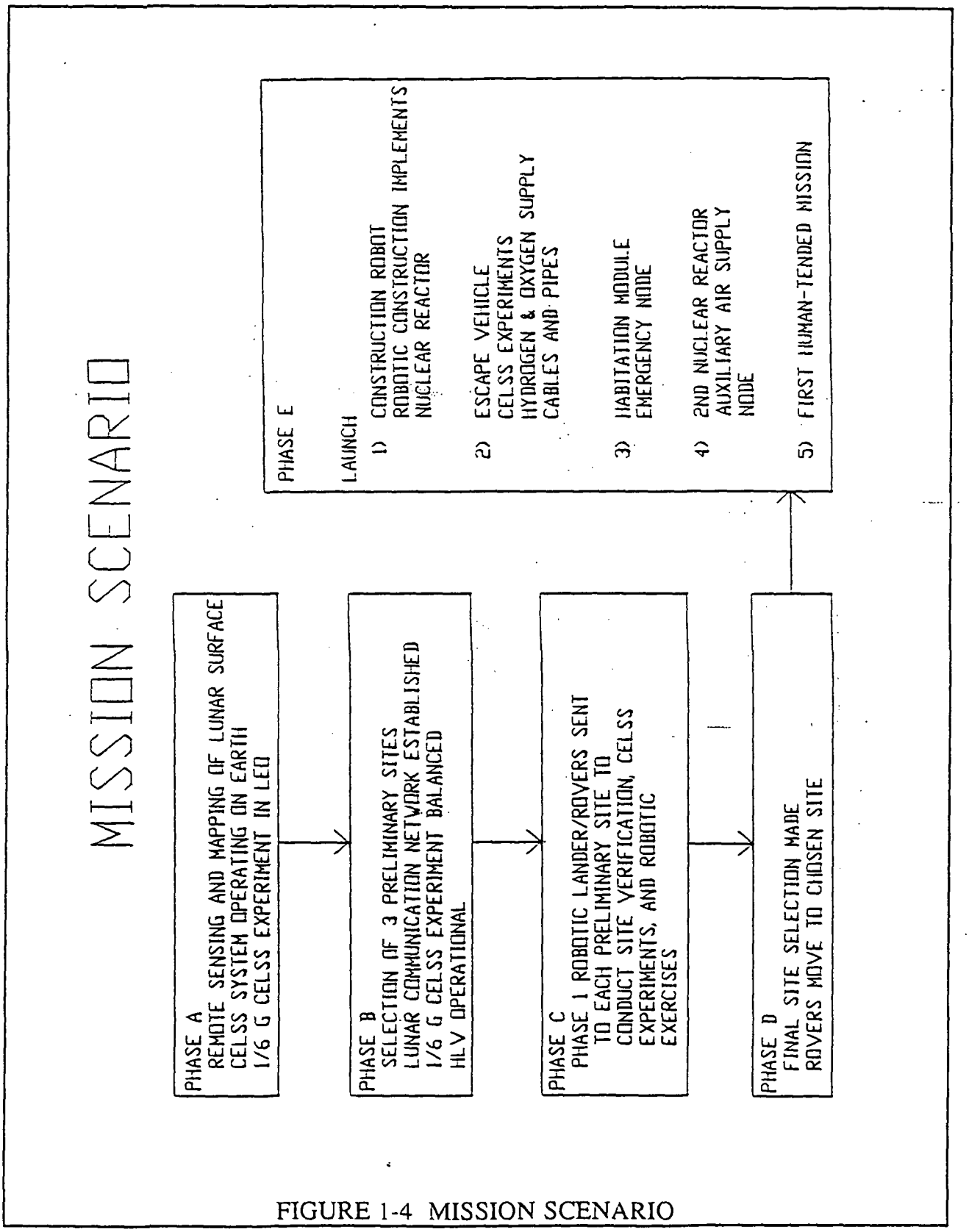


FIGURE 1-4 MISSION SCENARIO

2.0 CELSS

2.1 INTRODUCTION

As has been previously discussed, there is a strong desire, publicly and politically, to have a manned presence in space. Human tended missions, as well as, unmanned missions provide opportunities for economic, scientific, political, and educational benefits that are perhaps unique in origin to endeavors executed within the space environment. In order for the potential benefits from manned missions to come to fruition, safe and reliable life support systems must be provided.

In the beginning phases of manned space exploration life support systems were functionally nothing more than simple storage systems designed to provide astronauts with the appropriate amounts of air, food, and water. When these resources were fully used, they or their byproducts were discarded into space or stored for return to earth. However, while these initial systems were both successful as well as highly practical, they were developed for missions quite unlike missions being planned today. Early NASA missions concentrated on getting astronauts into space both quickly and safely. These missions, however, were very limited in terms of their length of duration similar to current shuttle missions. As the length of missions increased, the mass/dollar costs for resupply of life support system resources and equipment rapidly became excessive. Unlike these previous missions, current mission designs call for life support systems capable of functioning for periods of time that are orders of magnitude longer in duration than any previously executed missions. For example, current planned missions include a Lunar Base with eventual permanent occupation, and a manned Mars mission with a potential duration of 1000 days. A simple projection of water requirements, potable and hygiene, for 10 people at 27 kg/person for a 1000 day Mars mission indicates a mass commitment of near 270,000 Kg if traditional life support system methods are used. This projection would tend to indicate that alternative methods to fulfilling life support system requirements are necessary for the economic feasibility of currently conceived missions.

Unfortunately, recycling/regenerative technologies that would help reduce resupply costs have not been developed and/or utilized to the extent required for operational use in manned missions. On Skylab, some use of these technologies was seen when a molecular sieve was used to reduce the CO_2 content of the atmosphere. Thus life support system technology development and implementation has progressed little over the course of manned space exploration.

RATIONALE

Currently, there are two basic approaches to life support system development; physicochemical and bioregenerative. Physicochemical methods use well known physical and chemical mechanisms to perform a specific life support system task. Mechanisms such as filtering, pressure gradients, and sterilization are examples and both could be used (perhaps as part of a sequence of steps) in the purification of water or some other substance. Bioregenerative systems on the other hand utilize living organisms, which come "pre-packaged" with integrated physical and chemical mechanisms, that are able to perform a variety of life support tasks simultaneously. For instance, a plant can produce O_2, consume CO_2, purify water through transpiration, and provide biomass as a food source.

Physicochemical systems are, generally speaking, better understood than bioregenerative systems. This is partly due to the fact that physicochemical systems usually perform a single, relatively simple life support task within a well defined and predictable range of performance characteristics. In addition, physicochemical systems are relatively autonomous, relying very little on external inputs or other components of the life support system.

Although there appears to be a convincing argument for the use of physicochemical systems, these systems also suffer from a variety of deficiencies. For instance, while individual processors may have been tested, no fully integrated physicochemical system has ever been tested under closed conditions. As a result, physicochemical systems have never been truly proven either in space or on Earth. Furthermore, the components of many proposed systems produce a number of hazardous byproducts or operate under potentially dangerous conditions such as high temperatures and pressures. Finally, due to the man made nature of the components, repair and replacement of parts is inevitable.

On the other hand, there are many advantages for using bioregenerative systems. They have the capability to perform a variety of life support tasks simultaneously, as well as, are able to adapt to a wide range of environmental parameters contributing to the overall stability and robustness of the system. Another important characteristic of bioregenerative systems is, as the name suggests, the ability to continuously rebuild/renew itself through biological means. This has the effect of essentially providing new and working processors, thus minimizing the amount of repair and resupply needs. Furthermore, the byproducts of each component (organism) within such a system can be

used as primary inputs for other components within the system. As a result, the system has the potential for complete closure while providing the food, water, and atmospheric requirements of the crew. This again allows for a significant decrease in the amount of resupply required moving towards a self-sufficient eco-system.

Bioregenerative systems, however, primarily suffer from a lack of understanding by the engineering community as a whole. The 1990 design classes have addressed this issue and determined a way to depict organisms using a systems engineering approach. The first step of this "characterization" was to simply consider each organism as a "black box", in which all the complexities inherent to an organism occur, allowing simple handling of its inputs and outputs. This black box can then be broken down into three levels: functional, process, and operational. The functional level considers the inputs and outputs over an organisms lifespan in terms of mass. This allows a proper mass balance to be determined by correctly matching the inputs and outputs of the organisms. The process level allows one to consider the temporal aspect associated with these inputs and outputs derived form the organism's growth curve, enabling one to determine the correct phasing/harvesting of the organisms. In addition the operational level considers the power mass, and volume support requirements attributed to each organism. Utilizing this systems approach, a mass balance was arrived at by writing a computer program, whcih then provided us with numberous possible combinations of organisms for a closed system.

PURPOSE

As a result of the preceding evaluation, it becomes clear that the development and use of bioregenerative life support systems is necessary for the continued success of manned missions and the acquisition of associated benefits. The Space Habitation classes of fall and spring 1990 have conducted research on the characterization, integration, and implementation of Controlled Ecological Life Support Systems (CELSS). Therefore, the purpose of the CELSS group was to build upon this previous research and develop a strategy for the phased implementation of a CELSS into an existing physicochemical system on the surface of the moon. This system was assumed to be initially capable of supporting four humans. Potential benefits as well as critical technologies have also been identified.

HUMAN REQUIREMENTS

Human requirements were gathered from a wide range of studies, including three NASA contract reports (Calvin et al. 1986, Martin Marietta 1981, and Schwartzkopf 1990) and two past Space Habitation papers

(1987 and 1990). Data had to be normalized in concordance with the requirements for the proposed lunar mission scenario developed above. In addition, miscellaneous or obscure requirements (for example laundry needs and toothbrush requirements) had to be further investigated. The combined studies resulted in a range of values for each requirement (ie. minimum necessary oxygen per person was anywhere from .73 to .84 kg. per day). The highest value in each range was taken thus creating a "survival buffer" for added safety (ie. the minimum required oxygen chosen was .84 kg. per person per day. Figure 2-1 describes the minimum requirements in support of one person per day in the lunar environment.

Four separate requirement areas of inputs and outputs evolved from the studies. 1) Human consumption describes basic needs such as incoming oxygen and food as well as outgoing human waste. 2) Laboratory use describes average parameters based on 1987 Space Habitation studies covering a wide range of empirical and proposed in-space experiments. This area serves to illuminate experimental needs as an example of a possible laboratory scenario. 3) Cleaning use encompasses laundry and miscellaneous house cleaning needs. 4) Hygiene use describes general requirements for cleaning the body via sinks or showers.

2.2 PHASED IMPLEMENTATION

Before beginning to detail the phasing strategy developed by the CELSS group, a description of the rationale along with the basic trades will be given.

RATIONALE AND TRADES

As has been previously mentioned, a number of recent reports have expressed concern over NASA's ability to lead the United States space program into the 21st century. For instance, the Augustine Report has detailed several points that apply to both the development of a lunar life support system as well as to the space program as a whole. These include:

1) NASA is over committed relative to resources --> doing too much and allowing minimal or no margins for unexpected events.
2) Changes in project budgets result in management inefficiency.
3) There is a need for growth control over cost, complexity, etc.
4) Lack of a sound technological base from which to draw from.
5) The need to find flaws before deployment.

These and other concerns provide the top level set of requirements that help determine the shape of any proposed phasing strategy.
The strategy must then answer these concerns by providing the following:

* Flexibility to adapt to external economic and political pressures.
* Recognizable benefits at each step.
* Evolutionary building upon previous successes
* Implementation of technologies that have a proven basis.
* Allowing time for the "fixing" of unforeseen difficulties.

After providing for these concerns, another set of parameters must be investigated. These parameters consist of basic trade factors. Examples of trade factors used in the development of a phasing strategy include:

* Mass
* Power
* Volume
* Safety
* Complexity
* Maintainability
* Stability
* Ease of implementation
* Cost
* Reliability
* Other

PHASING
In order to achieve the goal of a Lunar Base with a Closed Ecological Life Support System there must be a realistic and flexible plan to implement it. the approach which broke that research down into three phases: a ground based phase, a space based testing phase, and an operational implementation phase. The basic rationale behind this particular phased approach is that CELSS research is so important to the understanding of the Earth as an eco-system as well as continuing many applications to industry that if only the ground based research was completed and the rest of the mission was scrapped that there would still be numerous benefits attained. Similarly, the space based and operational phases have direct and immediate returns that make each step a worth while regardless if the entire mission is realized or not.

Ground Based Research

Organisms

-examine existing methodologies on how to characterize organisms
-begin initial plant and animal experiments in severe environmental conditions such as low light, CO2, and O2 levels
-choose/develop the optimal methodology that accurately defines the organism's inputs and outputs over time
-choose a number of domesticated plants and animals to study that have a large amount of existing data and that meet the following requirements: high edible biomass, low maintenance, simple processing procedures, robustness, compatibility, cost effectiveness, relatively short lifespan, able to meet power, mass, and volume requirements
-compile existing data on organisms and begin initial research
-test and modify methodology
-fully characterize these organisms in closed growth chambers
-test and modify methodology
-begin initial testing of integrated systems in closed growth chambers
-perform experiments to determine the optimal environmental conditions to maximize productivity of organisms such as lighting, photoperiods, temperature, CO2 levels, humidity, spacing, etc. . .
-perform tests to determine acceptable radiation levels for plants and animals
-low gravity testing of plants and animals
-perform experiments examining transpired water, waste processing, etc. . .
-compile and examine existing data on approaches to phase organisms into a complete system so that one can choose the optimal method
-choose/develop the optimal phased versatile approach that provides specific returns at each step such as phasing plant growth to meet the potable water, oxygen, total water, and food requirements for animals
-examine existing waste water treatment systems
-compile existing data on waste water treatment systems and designs
-choose/develop optimal waste water bacteria treatment system that satisfies the power, mass, and volume requirements as well as is reliable, safe, cost effective, and compatible with other systems
-start compiling a database for fully characterized organisms

-perform crossbreeding experiments in order to optimize growth rates, robustness, edible biomass, compatibility, etc. . .
-begin initial experiments to examine phasing of organisms into a system
-expand number of organisms including hybrids to be examined based on the same parameters as above
-continue testing of integrated systems in closed growth chambers
-fully characterize additional organisms in closed growth chambers
-expand database on characterized organisms
-perform testing on phasing organisms into a system
-continue testing of integrated systems in closed growth chambers
-continue to expand the number of organisms to be examined based on the same parameter as above
-fully characterize the new additional organisms in closed growth chambers
-expand database on characterized organisms
-perform trade based on previously mentioned parameters to determine the candidate organisms for CELSS
-perform initial testing of plants in an Earth based SSF module
-perform initial testing of animals in an Earth based SSF module
-perform initial testing of multi-organism systems in an Earth based SSF module
-begin phasing organisms into an Earth based SSF module
-full scale plant and animal systems in an Earth based SSF module
-perform initial testing of plant and human system in an Earth based SSF module
-perform initial testing of plant, animal, and human system in an Earth based SSF module
-full scale plant, animal, and human system in an Earth based SSF module

Computer

-compile and examine existing computer algorithms for plant and animal growth modeling concentrating on three specific areas to be researched separately and later integrated: singular organism characterization, multiple organisms interactions, and environmental control
-choose/develop a computer algorithm that best characterizes the inputs and outputs of an organism in all three loops: gas, liquid, and solid and is compatible with other two algorithms for later integration
-choose/develop a computer algorithm that best characterizes the interaction of organisms for example plant with plant, plant with

animal, and animal with animal and is comparable with other two algorithms for later integration
-choose/develop a computer algorithm that models the monitor and control systems of the environment such as determining how to adjust the CO2 or O2 levels and is compatible with other two algorithms for later integration
-write code for all three computer algorithms
-test and debug all three computer programs
-perform trial runs with experimental organism data
-modify, test, and debug computer programs
-model organisms and compare to data attained from growth chamber experiments
-model environmental parameters and compare to actual environmental conditions and control
-modify, test, and debug computer programs
-integrate singular organism and organism interaction programs
-integrate the environmental parameter model with the compiled version of the other two programs
-test and debug integrated computer program
-perform trial runs with experimental organisms data
-modify, test, and debug integrated computer program
-model SSF ground based organisms experiments and compare to data attained
-model SSF ground based environmental conditions and compare to actual experiment
-modify, test, and debug integrated computer program

Environmental Systems
-choose a number of environmental hardware systems to study including plant and animal growth, monitor and control, regenerative physical/chemical systems, processing, and food delivery systems that have a large amount of existing data and that meet the following requirements: low maintenance, robustness, safety, compatibility with organisms as well as other systems, cost effectiveness, and ability to meet power, mass, and volume requirements
-compile existing data acquired on environmental hardware systems and begin initial research
-explore design options
-develop candidate hardware
-begin initial testing of hardware in low gravity KC-135 tests
-perform trade based on the previously mentioned parameters to determine the candidate environmental hardware systems

-perform initial testing of individual components in an Earth based SSF module
-begin initial testing of integrated hardware systems in low gravity KC-135 tests
-perform initial testing of integrated hardware systems in an Earth based SSF module
-perform initial testing of integrated hardware with plants in an Earth based SSF module
-perform initial testing of integrated hardware with animals in an Earth based SSF module
-perform initial testing of integrated hardware with plants and animals in an Earth based SSF module
-full scale hardware systems test in an Earth based SSF module
-perform initial testing of full scale hardware system with organisms
-perform initial testing of full scale hardware systems with a plant, animal, and human system in an Earth based SSF module
-full scale hardware system with a plant, animal, and human system in an Earth based SSF module

Space Based Research

Organism

-compile and examine existing data acquired form space based research on organisms
-choose a number of experiments to be performed based on acquiring more information on plant/animal growth in low and microgravity, as well as, radiation levels and effects on organisms
-germinate seeds in Space Shuttle and moon experiments
-test methodology for organism characterization by performing low and microgravity organism experiments on the SSF and the moon
-modify methodology and computer algorithms
-test salad machine on the SSF
-test a plant and animal systems in the Space Shuttle, SSF and on the moon
-perform plant and human systems experiments in SSF
-test and modify methodology
-perform plant, animal, and human systems experiments in SSF
-test and modify methodology

Computer

-adapt computer programs to model organisms in low and microgravity environments

-perform trial runs with experimental dat obtained from existing space based research
-modify, test, and debug computer programs
-model organisms and compare to data attained form space based research
-modify, test, and debug computer programs

Environmental Systems

-test components in Space Shuttle and SSF experiments
-test integrated systems in Space Shuttle and SSF experiments
-test components with organisms in Space Shuttle and SSF experiments
-test integrated systems with organisms in Space Shuttle and SSF experiments
-test components with organisms on moon
-perform trades to insure best system is chosen based on the data obtained from space based research

Operational

The main focus of the Spring 1991 Space Habitation Class was to determine a phased implementation of a CELSS for a Lunar Base.

Organism

Full Scale System:

The full scale system is, as the name suggests, the entire, optimally balanced system. Phasing would consist of simply a single phase in which the entire system of plants and animals is taken to the surface of the moon complete with fully functional support and integration systems. This system is the most stable as well as the most efficient. This method, however, has a significant number of drawbacks which include:

- Large initial mass cost (estimated at >300,000 Kg).
- No evolutionary progression.
- No flexibility to programmatic concerns (i.e.. funding).
- Significant difficulties in implementation.
- High complexity.

While this method of implementation would provide for immediate self sufficiency on the surface of the moon, it is not a realistic strategy.

Multiple Organism Addition:

This method of phasing would build up to a fully operational CELSS by using building blocks consisting of multiple organisms; for example, a catfish-algae system. By adding organisms in such a manner, it may be possible to maintain greater overall system stability. This method,

however, requires more sophisticated methods of integration as well as less significant impacts on resupply costs when compared to other methods.

After examining a number of possible phasing strategies such as establishing a full scale system right from the start, building a system by integrating organisms pairs until a full scale system was reached, or introducing one organism into the system at a time. The latter method was chosen because it had less initial mass costs, and evolutionary progression, was flexible to programmatic concerns for example funding, was less complicated, and easy to implement. In addition, it provides returns and benefits at each stage.

The initial Lunar Base would use a physical/chemical system with an integrated waste/water treatment system. then plants were chosen to be the next component added to the systems because they had the greatest impact in terms of resource recycling, as well as, being less complicated to integrate with existing physical/chemical systems and other organisms. Animals were eventually phased in until a full scale system is achieved. The optimal phased approach that provides returns at each stage was determined using "average" plant performance values (see Figure 2-2) and CELSS scaling (see Figure 2-3) is presented below.

CELSS PHASING

PHASE I	PHASE II	PHASE III	PHASE IV
SYSTEM CONFIGURATION			
Baseline P/C System with Bacteria			
	+ 6 m^2 of plants		
		+ 6 m^2 of plants + 6 m^2 of algae + 120 catfish	
CHALLENGES			+ 80-100 m^2 of plants
Bacteria Performance altered on moon			Expand Aquaculture Animal Production
	Organism performance		
IMPACTS	altered on moon		
90% water recycled			Automation
Reduce Resupply			Large Volume
	Increase P/C lifespan		High Power Needs
	Less Toxic Wastes		Increased Storage

This phased evolution of a balanced bioregenerative life support system provides immediate impact on the requirements for a crew of four. The amount of consumables provided by the bioregenerative part of the life support system for each phase are shown in Figure 2-4.

2.3 SPIN-OFFS/EARTH APPLICATIONS

A very important aspect of the overall methodology is that for each step there is a corresponding spin-off/Earth application. In the CELSS group for example, the characterization of the organisms is considered to be one of the first things to be determined. A direct Earth application of this is agricultural/greenhouse benefits such as more efficient use of resources such as fertilizer and water. Other agriculture/greenhouse advantages are higher yields due to the knowledge of optimal environmental conditions. Higher productivity will also occur in agriculture/greenhouses due to better automation and processing procedures. Another spin-off is that waste water processing can be improved in the United States as well as in third world countries from a better characterization of bacteria. Not to mention that a fully designed CELSS would have multiple Earth applications as a transportable eco-system capable of supporting life in a hostile environment. It would limit/eliminate resupply to remote places such as the Antarctic, underwater, or the desert. Also if a computer program could be determined that performed eco-system modeling, scientists would be able to better predict and understand the Earth's biological engines and eco-systems. Eventually, bioregenerative technology could be used in people's homes to recycle waste water and to remove air pollutants enabling one to conserve and recycle precious resources like water.

2.4 PHYSIOCHEMICAL/BIOREGENERATIVE INTEGRATION

The initial step to designing any system involves the identification of general requirements and the establishment of a comprehensive functional evaluation. In creating a conceptual life support system for a Lunar Base, human inputs and outputs were researched and technology tradeoff studies were assessed to determine optimal system design.

LIFE SUPPORT TECHNOLOGIES TRADE STUDY

There are four critical tasks needed to sustain life on the moon. 1) Oxygen generation helps meet breathing requirements. 2) Carbon dioxide removal collects metabolic waste from the atmosphere, and 3) carbon dioxide

reduction turns it into a useable substance. 4) Water system revitalization treats contaminated water for future use. The large number of different technologies available for each function made it prudent to come up with an initial set of limiting contingencies. In order to minimize resupply to the moon, only regenerative technologies were considered. In addition, maturity, reliability, and biological compatibility also weighed heavily. Although bioregenerative processes seem most favorable and are the eventual goal of the lunar CELSS, they were immediately eliminated from the baseline configuration because of their low maturity relative to physico-chemical systems. On the remaining candidate technologies, comprehensive trade studies were performed. Figure 2-5 lists critical operational parameters compared in these studies, but the trade offs were not limited to them, as described below.

2.4.1 OXYGEN GENERATION TECHNOLOGIES

Previous space missions have relied solely on oxygen storage and byproduct oxygen from fuel cells, but high resupply costs and the implementation of a lunar nuclear energy source make regenerative oxygen techniques a necessity. Initial limitation criteria produced two remaining technologies: solid polymer and static feed water electrolysis.

SOLID POLYMER WATER ELECTROLYSIS SUBSYSTEM (SPE)

The first SPE prototype was built in 1970, and has since been designed and tested for its potential applicability to naval submarines and space environments. The actual process is very simple (Figure 2-6). The solid polymer membrane allows water to permeate through the mechanism while electrodes decompose the water into oxygen gas and hydrogen ions. Hydrogen is then converted into a gas and collected as oxygen gas diffuses into the atmosphere. Recent tests (Erickson and McElroy 1986 and Erickson et al. 1987) have affirmed that the overall process and performance of the SPE don't appear to have any major critical stumbling blocks.

STATIC FEED WATER ELECTROLYSIS SUBSYSTEM (SFWES)

Space applications of the SFWES have been under development for at least seventeen years. The process is similar to that of the SPE in that water is broken down into hydrogen and oxygen gasses (Figure 2-7). The differences in technologies stem from different materials and designs. Like the SPE, no restrictive limitations are evident and performance tests have revealed favorable results for its use in space (Fortunato and Burke 1987, Larkins et al. 1986, and Larkins and Kovach 1985). Both processes have the ability to operate either cyclically or continuously making energy saving possibilities available. The SFWES, however, has considerable mass,

power, volume and resupply savings over the SPE. Moreover, researchers are investigating possibilities to utilize the SFWES as a hydrogen-oxygen fuel supplier and to couple it with a dehumidifier to increase process efficiencies. NASA has displayed considerable affinity for the SFWES as baseline technology for Space Station Freedom, and it seems the best choice for a lunar station as well.

2.4.2 CARBON DIOXIDE REMOVAL TECHNOLOGIES

Carbon dioxide must be removed from the limited atmosphere in the lunar modules. Previously on short duration missions, lithium hydroxide (LiOH) cannisters have been responsible for absorbing carbon dioxide, and spent LiOH cannisters were stored and eventually returned to Earth. Long duration lunar missions make this solution infeasible in terms of transportation costs. Regenerative technologies passing initial standards described above limited the following trade study to two possibilities: molecular sieve and electrochemical depolarized concentrator processes. The much lauded (Etoh et al. 1987 and Otsuji et al. 1987) solid amine resin carbon dioxide removal subsystem was not considered because it produced toxic vapors detrimental to plant life.

MOLECULAR SIEVE CARBON DIOXIDE REMOVAL SUBSYSTEM (MS)

The molecular sieve design, also known as the regenerable carbon dioxide removal subsystem (RCRS), had been used extensively on Skylab to alleviate the high resupply mass penalty. NASA has further contended to use the MS as baseline space station technology. The process of adsorbing carbon dioxide waste from the air onto the molecular sieve is completely reversible. However, its high sensitivity to atmospheric moisture levels can somewhat limit performance efficiencies.

ELECTROCHEMICAL DEPOLARIZED CARBON DIOXIDE CONCENTRATOR (EDC)

The EDC has developed from life support systems testings as early as 1964, and further extensive development has yielded a valuable space ready technology (figure 2-8). The EDC processes carbon dioxide, oxygen, and hydrogen gasses to create DC electrical energy directly usable by both the SPE or SFWE subsystems. More versatile than the molecular sieve, the EDC can work either cyclically or continuously and at levels controlled by power input. This makes it outstanding in the critical capability of energy conservation. NASA, however, is concerned with the abnormal oxygen consumption and extensive heat loss, and further research must go into these areas to optimize the subsystem. Regardless, the EDC can operate in a large moisture range (20-80%) and has lower overall mass, power,

volume, and resupply figures than the molecular sieve. Some studies have clashed with NASA's space station decision and confirmed the EDC to be the best available technology for carbon dioxide removal (Boyda et al. 1985 and Boyda and Hendrix 1986).

2.4.3 CARBON DIOXIDE REDUCTION

After carbon dioxide has been removed from the atmosphere, it needs to be turned into a usable substance or concentrated into a low-volume waste. Again, only two methods filtered through initial criteria: the Bosch and Sabatier processes.

BOSCH PROCESS

The Bosch process employs a catalyst to combine collected carbon dioxide with hydrogen gas to create water and concentrated carbon waste (Figure 2-9). Although it is a relatively undeveloped technology, NASA has chosen it for Space Station Freedom's life support systems. However, the subsystem has a low 10% reduction efficiency and cannot concentrate carbon waste as well as the Sabatier process.

SABATIER PROCESS

The Sabatier process has a working preprototype that has been extensively tested (Figure 2-10), but NASA is reluctant to employ it on the space station because, in addition to water and carbon byproducts, methane is produced. Methane emissions can alter astro-observational experiments provided a venting system is installed. Otherwise, methane waste storage can carry a large volume penalty. A Lunar Base, though, has the advantage of facilitating methane dumping away from experimental equipment. Furthermore, researchers (Noyes and Cusick 1985) have looked into coupling the Sabatier process with a methane decomposition unit to create useful substances from the unusable methane gas. Research into carbon dioxide reduction processes have favored the Sabatier over the Bosch system if a remedy for methane waste can be developed (Otsuji et al. 1987 and Wydeven 1988).

2.4.4 WATER SYSTEM REVITALIZATION

Since water represents over 90% of resupply mass, water recycling has become the most important issue of a long term missions. Moreover, the likelihood of spin-off technologies from developing a water revitalization system makes this trade study undeniably important. Water purification

has become a global concern, not only for its industrial applications, but also for its impacts on health in the prevention of disease in the third world. Water wastes can either be organic or inorganic depending on how the water was used. Initial technology screening resulted in three organic treatments (vapor compression distillation, thermoelectric integrated membrane evaporation, and vapor phase catalytic ammonia removal) and two inorganic filters (reverse osmosis and multifiltration). Super critical water oxidation (SCWO) may be a valuable future technology because it has the capability to remove 100% of waterborne wastes in a matter of seconds, but it is presently too underdeveloped to be considered as a viable treatment technology. An innovative bacterial design technology developed by Space Habitation studies in 1990 treats both organic and inorganic waste and is also described below.

VAPOR COMPRESSION DISTILLATION (VCD)

The VCD process (Figure 2-11) has been tested for over twenty years and is the most highly developed water treatment process. It heats wastewater into pure water vapor and residual wastes. The water vapor is then collected for future use. Studies have proven that the process works well for organic wastes (Mallinak 1987 and Zdankiewicz and Chu 1986), but inorganic wastes seem to reside in treated water at an unacceptable level. VCD also requires intensive pre- and post-treatment technologies that add to the mass, power, volume, resupply, and complexity of the subsystem making it unfavorable for consideration.

THERMOELECTRIC INTEGRATED MEMBRANE EVAPORATION SUBSYSTEM (TIMES)

The TIMES (Figure 2-12) has not been under development as log as the VCD process but remains a wastewater treatment candidate. The similar phase change process is limited by the same susceptibility to inorganic waste and limited by the same pre- and post-treatment requirements. Moreover, the TIMES system displays higher mass, power, volume, and resupply penalties than the VCD process.

VAPOR PHASE CATALYTIC AMMONIA REMOVAL (VPCAR)

The VPCAR process (Figure 2-13) remains the most viable technology for the treatment of organic wastes. Like both VCD and TIMES, VPCAR involves a phase change to clean wastewater. No pre- or post-treatment is required, and wastes are removed with a 98% efficiency. A trade study comparing all three processes decisively favored the VPCAR, although it is a relatively young technology (Budininkas and Rasouli 1985). It also shows the best mass, power, volume, and resupply figures. Some more

research must be done, however, to perfect the process before it will be ready for the lunar environment.

MULTIFILTRATION (MF)

Multifiltration has been studied since its initial prototype in 1973. It uses a system of filters with decreasing pore size to remove wastes without chronically clogging the subsystem. Organics and inorganic salts are also removed by adsorption and ion exchange. MF is the simplest wastewater treatment process available, and is the only subsystem to produce potable quality water. Heavy, expensive filters, and frequent resupply pose the greatest disadvantages. This is especially true for the organic waste adsorbing charcoal beds which need almost chronic replacement. The MF process is ideal for treating wastewater with low contaminant concentrations.

REVERSE OSMOSIS (RO)

The reverse osmosis process (Figure 2-14) forces wastewater at high pressures through waste collecting membranes. It is a reliable technology presently being used on a larger scale in desalinization plants across the world. The main stumbling block in its development has been finding a membrane that can withstand higher pressures to raise waste removal rates, and additional research is required in this area. In addition, organic wastes can clog current membranes, and effluent water is not of potable quality and warrants further treatment. Coupling reverse osmosis with multifiltration would be a valuable complementary system, overcoming the weaknesses the two technologies have on their own. The hybrid membrane configurations have been well documented for their very high recovery abilities (Ray 1985, Ray et al. 1986, and Space Habitation 1990).

BACTERIAL DIGESTION

In the fall of 1990, the University of Colorado Space Habitation group created a bacterial wastewater treatment design (Figures 2-15 & 2-16) based on a scaled down version of existing municipal waste plant systems. The results were speculative, but highly favorable. The bacterial culture thrives on oxygen and waterborne wastes producing more water than it receives at very low mass, power, and volume values. Resupply estimates need further development but seem negligible. A drawback, however, is that along with carbon dioxide and usable water, methane gas is produced. Bacteria seem to have the greatest positive impact than any other biological organism on a physico-chemical system and may be the prudent first step to a bioregenerative lunar CELSS.

TRADE STUDY CONCLUSIONS

Based on the above discussions, the baseline lunar CELSS will consist of: SFWES for oxygen generation, EDC for carbon dioxide removal, Sabatier for carbon dioxide reduction, and a combination of VPCAR, RO, and MF for wastewater treatment with the future possibility of an integrated bacterial digestion subsystem. Other future possibilities include a SCWO subsystem discussed above, and possibly a carbon dioxide electrolysis subsystem that can supply oxygen and reduce carbon dioxide without significant resupply penalty.

FUNCTIONAL INTEGRATION

After realizing system requirements and components, the next step was to integrate them together into a functional system design. Functional diagrams for an open loop system (Figure 2-17), a completely physico-chemical system (Figure 2-18), and a hybrid system utilizing bacterial digestion as the main wastewater treatment mechanism and physico-chemical technologies solely as backup were designed (Figure 2-19). The ease in which the bacterial system can be added to the overall life support system is representative of how well biological components can fit into the baseline CELSS. This phased biological implementation will be discussed a little later.

It is recommended that operational ground tests be conducted to ensure the reliability and robustness of the individual technologies as well as the entire system.

SYSTEM COMPARISONS

A number of system comparisons can be interpreted from the diagrams. Figures reveal that the extent of closure dramatically increase from the open loop to the hybrid system. Moreover, as more biological are added, a higher level of closure is expected. For example, the baseline systems does not curtail food resupply, but small scale integrated lettuce or catfish farms will create in-house supplies. Resupply of parts for physico-chemical system maintenance will drop as non-biological technology use drops. Furthermore, the amount of untreatable waste also decreases with the increase in closure. These trends are exemplified in Figure 2-20. As long as non-recyclable wastes exist, there is a need for further advances towards a completely bioregenerative life support system.

2.5 CRITICAL TECHNOLOGIES

While this phasing strategy is feasible, there are a number of critical technologies/challenges that must first be met before a Lunar CELSS can become fully realized. Such technologies include:

* Control and Monitoring
* P/C-Bioregenerative Integration
* Organism Characterization
* Organism Maintenance
  - Nutrient Delivery Systems (e.g. hydroponics)
  - Environmental Concerns (lighting, humidity, etc.)
  - Optimal Growth Maintenance
* Processing and Automation
* Organism-Organism Phasing (harvesting schemes, etc.)
* Etc.

One important area worthy of special attention is the problem of consistent food production within the lunar module. In order to accomplish this critical step in the phasing scheme, both hydroponic plant production and plant lighting systems were investigated.

2.5.1 HYDROPONIC PLANT PRODUCTION

RATIONALE

Plant growth is essential to a Lunar Closed Environment Life Support System (LCELSS) because of the initial beneficial impacts resupply augmentation, as well as the ultimate contribution to the eventual closure of the system. In order to provide a nutrient delivery system as well as a growth facility, the general methodology for the class project was similarly followed in determining recommendations for a hydroponic unit. First, a rationale for using hydroponics was established, followed by a list a requirements for a plant culture. Next, a list of hydroponic options was identified and a trade study was accomplished to determine the best option. Finally, a preliminary design was created along with a list of technological challenges to be faced before large scale production could ensue.

Hydroponics can be loosely defined as "the growing of plants without soil, but by use of an inert medium," (Resh, 1987) whereas "true" hydroponics would utilize a water culture as that inert medium. Hydroponic, or soilless, plant cultures have many advantages over traditional soil production. Nutrition flow in hydroponics is completely controlled and more stable than in the open field. There is no need for crop rotation or replacement of

medium as is the case with rotation and fertilization of soil crops. Further, there is a higher quality of produce, with little or no spoilage, unlike in soil cultures that are not as regulated and are more susceptible to damage. On a quantitative scale, hydroponic production provides a more efficient use of water, produces a faster maturation and yield, and utilizes space much more effectively. Using lettuce as an example, to produce 1 Kg of mature produce requires 50 Kg of water in the open field as opposed to 5 Kg of water in a hydroponic system (Field, 1988), reducing the mass requirement for water alone by a factor of ten. The faster yield can once again be exemplified by lettuce, whereby open field crops require 42-60 days to mature, hydroponic production is complete in 22-26 days (Field, 1988). Finally, the amount of plants that are produced in 100 acres of open fields can be produced in 10 acres of greenhouses, and only 1 acre of hydroponic facilities (Field, 1988), demonstrating a marked advantage in space efficiency. All of the above factors are naturally important considerations for any type of unit to be placed on the lunar module, where mass, volume, power, and time are all critical assets to be conserved.

REQUIREMENTS

Having established hydroponics as a more efficient means of plant growth than a soil based production, a list of requirements are needed. Any plant culture or nutrient delivery system must ensure the following needs. The system must provide nutrients, CO2, and H20, in the correct amounts and intervals. It must provide support for both the crown and roots of the plant. It must ensure both water retention and adequate draining of excess fluids. Finally, the system must provide constant and consistent structure and aeration of roots and crown. (Resh, 1987)

TRADE STUDIES

In order to meet these requirements, many hydroponic plant culture options are available and provide varying degrees of success. The first of these options is a water culture, or "true" hydroponics as defined earlier. In a water culture, the plant roots are suspended in a liquid medium consisting of a water/nutrient solution. The crowns are supported in a thin layer of inert material and nutrients are delivered to the plant by a constant flow of the liquid solution. This procedure is often called the Nutrient Flow Technique (NFT) and provides for the most efficient use of materials in a hydroponic design (Resh, 1987).

The next option in soilless cultures are the soil substitutes. With a soil substitute, an inert medium provides the support for both the roots and the crown. Nutrients are then delivered by a flow of nutrient solution

through the inert medium. There are two divisions of soil substitutes available to the lunar station: Earth materials and in situ Lunar regolith. Earth materials could be any inert material such as gravel, sand, or sawdust, any of which would obviously require extra volume and mass in transport from Earth (in addition to the water and nutrient solution), as well as additional handling and packaging. Lunar regolith, on the other hand, would side-step these transportation costs, but would require collection and processing, both of which would be mass intensive in the machinery required. The processing of the lunar soil itself could be very complicated, because it contains many toxins that would need to be extracted before it would serve as a truly inert material.

The final option in soilless cultures is a newer delivery system called aeroponics, wherein the plant roots and crown are supported by an inert material (similar to the "true" hydroponics structure). But, the water and nutrient solution requirements are delivered by a periodic spray, leaving the roots otherwise exposed. All of the above options meet the requirements of a plant culture, but the consideration of mass requirements, simplicity, and existing experience in that technology helped to make a clear choice.

A "true" hydroponics nutrient delivery system with a water culture stands out as the best choice given the above options. Over soil substitutes, it has the advantage of requiring a minimum of materials for structure and support. The support of the crown requires only a thin sheet of inert material, whereas the soil substitutes would require both an enclosure structure as well as the substitute material itself. Again, the Earth types would require costly transport, and the Lunar regolith would need collection a processing, all of which is unnecessary in a water culture, where the water flow, which is required in all cases, provides the culture itself.

Over aeroponics, water culture has the advantage of being a proven technology and is already highly developed. Aeroponics, meanwhile, is somewhat undeveloped, and would require more equipment of greater complexity to provide the consistent, periodic delivery of the proper amounts of nutrient solution. Furthermore, the reduction of water mass flow gained by an aeroponic system would be ineffectual in the initial scale of two square meters of growth, making its one advantage inconsequential.

DESIGN RECOMMENDATIONS

With a decision to use a "true" hydroponic unit with a water culture for plant growth, an initial design is in order to determine some of the space

requirements within the lunar module. Once again, lettuce is taken as an example crop to provide the guidelines of a design. The growth volume for the plants themselves (based on 2 square meters of produce) is 0.76 cubic meters (Figure 2-21). Notice that the plant crown would require 30 cm (approximately 12") for spacing from the lighting above, and 7.6 cm (3") of room for the roots and flow of nutrient solution. Including the small thickness of the inert support material, the total height requirement is 38 cm.

The unit would integrate into the lunar module as seen in Figure 2-22, with the 2.0 meter expanse along the wall, and 1.0 meter depth allowing for manual tending of all of the plants to the rear of the growing area. Another 30 cm is provided for storage of both the nutrient solution as well as the water supply and other plumbing such as pumps and piping. Finally, the design will have to allow for the installation of fans to provide heat removal due to the lamps, as well as conduction of the oxygen and water transpiration to the lunar module life support system. All things considered here, the total volume of the hydroponic unit will be 1.35 cubic meters (per 2 square meters of growth). Of course, this volume would be doubled and quadrupled for the 4 and 8 square meter crops, respectively. For the further upscaling of plant production, a redesign of larger, more space efficient units would be required.

CONCLUSION

There are still some technological challenges that will need to be addressed before the large scale plant production (Phase V and VI) is possible. First, automation of seeding, tending, harvesting, and processing of the crops will certainly be necessary to allow the crew members to do more than continually procuring their daily crops. Secondly, flow control technology will be needed for both integrating the hydroponic system throughputs (O2, CO2, H20) into the LCELSS, which will involve such issues as having an open growth system versus a closed growth area with collection and storage apparatus. As mentioned above, a third concern will be to develop a more space efficient design that will account for the variable spacing required at each stage of growth, as well as adapting to the cylindrical shape of the lunar modules. A fourth challenge will be to determine the requirements and advantages of the different crops available, and to come up with a flexible system that will allow for a multitude of crops. Finally, although aeroponics was ruled out initially, it should be further investigated and refined for use in a large scale production. Because of it's lesser requirements of water mass flow at such a large scale as in Phase VI, an aeroponic system would prove to be much more efficient than a water culture nutrient delivery system. Given the initial design for a

water culture hydroponic system, the Lunar Base crews can develop investigate the potentials and abilities of plant growth on the lunar surface, and augment the research and development of the above mentioned technological challenges.

2.5.2 PLANT LIGHTING

RATIONALE/REQUIREMENTS

One of the most important aspects of healthy plant growth and biomass production is lighting. Once the leaves of a plant open, chlorophyll begins to convert carbon dioxide (CO_2) in the air, water (H_2O) with nutrients, and energy from light, into food, in the form of carbohydrates (CH_2O), and Oxygen (O_2). This process is called photosynthesis, and is described in the following equation:

$$CO_2 + H_2O + \text{chlorophyll} + \text{light} = CH_2O + O_2$$

Several aspects of the light govern how productive the plant will be. One such aspect is the Photosynthetic Active Radiation, or PAR. PAR is the amount of light that reaches a plant, and is measured in micro-mole/meter squared/second (or umole/m2/s, which is defined as the photon flux density). On earth, potentially 2000 umole/m2/s can be obtained on a clear day, which is 400 umole/m2/s less than that available in space (or on the moon) (Schwartzkopf, 1990). However, this amount is greater than actually needed to grow plants, which can grow with as little as 300 umole/m2/s.

Another important factor is the spectrum of light the plant receives. Although plants absorb light mostly over a range of 400-700 nm, specific areas of the spectrum are more important than others (Figure 2-23). The wavelength most important for photosynthesis is typically 446nm (blue-violet) and 664 nm (orange-red) for chlorophyll synthesis. Other functions of the plant can be affected by the wavelength of light received. For example, red light enhances germination and flowering (Hoehn1). Therefore, a good lighting device must provide both a sufficient amount of light with the right wavelengths available to maximize plant growth and biomass production.

TRADE STUDIES

Natural Lighting

There were three different lighting scenarios identified as available to a Lunar Base with a CELSS, or LCELSS: All natural lighting, artificial lighting, and a hybrid system of these two. At first glance, all natural lighting

seems like the best option because it would have theoretically little to now power or mass requirements (just the module or "tent" it was contained in, and a need for thermal control). However, because plants are sensitive to the time they are exposed to light on a daily basis (called the photoperiod), there are inherent problems with an all natural light scenario. On the moon, periods of darkness, depending on location, may last for several days, typically 14 days, followed by 14 days of light (Schwartzkopf, 1990). The photoperiod for plants varies. Some plants can live in constant exposure to light, while others must have 12 hours of darkness to flower (Cervantes, 1986). But, for the most part, plants must have nearly daily exposure to light to remain healthy. Plants subject to periods of darkness for 15 day periods, even when refrigerated, either died or had their yields cut by 30-50% (Schwartzkopf, 1990). Therefore, some type of additional lighting is required for plant growth in an LCELSS.

Hybrid Systems

1. Greenhouse like natural lighting

With a hybrid system, three different methods for utilizing natural lighting during the day-light periods, supplemented with artificial light during the night-time, were examined. The first was a type of greenhouse structure, where the walls of the structure housing the plants would permit the transmission of light, possibly in an inflatable structure. This idea was disregarded for several reasons, the first of which is because the design goal was to include the entire base within one SSF module for the first stage implementation. Despite any construction problems of a greenhouse section to a SSF module greenhouse, this idea wouldn't work because the base is placed in a dark area. Placing a greenhouse within the light would then require EVA's to service it. Lastly, exposure to long term lunar radiation for plants is unexplored and there would have to be sufficient back-up yield for crop failures due to solar flares. This idea may have potential for later implementations for the base, and is especially attractive because it represents low mass and power expansion, but it is impractical for a first stage design.

2. Fiber optic natural lighting

The second option involves "piping" in light through fiber optics. In this method for station, solar collectors concentrate light into fiber optic cables through a Frensel lens; then the fibers are combined in bundles (one 2mm fiber from each lens) and directed to the plants. A motor driven receptor would be needed to track the sun, and would represent basically the only power needed (375 W for a design proposed for SSF) outside of cooling power requirements. This design makes sense for the space station because the station uses solar power, and thus has tight power constraints.

But breaks are needed in the bundle systems for maintenance reasons, and eventually to distribute it, causing between 2-35% of the light to be lost at each junction (Oleson, 1987). This, in combination with the mass of the motors, collectors, cables and diffusers needed for a lunar scenario, drives the system's original mass up. Using a 50% transmittance rate, which is that currently projected for efficiency, the mass per illuminated area will be 54.9 kg/m2 (Schwartzkopf, 1990). As will be shown in a following section, this is a large mass penalty. Also, additional mass would be needed for the dark periods. It is possible that for a polar location, a tower could be built to allow a collector to "see" below the horizon and thus be able to observe sunlight at all times. But the additional tower mass, and complexity of such a project for the initial stage of a base, rules this idea out as well.

3. Reflected natural lighting

The last method examined for natural lighting is the use of light weight reflectors to direct sunlight in through module windows, and then pipe it to the plants. The idea seems worthwhile from a mass and power perspective. However, the original reflector would have to be on a motorized mount, much like the one for the fiber optic system, in order to track the sun. This creates what seems to be a significant technical challenge in getting all the mirrors aligned to beam the light back to the module as the original reflector moves to track the sun. This again is impractical for a first stage base implementation.

For these reasons, although utilizing natural lighting has outstanding abilities to reduce power requirements, none of the systems examined have required potential for the first stage implementation of a Lunar Base.

Artificial lighting

Lighting Devices and their Parameters

There are a number of artificial lighting sources available besides the incandescent bulbs that Edison invented. For years, fluorescent bulbs were utilized in greenhouses, but in recent years, High Intensity Discharge (HID) Lamps have been used. The difference in design is primarily how the charge is passed through the lamp. For instance, in an incandescent bulb, electricity is run through a thin wire; in fluorescents and HIDs, a charge is arced through a gas, under low pressure for a fluorescent, and under high for a HID. One other kind of source examined is a Light Emitting Diodes, or LED.

After identifying the biological requirements for the plants, there are other considerations that might make a lighting device more applicable to

LCELSS applications, including mass, power and volume, plus safety (HIDs and fluorescents, if broken, can release dangerous products), and maintenance needs (such as lifetime and difficulty in determining both loss of device and replacing it). Information was gathered on a number of parameters for several different models of the lighting sources mentioned above. In addition to different models (such as the type of gas in an HID, or the wattage of an incandescent) different operating ranges were examined (such as the running a 225W peak fluorescent lamp at 110W). The peak wattages are listed next to the device in cases where different operating parameters were listed.

A description of the parameters that were compiled are given below. Most of the information was obtained from two sources, Lighting Considerations for Artificial Plant Lighting: A Database, by A. Hoehn with BioServe Space Technologies (University of Colorado, Boulder) and from LCELSS, Preliminary Conceptual Design Study by S. Schwartzkopf with Lockheed.

Wattage: Operating wattage that parameters were measured at.

kg/m2: The mass of the system in kilograms per meter squared of growth area illuminated.

conv eff (light/w): The percent efficiency of the device to convert electricity in watts to watts of light.

%UV out: The percent efficiency of the device to convert electricity in watts to watts of energy in the ultraviolet range (<400nm).

Lifetime (hours): Hours that a device will operate before need of replacement. Note: this does not insure the same efficiency over this time.

%heat out: The % of energy converted from electricity in watts to heat in watts (as opposed to light). This is important for cooling requirements.

Wattage for PAR: This is the operating wattage to obtain 300 umole/m2/s of light in the visible region. For some devices, this is not possible (np) at the operating wattage given.

eff:Watts
to Par %: The percent efficiency of the device to convert electricity in watts to watts of light in the visible spectrum (400-700nm).

The parameters for each lighting devices is summarized in Figure 2-24.

As mentioned above, there are certain characteristics that each device has that make it more highly suitable for an LCELSS then others. These design qualities, POWER EFF., MASS EFF., MAINTAINABILITY, SAFETY AND INDEPENDENCE, are listed and described in more detail below. Each had between 1 and 3 variables, each given a score of H, M, or L for High, Medium, or Low, respectively. High was always the qualitatively best case scenario, and not based on whether the value of the parameter itself was in comparison, quantitatively larger or smaller. For example, a lamp with a HIGH mass would have a LOW efficiency, whereas a lamp with a high power efficiency would also be given a HIGH rating because both are desirable LCELSS design qualities.

Power Eff. Power efficiency took into account two parameters from the list above, conv. eff and eff:Watts to PAR%. They represent the lighting devices ability to convert electricity to light in general, and specifically to the visible range. Each of these parameters were given a score based on the following scale:

eff:Watts to PAR%		conv eff (light/w)	
0-9	L	0-10	L
10-19	M	11-20	M
20+	H	21+	H

MASS EFF- Mass efficiency took only one parameter into account, and that is the mass of the lighting system needed per 1 m2 of growing area illuminated. It was given the following scale:

kg/m2	
0-6.9	H
7-15	M
16+	L

MAINTAINABILITY- System maintainability took into account three areas representing the requirements to keep the system operating. The first is the lifetime of the device. The second is how hard replacement of the device would be once it had been burned out. Basically, this was based on

whether it was easy to identify and replace a source, like a bulb, or whether long arrays would have to be tested and replaced in bulk, such as with LEDs. Information from this came from the primary sources listed above, from general reading, and on lighting and with conversations with A. Hoehn. The last parameter considered is the %heat out, representing the cooling needs for some type of thermal control for the lighting system. The parameters are scaled as follows:

Lifetime (hours)		Replacement		%heat out	
0-15,000	L	hard to replace	L	0-20	H
16-30,000	M	easy to replace	H	21-30	M
31,000+	H			30+	L

SAFETY- There was really only one aspect considered for safety, and that was the possibility of the device exploding. In order to insure against contamination of the crop, or danger to the astronauts, dangerous devices must be somehow encased or shielded, thus complicating the system and increasing volume and mass. This parameter was scored as follows, with the information for the score based also on general reading and conversations with A. Hoehn:

Safety	
Chance of exploding	L
Little to no chance of explosion	H

INDEPENDENCE- Independence is the only characteristic that was not scored as H,M, or L. Devices were scored as either independent, that is able to provide the entire spectral quality and quantity for plant growth, or not. Most systems were not independent.

Independence	
Independent	I
Not-Independent	NI

Because all of the information for each device has yet to be determined (Listed as TBD: To Be Determined), estimates had to be made in certain cases. These were based on general reading and again on conversations with A. Hoehn. They are noted as follows:

*Information on an specific mass numbers for an incandescent system was unavailable, but the consensus of a number of CELSS papers was that it

was fairly mass intensive and was disregarded from many designs for this reason.

**For the same reason as in case of * for incandescents, fluorescents are also regarded as mass intensive, which is supported by two of the data points, so all were given an L rating.

***For data points unavailable for some of the HID lamps, a rating was given based on an estimate that matched those for almost all of the other HIDs that numerical values were available for.

**** For LEDs, cooling wasn't determined at a numeric level, so the MAINTAINABILITY score was based on the average of the other two scores, but weighted equally with other maintainability scores.

The results of this characterization are given in Figure 2-25.

Summarizing the Trade Study
In order to access the information quickly, the design qualities were scored in the following manner. For the most part, each "quality" was weighted according to the number of parameters it took into account. For example, Maintainability included lifetime, replacement and cooling, so it was weighted 3, or had its average score multiplied by 3. Safety was 1 and Power Eff. was 2. Since mass is the driver for the Lunar Base, it was also weighted as 3. Lastly, independence was not considered in the "grading" summary.

The method of summarizing the lighting information can be easily distilled with "grades" as follows. Each design quality received 95 points for each H rating, 85 for each M, and 75 for each L, (except Mass Eff., which received 3 times this score because of its weighting). Then, for each device, all the scores were added, divided by the total number of scores (9), and given a GPA and a grade based on the following scale:
80-82: B-; 83-87:B; 88-89:B+; 90-92: A-;

These results are summarized in Figure 2-24. As can be seen, the grades are pretty related to the family that each device belongs to. The "brightest" pupils were Metal Halide (MH) 125W, the MH1000W, the High Pressure Sodium 1000W and LEDs. Since all these scores were so similar, another trade was examined to pick from these four devices. Since mass is the driver, a mass calculation was performed based on the mass needed to light 1 square meter for 100,000 hours (approximately 11.4 years). Because LEDs have such long lifetimes and low mass, they come out by far

in front of the other devices. The closes is over 15x greater for mass over 11.4 years, and this is almost 30x less than that provided by fiber optic lighting. In addition, LEDs tend to have much better efficiencies over their lifetimes, creating an even larger margin for the mass requirements. LEDs also stand out over the others in other qualities that were not examined above, such as distribution of uniform lighting, the ability for the LEDs to be tuned to the distinct frequencies most needed by a plant. Also, a short rise time allows potential that the idea of intermittent pulsed lighting can be applied, which exhibits unexplored potential for energy savings for the light needed for photosynthesis. Unfortunately, LEDs are incredibly inefficient in the blue range, on order of magnitude 3x less, therefore an LED system is not independent (Hoehn3, 1990). A secondary source of lighting, to provide blue and possibly UV light, is needed.

Secondary Lighting Source for an LED Primary System

Because the LEDs are arranged in large arrays, uniform distribution of the blue light with the red light from the LEDs is a significant problem. A rule of thumb value for this amount is approximately 50 umole/m2/s (Hoehn, conversation). Obviously, a ring around the outside of the growth area consisting of fluorescent lights would provide uneven lighting, where the outside plants would get more blue light then the inner plants. This can be remedied by placing the fluorescents interspaced between the LED arrays, above the plant. However, because the danger of explosion, these must be encased. A different solution is to have some lamp, possibly a HID, in some remote site in the module, where all the HIDs can be encased, cooled and monitored at one location. Then the light can be pumped in via fiber optic cables, and distributed uniformly over the plants. This idea also provides a back-up to the LEDs since it is a potentially independent source, and also an easy interface if fiber optic lighting technology is ever improved enough to make it more mass efficient. However, this could be more mass intensive then fluorescents, and the efficiency of the transmission would have to be examined. An example of these two designs can be found in Figure 2-27.

CONCLUSION

LEDs represent a viable lighting source for an LCELSS, and are vastly superior with respect to the primary mission driver, mass. They also have other design qualities that make them compatible with the design qualities needed for a base, such as safety, and intermittent lighting. The latter application, replacement technology, and especially the integration of a secondary lighting source that provides blue light need to be investigated before the design of an LED system can be completed.

2.6 SUPPORT AND MAINTENANCE REQUIREMENTS

There are certain infrastructure needs for a CELSS as well as many tasks to operate it.
The infrastructure needs are the following:

- -plant growth structure
- -accessibility and maintenance
  - -human and robotic access to plants and animals
  - -plant growth units designed for modular service
- -thermal control
- -nutrient delivery system
- -waste and water management
- -lighting
- -storage
- -automation
- -atmosphere control system
- -phototoxicity control (ethylene, ozone, heavy metals, fluorides)
- -monitor plant gas exchange

There are also numerous tasks that are required to maintain a CELSS such as the following:

- -Setup
  - -sterilization
  - -cleaning/rinsing
  - -planting/replanting
  - -hatching
- -Daily Care
  - -watering
  - -feeding
- -Efficient volume control
  - -evolutionary growth
  - -plant/animal spacing
  - -maintain isolation requirements between species/compatibility
  - -adjust shelves and racks
- -Efficient environmental monitor and control
  - -atmosphere regenerated
  - -humidity levels
  - -measure and monitor (growth rates, mass, volume, nutrient levels, moisture, and light levels)
  - -waste and water management
- -Harvest
  - -cutting (lettuce)

-picking
-slaughtering animals
-Processing
-preparation
-packaging
-Maintenance
-sterilization
-cleaning/rinsing
-transporting/moving
-separation
-storage
-carry
-supply
-collection
-repair
-fan
-pump
-trash disposal

Ideally these needs could be partially met with robotics.

2.7 CELSS RECOMMENDATIONS AND CONCLUSION

After accessing the current CELSS technology the CELSS group proposes the following recommendations. Testing with plants and animals in closed environments needs to be started now. Concurrently with this, the organism characterization and methodology testing needs to be started. Research into the critical technologies also need to be performed in order to overcome stumbling block such as lighting, hydroponics, and optimal plant animal requirements. Next a study of the optimal physical chemical/biological integration needs to be determined as well as problems associated with it. Another major area that needs to be researched is that of optimal phasing of biological elements into a physical chemical systems. In addition it is necessary to research the optimal overall systems organization such as the interior design and plumbing of a CELSS.

Many task must be performed daily for CELSS research to bear fruit. For instance, care of plants and efficient volume control ensures the longevity of bioregenerative experiments. Robots must be utilized to partially tend the CELSS, freeing astronauts to further pursue their research. Also, a number of support requirements including power, mass, and volume must be met.

HUMAN REQUIREMENTS

	Inputs		Outputs
Human Consumption			
Oxygen	.84	Carbon Dioxide	1.00
Food Solids	.62	Respiration	1.81
Food Liquids	.50	Perspiration	.02
Food Preparation	.72	Urine Solids	.06
Drink	1.86	Urine Liquids	1.50
		Fecal Solids	.02
		Fecal Liquids	.09
		Humidity	.06
Laboratory Use			
Experimental Water	1.00	Waste Solids	.50
Material Solids	.50	Waste Liquids	1.47
Material Liquids	.50	Humidity	.22
Cleaning Use			
Dishwash/Cleaning	4.00	Waste Solids	1.36
Laundry Water	12.50	Waste Liquids	17.44
Soil Solids	1.36	Humidity	.22
Soil Liquids	1.16		
Hygiene Use			
Shower	3.64	Waste Solids	.81
Hand/Face Wash	1.82	Waste Liquids	5.69
Toothbrush/Shampoo	.50	Humidity	.08
Soil Solids	.81		
Soil Liquids	.15		

Values are in kilograms per person per day.

FIGURE 2-1 HUMAN REQUIREMENTS

Average Plant Performance

Oxygen Production _____ 125 (g/m^2/day)

Carbon Dioxide Consumption ___ 170 (g/m^2/day)

Water Transpired _____ 7.5 (kg/m^2/day)

Edible Biomass Production ____ 30 (g/m^2/day)

Data taken from "From Space Station Freedom Technologies to a Mature Lunar Outpost LCELSS" by Bioserve Space Technologies and From Space Habitation Fall 1990 Final Report.

FIGURE 2-2 AVERAGE PLANT PERFORMANCE

CELSS SCALING

Human Requirements	Plant Growth Required
Oxygen app. 1 kg/person day	6.0–30.0 m^2
Potable Water app. 6 kg/person day	0.6–1.2 m^2
Total Water app 30 kg/person day	3.0–6.0 m^2
Food 600 g dry biomass/ 10,000 kJ	15.0–20.0 m^2

Data taken from "From Space Station Freedom Technologies to a Mature Lunar Outpost LCELSS" by Bioserve Space Technologies.

FIGURE 2-3 CELSS SCALING

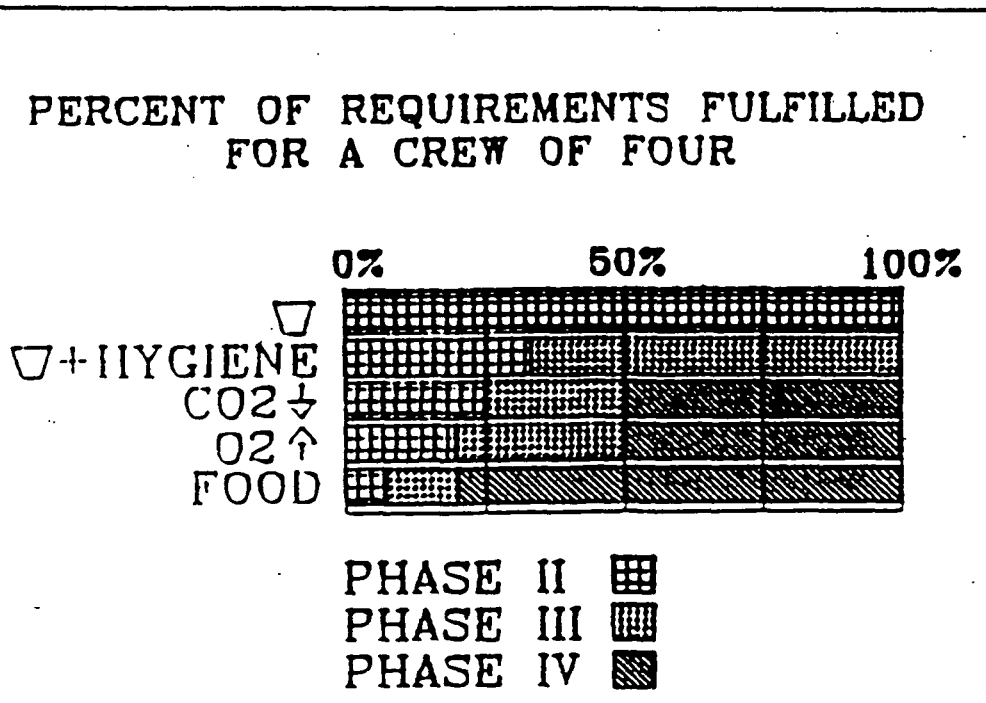


FIGURE 2-4 IMPACTS FOR A CREW OF FOUR

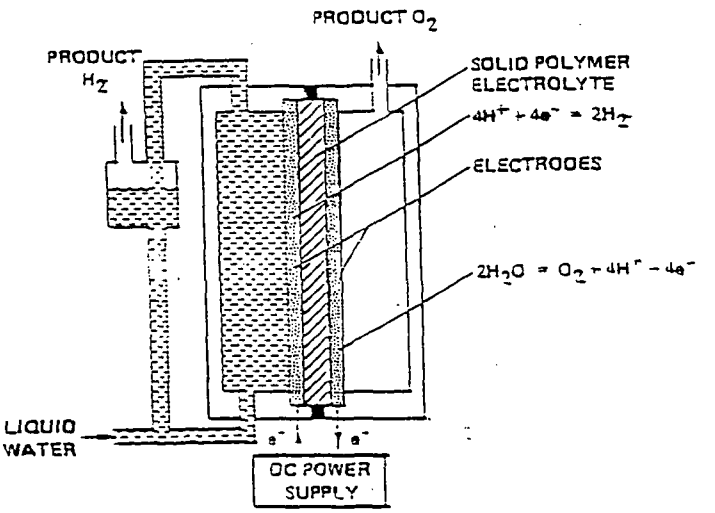
CANDIDATE TECHNOLOGY TRADE STUDY

	Mass kg.	Power Watts	Volume cmJ	Resupply kg.
Oxygen Generation				
Carbon Dioxide Electrolysis	19	150	.028	0
Superoxides	?	?	?	?
SPE	26	366	.042	0
+ SFWES	18	274	.025	0
Carbon Dioxide Removal				
LiOH	1	0	.014	83
SAWD	25	153	.099	0
MS	28	192	.099	0
+ EDC	19	58	.035	0
Carbon Dioxide Reduction				
Open System	0	0	0	57
Carbon Dioxide Electrolysis	19	340	.028	0
Bosch	52	98	.013	27
+ Sabatier	6	13	.011	19
Wastewater Revitalization				
Wet Oxidation (SCOW)	?	?	?	?
VCD	185	220	.460	328
TIMES	145	520	.364	241
+ VPCAR	85	385	.319	23
+ MF	82	130	.303	24
+ RO	87	202	.660	10
+ Bacterial Digestion	20	20	.200	0

+ Indicates baseline lunar CELSS technologies

Values are in support of one person per day except resupply which is in one person per two weeks.

FIGURE 2-5 P/C CANDIDATE TRADE STUDY



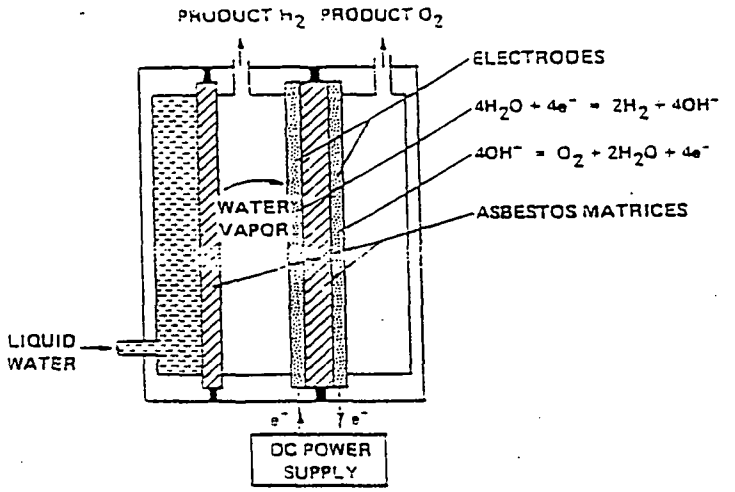
OVERALL REACTION:

$2H_2O + ENERGY = 2H_2 + O_2 + HEAT$

Schematic of a solid polymer H_2O electrolysis cell (reprinted with permission of Life Systems, Inc.).

from (Wydeven, 1988)

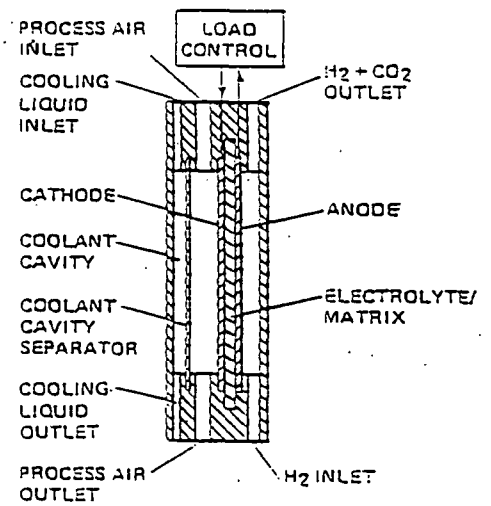
FIGURE 2-6 SOILD POLYMER WATER ELECTROLYSIS SUBSYSTEM



- Schematic of a static feed H_2O electrolysis cell (reprinted with permission of Life Systems, Inc.).

from (Wydeven, 1988)

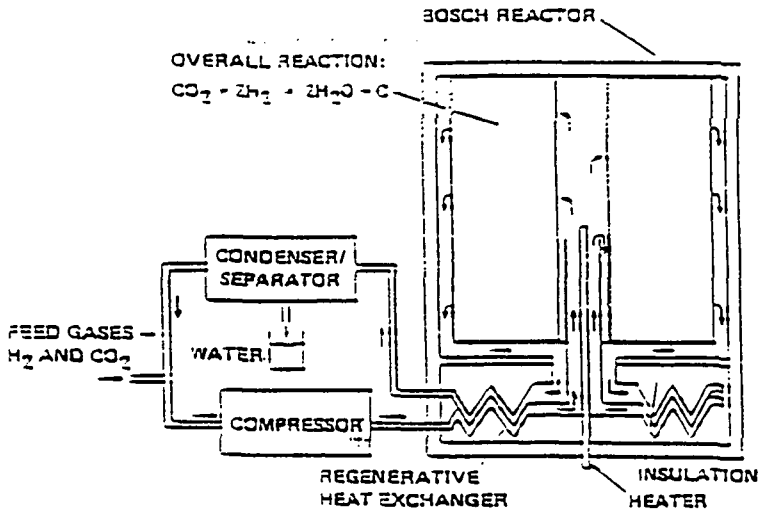
FIGURE 2-7 STATIC FEED WATER ELECTROLYSIS SUBSYSTEM



- The EDC single cell functional schematic (Heppner and Schubert, 1983) (reprinted with permission cc 1983 Society of Automotive Engineers, Inc.).

from (Wydeven, 1988)

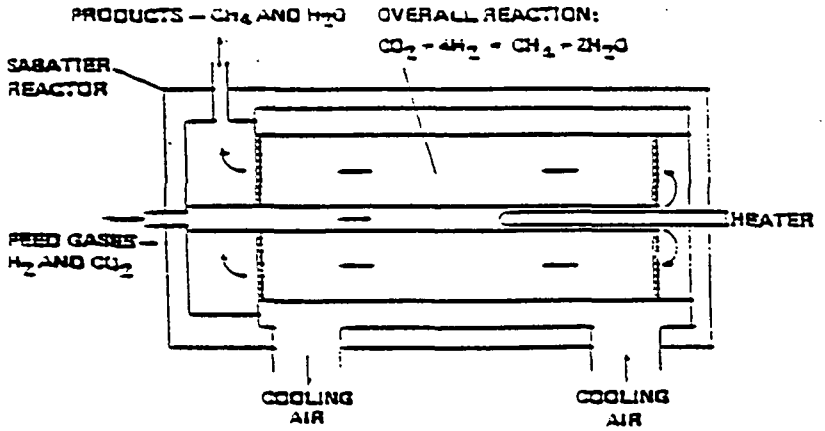
FIGURE 2-8 ELECTROCHEMICAL DEPOLARIZED CARBON DIOXIDE CONCENTRATOR SUBSYSTEM



Simplified schematic of the Bosch CO_2 reduction process (reprinted with permission of Life Systems, Inc.).

from (Wydeven, 1988)

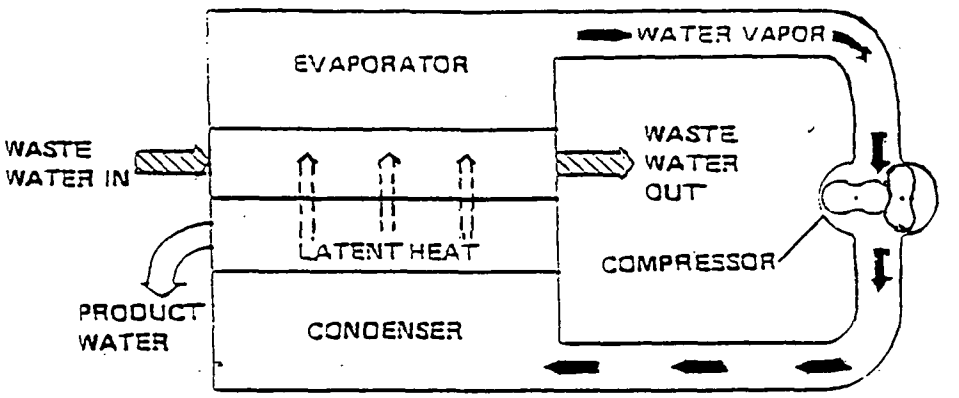
FIGURE 2-9 BOSCH CO2 REDUCTION SUBSYSTEM



Simplified schematic of the Sabatier CO_2 reduction process (reprinted with permission of Life Systems, Inc.).

from (Wydeven, 1988)

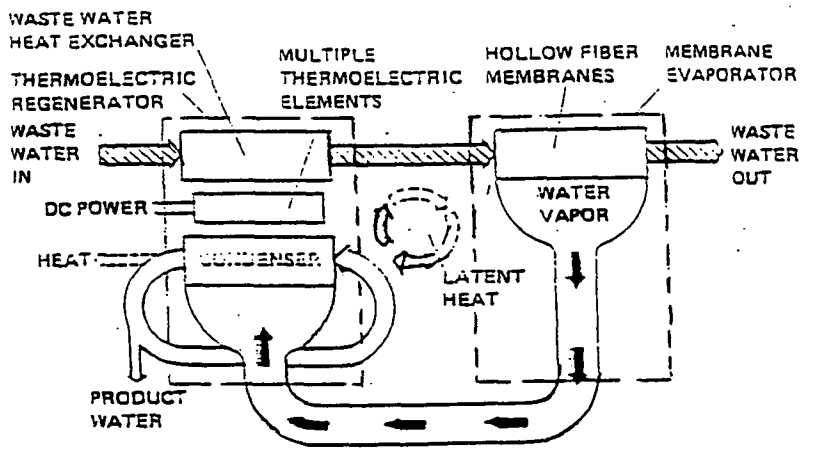
FIGURE 2-10 SABATIER CO2 REDUCTION SUBSYSTEM



- Simplified schematic of the vapor compression distillation water reclamation process (Schubert, 1983) (reprinted with permission cc 1983 Society of Automotive Engineers, Inc.).

from (Wydeven, 1988)

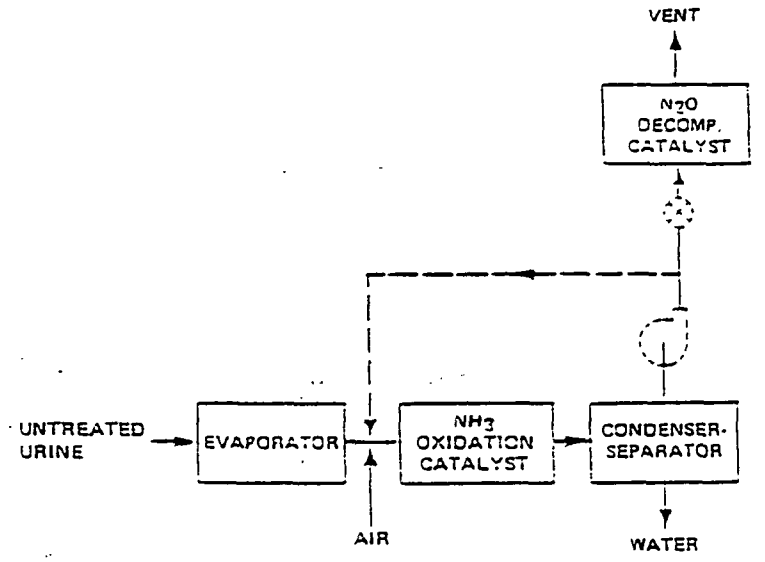
FIGURE 2-11 VAPOR COMPRESSION DISTILLATION WATER RECLAMATION SUBSYSTEM



- Simplified schematic of the thermoelectric integrated membrane evaporation process for water recovery (Schubert, 1983) (reprinted with permission cc 1983 Society of Automotive Engineers, Inc.).

from (Wydeven, 1988)

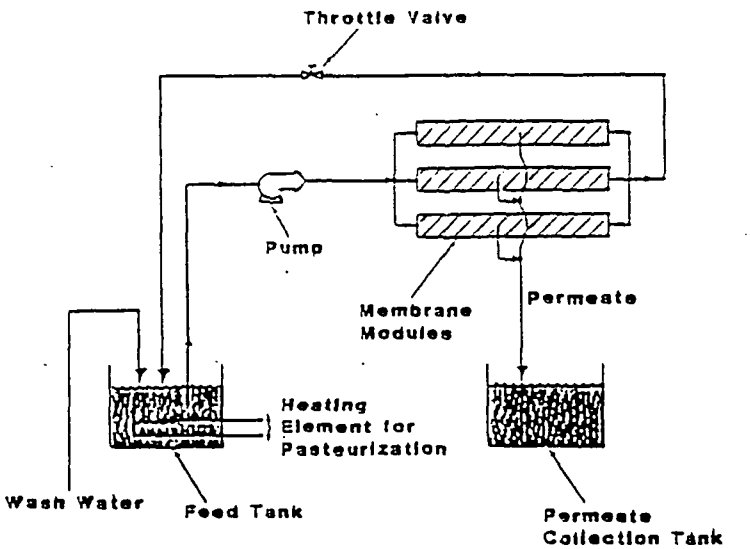
FIGURE 2-12 THERMOELECTRIC INTEGRATED MEMBRANE EVAPORATION SUBSYSTEM



- Simplified flow diagram of the vapor phase catalytic ammonia removal process for water purification.

from (Wydeven, 1988)

FIGURE 2-13 VAPOR PHASE CATALYTIC AMMONIA REMOVAL SUBSYSTEM



Laboratory Wash-Water Treatment System Used in Long-Term Test

from (Wydeven, 1988)

FIGURE 2-14 REVERSE OSMOSIS SUBSYSTEM

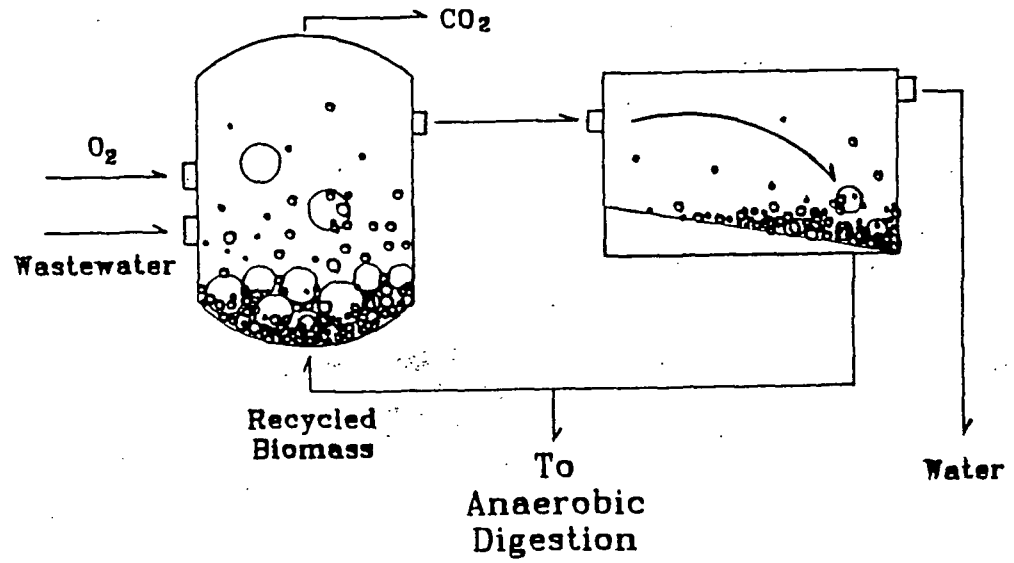


FIGURE 2-15 AEROBIC TREATMENT

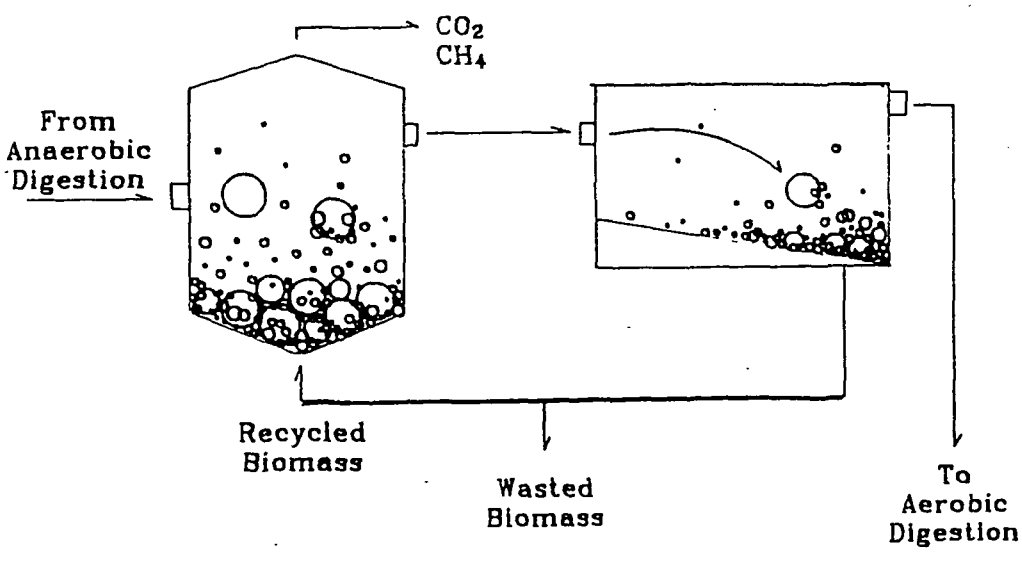


FIGURE 2-16 ANAEROBIC TREATMENT

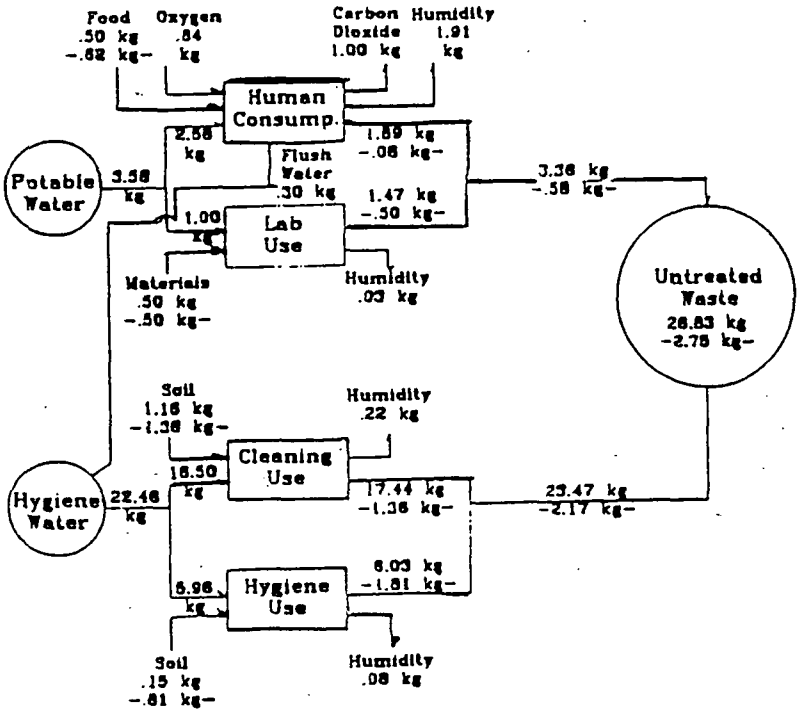


FIGURE 2-17 OPEN LOOP SCHEMATIC

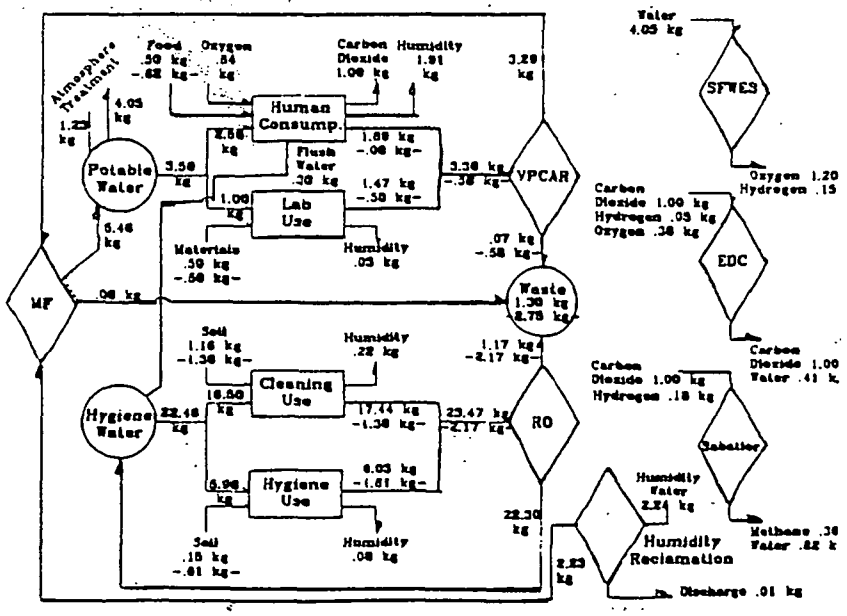


FIGURE 2-18 PHYSICAL/CHEMICAL LIFE SUPPORT SCHEMATIC

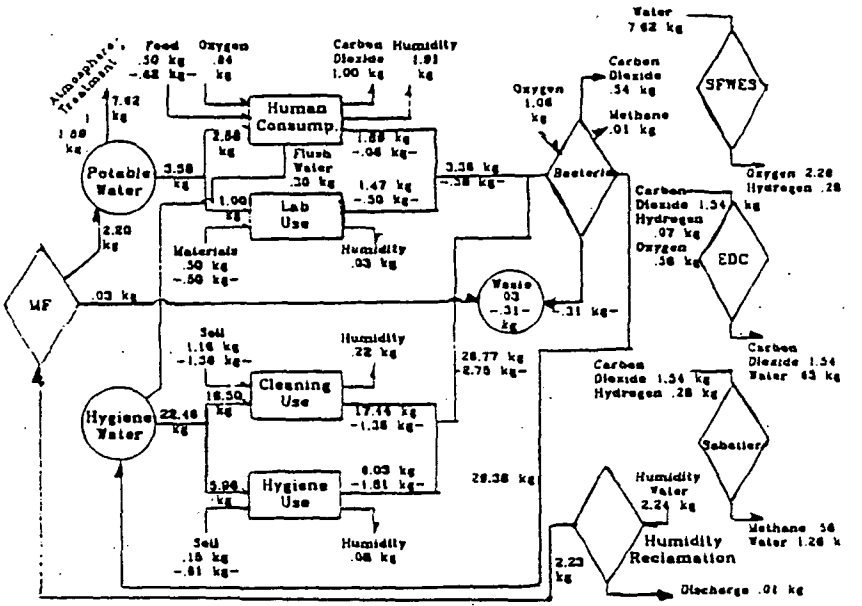


FIGURE 2-19 BACTERIA PHYSICAL/CHEMICAL HYBRID

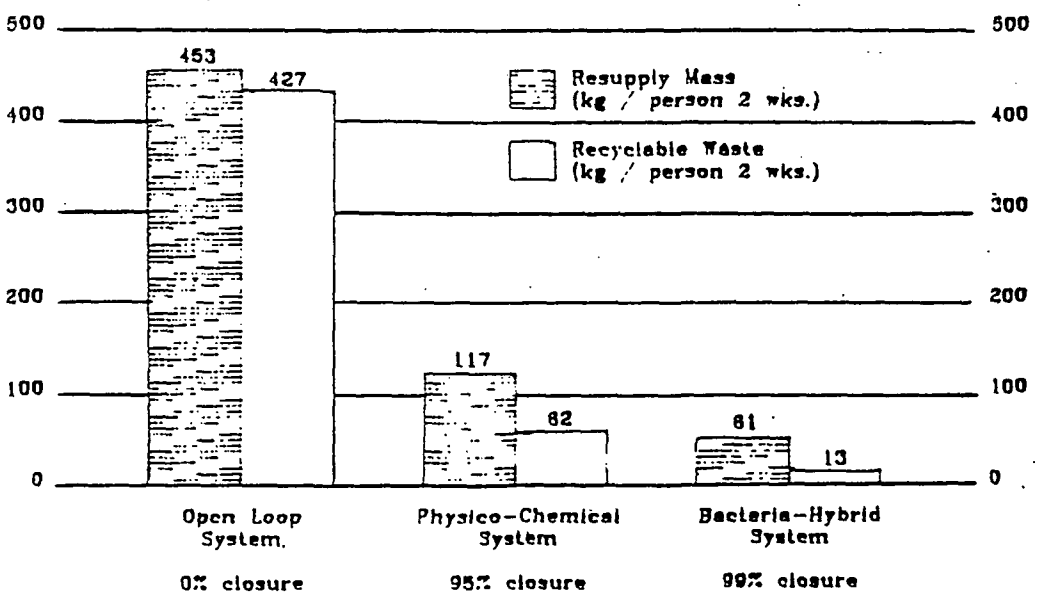


FIGURE 2-20 SYSTEM CLOSURE COMPARISIONS

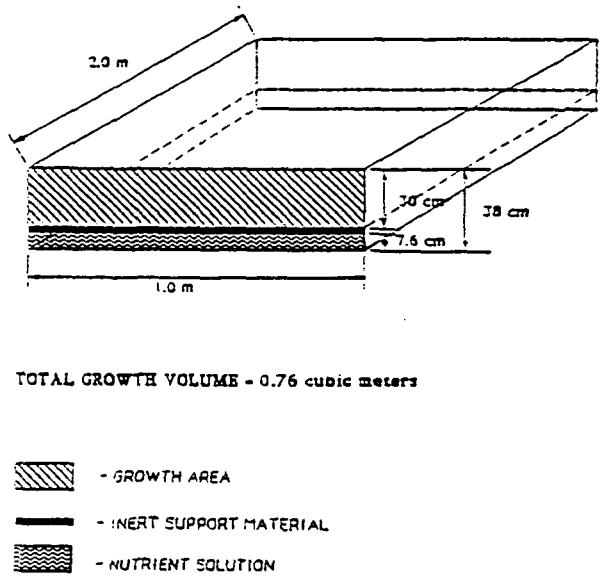


FIGURE 2-21 VOLUME REQUIREMENTS FOR PLANT GROWTH UNIT

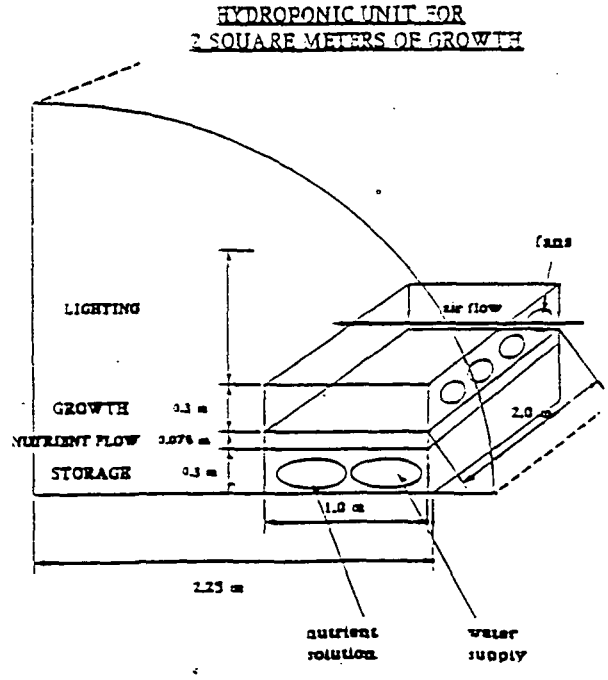
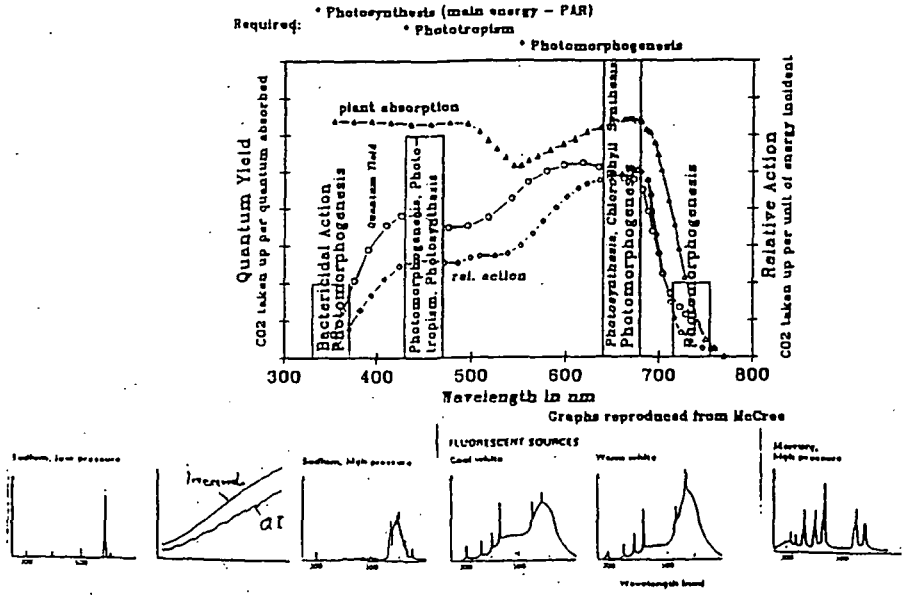


FIGURE 2-22 HYDROPONIC UNIT FOR 2 m2 OF PLANT GROWTH

$$CO_2 + H_2O + Light + Chlorophyll \rightarrow O_2 + CH_2O$$

Light and Plant Functions



SOURCES: Hoehn, A. & Luetgee, M.W. Plants and Artificial Lighting. December, 1989. & Lighting Considerations for

FIGURE 2-23 LIGHT AND PLANT FUNCTIONS

Lighting Device Parameters

Lighting Device	Wattage	kg/m2	conv eff (light/w)	%UV out	Lifetime (hours)	%heat out	Wattage for PAR	eff:Watts in PAR
INCANDESCENTS:								
60A	60	TBD	6	TBD	2000	19	TBD	6
100A	100	TBD	6	TBD	2000	19	TBD	7
200A	200	TBD	6	TBD	2000	19	TBD	8
FLUORESCENTS:								
Cool White 48	48	TBD	22	2	18,000	43	np	20
Cool White 225	110	34.3	22	2	18,000	43	np	20
C W 225	215	20.9	22	2	18,000	43	np	20
Warm White	46	TBD	22	2	18,000	43	np	20
Plant Growth A	46	TBD	22	2	18,000	43	np	13
Plant Growth B	46	TBD	22	2	18,000	43	np	15
Clear Mercury (HG)	440	TBD	16	2	TBD	30	TBD	12
HG Deluxe	440	TBD	16	2	TBD	30	TBD	13
Low Pressure HG	TBD	TBD	5	56	24,000	24	TBD	TBD
Metal Halide (MH)	175	6.6	24	3	20,000	36	np	20
MH	250	8.7	24	3	20,000	36	np	20
MH	400	10.9	24	3	20,000	36	319	20
MH	1000	6.2	24	3	20,000	36	319	20
High Press Sodium	150	7.7	TBD	TBD	6,000	TBD	np	25
HPS	250	8.4	TBD	TBD	6,000	TBD	np	25
HPS	400	11.2	TBD	TBD	6,000	TBD	255	25
HPS	1000	6.1	TBD	TBD	6,000	TBD	255	25
Low Press Sodium	90	31.8	30	<1	18,000	26	np	27
LPS	180	23.5	30	<1	18,000	26	np	27
LED	400	2	14	0	100,000	TBD	TBD	14

TBD: To Be Determined np: not possible at operating wattage

FIGURE 2-24 LIGHTING DEVICE PARAMETERS

LUNAR CELSS LIGHTING DESIGN QUALITIES-

Lighting Device	POWER EFF.	MASS EFF.	MAINTAINABILITY	SAFETY	INDEPENDENCE
INCADESCENTS:					
60A	L/L	L*	L/H/H	H	TBD
100A	L/L	L	L/H/H	H	TBD
200A	L/L	L	L/H/H	H	TBD
FLUORESCENTS:					
Cool White 46	H/H	L**	H/H/L	L	HI
Cool White 225	H/H	L	H/H/L	L	HI
C W 225	H/H	L	H/H/L	L	HI
Warm White	H/H	L	H/H/L	L	HI
Plant Growth A	H/H	L	H/H/L	L	HI
Plant Growth B	H/H	L	H/H/L	L	HI
Clear Mercury (HG)	H/H	H***	H/H/H***	L	TBD
HG Deluxe	H/H	H	H/H/H	L	TBD
Low Pressure HG	L/	H	H/H/H	L	TBD
Metal Halide (MH)	H/H	H	H/H/H	L	HI
MH	H/H	H	H/H/H	L	HI
MH	H/H	H	H/H/H	L	I
MH	H/H	H	H/H/H	L	I
High Press Sodium	H/H****	H	L/H/H****	L	HI
HPS	H/H	H	L/H/H	L	HI
HPS	H/H	H	L/H/H	L	I
HPS	H/H	H	L/H/H	L	I
Low Press Sodium	H/H	L	H/H/H	L	HI
LPS	H/H	L	H/H/H	L	HI
LED	H/H	H	H/L/TBD*****	H	HI

FIGURE 2-25 LUNAR CELSS LIGHTING DESIGN QUALITIES

PLANT GRADES: A Summary

Report Card

DEVICE	AVG	GRADE
Inc.	82	B-
Fluor.	83	B
HG	83-85	B
MH	88-89	B+
HPS	85-88	B/B+
LPS	84	B
LED	89	B+

Honor Roll

MH 125:	89	B+
MH 1000:	89	B+
HPS 1000:	88	B+
LED:	89	B+

PLANT FINAL: SYSTEM MASS PER LIGHTED AREA

100,000 Hour Base (11.4 years) 100,000/liftime * kg/m2 =

MH 175 33 kg/m2 over 11.4 years
MH 1000 31 kg/m2 over 11.4 years
HPS 1000 102 kg/m2 over 11.4 years

LED 2 kg/m2 over 11.4 years

FIGURE 2-26 LIGHTING DESIGN TRADE STUDY

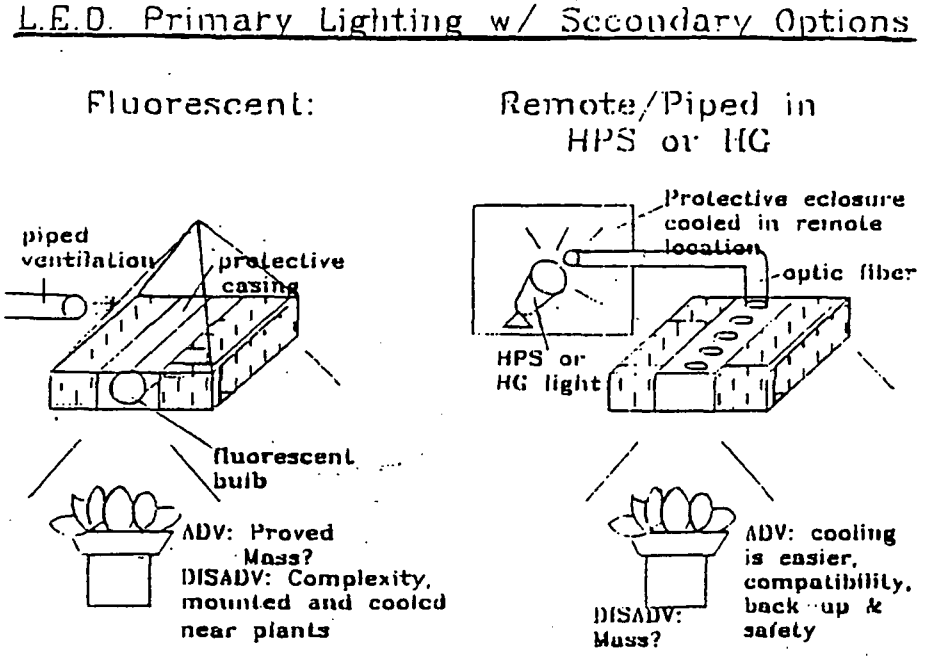


FIGURE 2-27 L.E.D. PRIMARY LIGHTING W/SECONDARY OPTIONS

3.0 INFRASTRUCTURE

An infrastructure is the basic foundation or underlying framework that supports a mission and supplies its fundamental needs. Ideally, once in place, this infrastructure can then be taken for granted, like a highway system or telephone network is today. Also, although the primary mission of the infrastructure is to enable a Lunar Base, each of its elements should have specific returns and Earth applications.

Since the initial phases of lunar CELSS development involves ground based research and testing, an infrastructure must be provided to support this work. A life enabling closed volume is needed to allow the CELSS experiments to be completely isolated from all outside influences. Facilities, such as a galley and personal quarters, must also be provided so that humans may be integrated into the CELSS. Along with the CELSS and human support structure, a small self-contained power system is needed to provide the electricity needed to create a life enabling environment, and a thermal control system is required to dissipate the excess heat generated by the electrical and mechanical systems.

Once the ground based elements have been thoroughly tested they must be modified for the different thermal, radiation, and gravity constraints of the lunar surface. Also, several additional elements must be added to achieve the goal of a Lunar Base. A lunar site that will provide the best environment for the Lunar Base must be chosen. Since adequate information concerning the lunar surface is not available, the site selection process will require extensive remote sensing and mapping followed by robotic site verification. A communication network is needed to provide an audio/visual link between the Earth and the lunar surface. Lastly, a transportation system must be provided to allow the transfer of the other infrastructure elements to the chosen lunar site. Also, once the space based phase begins, safety becomes of paramount importance for all infrastructure elements.

3.1 STRUCTURE

RATIONALE

Due to the lack of an atmosphere, the extreme temperatures, and the radiation hazards present on the lunar surface, a structure is needed to provide a life enabling environment for both the CELSS organisms and the crew. Without such a structure, life would not be possible on the lunar surface.

REQUIREMENTS

The basic requirement of the structure is that it must support and enable life on the lunar surface. This includes providing shelter from radiation, meteorites, and the cold vacuum of space, as well as supplying all life support functions required by both plants and animals. Since ground based testing will precede the space based phase, a structure must also be developed for this purpose. However, this facility should not be a separate entity, but rather a testbed for the same structures and systems that will be utilized on the moon.

TRADE STUDIES

The first aspect to be considered is what type of structure is to be used for housing the crew on the moon. There are two basic structural types that are feasible for use in an initial lunar base: inflatables, and hard modules. Inflatable structures are favored by many for their low mass and ease of transportation and setup. However, all of the structure's contents, such as the life support equipment and interior furnishings, must be shipped separately and integrated on the lunar surface. This requires extensive EVA time or sophisticated robotics and was deemed expensive and impractical by the Infrastructure Group. Therefore, a hard modular structure was chosen for the lunar base. This allows for all of the module's subsystems to be assembled and tested on the Earth, where construction costs are dramatically lower. The module would then require a minimum of setup and evaluation on the moon before it is ready to sustain life.

The size of the module was the next variable to be studied. The baseline was taken to be a module designed for the Space Station Freedom (SSF). These modules are composed of a cylindrical section approximately 11.5 meters long and 4.3 meters in diameter (NASA, 1983). The ends of the cylinder taper to a docking collar that has a diameter of 1.78 meters. Such a module has a total volume of approximately 200 m^3. As will be shown later, this is sufficient volume to support CELSS expansion through phase III as well as a crew of four. In addition the use of a SSF module will minimize development and manufacturing costs since they will already be in production.

The first segment of the ground based infrastructure is a closed life enabling volume to support CELSS research. Such a volume must be completely closed and self-contained to eliminate all outside inputs. It must also provide the proper environment for the healthy growth and maturation of the CELSS organisms, namely plants and animals. This involves maintaining the correct temperature, humidity, and gas concentrations, as well aa providing the subsystems needed for organism

growth. These subsystems include lighting, nutrient delivery, and waste and water handling systems. The CELSS structure should also be expandable to allow for a phased implementation.

Once the CELSS structure has been thoroughly tested on the ground, it will be implemented into the Lunar Base module. As previously stated, the CELSS will be phased into the Lunar Base. Through the use of hydroponics and LEDs, the total volume, including all support equipment, needed to grow 1 m^2 of lettuce was estimated to be 1 m^3. Also, 3.2 m^3 was found to be sufficient to support 120 catfish and an algae system. Therefore, to allow for expansion through phase III, the total volume of the CELSS support structure must be 15.2 m^3.

Once the CELSS has been tested using plants and animals, humans may be integrated into the system. While humans are technically animals, they require different, albeit mostly analogous, support facilities. A crew of four was chosen for the initial Lunar Base. This provides for a large enough skill base, a redundancy of critical skills, and the ability to complete labor intensive tasks with the initial crew, while minimizing the initial Lunar Base mass. A list of the required facilities and the volume needed for a crew of four are listed in the table below.

FACILITIES	VOLUME (m^3)
personal quarters	18.8 [1,2]
galley	6.4 [3]
hygiene/waste	4.5 [1]
health maintenance	4.5 [1]
dining/recreation	4.8 [2]
data management/comm	2.7 [3]
exercise	varies
maintenance	2.7 [3]
EVA storage	12.0 [1]
ECLS	9.5 [3,4]
storage (90 days)	22.6 [3]
CELSS	15.2
circulation	40.1 [1]
TOTAL	143.8

1 (Capps, et al, 1989)
2 (Woodson, 1981)
3 (NASA, 1985)
4 (NASA, 1983)

The above table clearly shows that a SSF module is of sufficient volume to accommodate the required support facilities. A design for the interior of the module was not done during this study since the preferred design would incorporate as many Space Station elements as possible. Since the SSF design process is still ongoing, a lunar module design should not be done until the Freedom design is completed.

SPINOFFS

There are many Earth based applications of the CELSS infrastructure. For instance, small, reliable gas sensors could be utilized by material processing industries and others in which gas purity levels are important. The obtainment of complete closure could also benefit these same industries by improving and lowering the cost of clean room technology, thus facilitating the production of cheap, yet high quality, medical. products, computer chips, and aerospace components.

RECOMMENDATIONS AND CONCLUSIONS

The first step in the development of a lunar base is the design of a life enabling structure to support the crew and CELSS organisms. A Space Station Freedom module should be utilized for ground based testing as well as for the Lunar Base. The structure must be self contained and supply all the needs of both plants and animals. Also, adequate facilities must be provided to support a crew of four in a comfortable and safe manner while minimizing the mass and volume of the structure.

3.2 NODES

RATIONALE

Although the Lunar Base is designed as first stage implementation, later expansion of the base should be accounted for in its structural design. This fact is the driving force behind the use of components separate from the main module that will act as ingress and egress points for the initial module, but later will also serve as connectors for additional modules.

REQUIREMENTS

These connecting units, called nodes, will be designed to provide the base crew with efficient means of module ingress and egress, will allow for future expansion. In order to accomplish these goals, several requirements present themselves.

To allow for expansion, it will be necessary to have some form of unused connecting points in each node in addition to any that will be used in the initial implementation. Also, in the event that the Lunar Base program is

canceled or delayed, access to the module through a node airlock should be available as soon as the module is in place on the lunar surface.

For safety purposes, there should be at least two ways into and out of the module. If an accident were to cut the crew off from one of the exits, there must be another that they will be able to access. Our present module design, which is based on the Space Station Freedom habitation module, has a hatch at both ends of its cylindrical design. This format will require two nodes meet the safety requirements. In the event of an emergency that requires the crew to evacuate the module for repairs or abandonment, there should be EVA suits for each crew member in each node.

The normal function of the nodes will be to act as airlocks. This will allow crew members to enter and leave the module without disturbing the atmosphere in the main module section. At least one of the nodes should also function as a hyperbaric chamber in case a crew member experiences the bends during an EVA activity.

CRITICAL TECHNOLOGIES

The node design for the SSF includes six penetrations in the hull where hatches, airlocks, and cupola windows can be placed (SSF Media Handbook, 1989). A major technology that must be developed is the use of seals and hatches (Capps, et al 1989). Current seal designs are generally either leaky or hard to fasten. In a long term space facility design, leaks in seals will create air supply problems, especially for a very remote structure such as a Lunar Base. To keep resupply of air to a minimum, seals should be as close to airtight as possible.

Some designs for airtight seals require so many bolts and other fastening devices that the connection of such a seal on the lunar surface would be time consuming and dangerous for a man, and beyond the precision tolerance limits for a robot. The development of better robotics may allow the use of robots during lunar surface assembly, but it would be simpler to make the design more forgiving in terms of precision. A balance between good, airtight seals, and easy installation should be of high priority.

TRADE STUDIES

The structure Group identified three main choices for node design. The first is a SSF-type cylindrical hard node, approximately 4.3 by 5.2 meters, designed by McDonnell Douglas. It is a rigid design that has six access points for connections and hatches. It could act as both a normal airlock and a hyperbaric chamber. It is big enough to allow the storage of EVA suits, plus room to put them on. The design's main drawback is its mass.

At 5000 to 6000 kg, it constitutes a major payload for transportation to the lunar surface.

The second is soft connector design suggested in the University of Houston Partial Gravity Habitat Study. This design is a flexible tube approximately two meters in diameter. It is designed on a movable base with adjustments possible in all directions to compensate for alignment differences between the two structures that are to be connected. The soft node could function as and airlock, but the leaky characteristics of flexible connector would make it necessary to leave the connection empty except when in use for EVA activity. There would not be room for EVA suit storage or use. It would also be ineffective as a hyperbaric chamber. It is, however, not as massive as the hard node.

The last option is one the Infrastructure Group suggested. It is a small hard node designed to act as an airlock, but not as a hyperbaric airlock. It would measure approximately three meters in diameter, and three to four meters long. There would be sufficient room for EVA suit storage, and room to put them on as long as the whole crew does not try it at once. The main reason for this design is the mass savings. Using a shell design similar to the main module (double walled Aluminum), the mass would be around 1700 kg. In the case of all three node designs, it would be necessary to have ladders down to the lunar surface.

To meet all of the requirements listed above limits the number of choices for combinations of nodes. Two hard nodes meet all the requirements except that to land the module with one hard node attached raises the mass requirements of the lunar lander.

One hard node and one soft node reduces the mass involved, but does not allow for the storage of EVA suits in one of the exits. This makes the use of soft nodes in any way undesirable.

The combination the Infrastructure Group decided on was to use on full size hard node and one mini hard node. The mini hard node would land attached to the module. While the full size hard node would land on the next flight and would be attached either by robotics, or by the crew when they arrive. This configuration meets the requirements of dual ingress and egress, immediate access to the module, airlock and hyperbaric chamber capabilities, and takes into account any emergency situations.

RECOMMENDATIONS AND CONCLUSION

The technology required to develop nodes for the Lunar Base will not be the most demanding in the project. Items such as seals, however, are critical, especially since the eventual goal is to maintain a closed environment. Once a true CELSS system exists in the Lunar Base, resupply missions will be spread out over long periods of time. Leaks in seals cannot be tolerated at that stage since the air supply is limited and cannot be replenished as often as it will be initially.

Robotics technology will be necessary for more than just the node assembly. Almost every aspect of the Lunar Base can be at least augmented by the use of automation and robotics. Every part of the mission will demand new capabilities from the robots, and each capability will aid all the other areas. The node technology requires precision and correction abilities. These abilities in a robot will be useful in other parts of the Lunar Base construction, maintenance, and repair.

The recommendation of the Infrastructure Group is to have one full size and one mini hard node. This will enable the Lunar Base mission to progress as efficiently as possible while still meeting the requirements necessary for the mission's success.

3.3 POWER

RATIONALE

One of the fundamental requirements of a Lunar Base is that it must have some sort of power system to provide the electricity needed to sustain life. Without power, there would be no way to maintain an atmosphere, regulate temperature, operate any kind of electronic or robotic equipment, or provide communication with the Earth. Therefore, an efficient, dependable power system is a crucial element in the design of a Lunar Base.

REQUIREMENTS

As with other lunar infrastructure elements, reliability, safety, and low system mass are primary requirements of a lunar power system. It must also be able to provide for all of the electrical needs of the lunar module and supporting equipment. Based upon the projected power needed to provide basic housekeeping on the Space Station Freedom, it was determined that an average of 10 kW of power per person would be required. Since for the initial phases of the Lunar Base no more than four crew would be present at any given time, a total of 40 kW would be needed by the module. There are also CELSS and robotic power

requirements, however, these are more difficult to estimate. It was determined that 100 kW would allow for a sufficient power margin to support the phased growth of both of these areas, at least for the initial phases of the Lunar Base. Consequently, 100 kW defines the wattage requirement for a lunar power system.

CRITICAL TECHNOLOGIES

There are presently two basic types of power systems that are feasible for near term lunar operation. These are solar, including photovoltaic and solar dynamic systems; and nuclear, including radioisotope power and space nuclear reactors. Radioisotope and solar photovoltaic power have provided the bulk of the knowledge concerning space power systems, the former being used on Galileo and other planetary spacecraft while the latter provides power for many satellites.

Although both solar dynamic and photovoltaic systems convert the sun's energy into electrical power, there are fundamental differences in how this is accomplished. Solar dynamic systems focus solar flux at a collector and convert the heat generated into electricity, usually by means of a turbine. This is in contrast to photovoltaic systems where the solar energy is converted directly into electricity.

Both of these systems are similar in that an energy storage method is needed for use when solar flux is not available, such as would occur during the lunar night. As shown below, this storage system is actually the predominate mass for each of the options, making up nearly 92% of the gross mass of a photovoltaic system. The total mass for the solar dynamic system is much greater than that for a photovoltaic system providing an equal amount of power. This is due to the solar dynamic system's need for radiators to dissipate the excess heat and engines to convert the thermal energy to electricity.

Photovoltaic Power System	
Power Storage:	44,589 kg
Solar Arrays:	4,056 kg
Total Mass:	48,645 kg
Solar Dynamic Power System	
Solar Concentrators:	7,973 kg
Power Storage:	44,589 kg
Receivers:	2,587 kg
Engines/Alternators:	4,396 kg
Radiators:	24,936 kg

AC/DC Converters:	648 kg
Total Mass:	85,129 kg

These masses were calculated by Eagle Engineering based upon a system using Stirling engines, gallium arsenide solar cells, and alkaline capillary matrix fuel cells for storage purposes (Eagle Engineering, 1988e). As these numbers demonstrate, a photovoltaic system is far less massive, and hence more cost effective, than a comparable solar dynamic system. This leads to the conclusion that photovoltaic is preferable to solar dynamic for lunar power system applications.

The second option for a lunar power system is to use nuclear power. Possible options include the use of radioisotope generators, thermionic reactors, and heat pipe power systems.

Radioisotope systems have been used on several interplanetary spacecraft to supply them with power for their long voyage through space. They are ideally suited for this purpose because of their long lifespan and the fact that such craft have relatively small power needs. However, the low power output of radioisotope generators, on the order of a few kilowatts (Angelo and Buden, 1985), is far less than the 100 kW that would be needed for a Lunar Base. Therefore, radioisotope generators are not an appropriate choice for a lunar power system.

Thermionic reactors, such as the Topaz 2 system recently acquired form the Soviets, are a second form of nuclear power suitable for space applications. The Topaz system is capable of producing from 6 to10 kW of power over a life span of five years. There is a possibility that this could be upgraded to 30 - 40 kW with only minor technical modifications (Henderson, 1991).

There are several advantages and disadvantages to using this system as the power source for the Lunar Base. To meet the 100 kW power requirement several reactors would be needed. This would provide a small measure of redundancy so that if one of the reactors should fail, there would still be some power available. Also, the technology is currently available, so development costs would be low. The major disadvantage of using thermionic nuclear reactors is the system mass. The total mass needed for a lunar power system capable of generating 100 kW would be approximately 10,000 kg. A second disadvantage would be its short lifespan. The Topaz 2 would need to be replaced every five years, since there is no provision for refueling it.

A heat pipe reactor, such as the SP-100, is a third option for a nuclear power system. The advantages of this system would include a long lifespan and small system mass. The SP-100 is designed to produce 100 kW of power with a total mass of approximately 3,600 kg, much lower than the mass of a thermionic system. The disadvantage of using a heat pipe reactor is that one has not been completely developed, and hence never tested. If the SP-100, or a comparable heat pipe reactor, can be developed, it would be preferable to the Topaz as a lunar power source. However, since most mass and power projections are very optimistic, the SP-100 can not be counted on to meet the specifications that it is being designed to.

Once the candidate technologies for a lunar power system have been identified, a trade study can be done to determine the most desirable option. Since total system mass is the primary design consideration, a mass comparison between nuclear and solar power systems was done for a 35 year period. Since the Topaz 2 is currently available, its mass was used to represent the nuclear option. If the SP-100 is developed the nuclear system mass could be even lower. In determining the resupply mass for a photovoltaic system, degradation of the solar cells was taken into account. It was determined that 10.6% of the solar cells would be lost after five years, translating into a resupply mass of 5,100 kg. Degradation of these replacement cells is also taken into account.

	Mass (kg)	
Time (years)	Topaz 2	Photovoltaic
0	10,000	48,600
5	20,000	53,700
10	30,000	58,800
15	40,000	63,400
20	50,000	67,500
25	60,000	71,200
30	70,000	74,500
35	80,000	77,500

As shown in the preceding table, a photovoltaic system only becomes more efficient than the Topaz after 35 years. If a comparison was done with the SP-100 this time period would even be much longer. However, this trade study was done using the mass of a photovoltaic system that has sufficient battery backup for the fourteen day lunar night. If the solar arrays were located where continuous sunlight was available, such as on a mountain near one of the poles, the initial photovoltaic mass would be reduced to that of just the arrays (4,056 kg). This would bring the photovoltaic

system mass in line with that of a nuclear power system, while avoiding the safety problems inherent in all nuclear designs.

Since no power system is 100% reliable, a backup system must also be provided. It has been estimated that 1050 Watts of power will be required to keep a person alive in space. This number assumes that the average power needed is 350 Watts and would peak at three times that figure (Ruppe, 1980). Therefore, a backup power system should provide around 5 kW of power for a period of 72 hours.

The first candidate technology for a backup power system is battery storage. It has been estimated that a battery power density of 150 Watt hours per kilogram is attainable in the next 15 years (Attia, 1989). This would put the system mass for 360 kW hours at approximately 2400 kg.

An alternative to using batteries for the backup power system would be to use fuel cells. With alkaline capillary matrix fuel cells, such as are used on the Space Shuttle, the mass of a system capable of generating 360 kW hours of power would only be approximately 735 kg, much lower than the mass of a battery system. Therefore, due to their low mass, fuel cells are the best choice for a backup power system.

SPINOFFS

The development of either a nuclear or solar power system would have definite near-term Earth applications. Currently, nuclear power is viewed as unsafe by the general public, and solar cells are not efficient enough to make solar power commercially attractive. Both of these problems would need to be addressed in the power system development. If solved, then either nuclear or solar would become a viable alternative to using environmentally damaging, and increasingly scarce, fossil fuels as our primary energy source.

RECOMMENDATIONS AND CONCLUSIONS

In conclusion, development of a efficient, reliable power system is a critical element of the Lunar Base design. After analyzing the various options, several recommendations can be made for a lunar power system. If a lunar site that having access to continuous sunlight can be located, then a photovoltaic system is the best choice for a lunar power system. However, if such a site is not feasible a nuclear reactor should be used. The first choice for a nuclear power system is the SP-100. However, if it can not be developed to meet design specifications a thermionic reactor, such as the Topaz 2, should be employed. Finally, due to their low mass, fuel cells should be utilized as the backup power system for the Lunar Base.

3.4 HEAT REJECTION

RATIONALE

The harsh environment of space will require a lunar module capable of withstanding extreme temperature fluctuations, while expelling waste heat produced in the module. Various methods exist or are currently under development that have the ability to radiate excess heat produced through power generation, equipment operation, and by humans. Although any one of these methods might offer a viable solution, several requirements will have to be met before a selection can be made.

REQUIREMENTS

In order to provide a criteria for the selection of a thermal control system, it is important to understand the thermal problems characteristic of the moon. During the lunar day at the equator, the temperature may change from a low of 80 K to a high of 390 K (Schwartzkopf, 1990). The lunar surface can also cause, depending on the conditions, the solar energy to be reflected back and forth between peaks and valleys. These radiation traps will cause substantial increases in the measured temperature, possibly as great as 38 K, as well as the obvious increases in radiation exposure. Our solution to this problem has been to place the lunar module in a permanently shaded area in the North Pole region. The temperature at the poles, although unknown, may be as low as 40 K (Schwartzkopf, 1990). This creates a temperature gradient favorable to the transfer of heat from the interior of the module to the external surface.

The prime consideration that will effect the selection of a heat rejection system is its power effectiveness relative to its absolute weight. Safety and efficiency are also important criteria. The heat transfer systems considered include the following: Radiative Fins, Mechanical Refrigeration, Pulse Tube Refrigeration, Heat Pipe Radiators, Moving Belt Radiators, and the Liquid Droplet Radiator.

TRADE STUDIES

Although heat convection is a more effective method of heat transfer, the absence of an atmosphere makes radiation the only way of disposing of waste heat on the moon. The idea of using the Lunar surface as a heat sink is unacceptable because of its low thermal conductivity. For a comparison, the specific heat of the lunar soil is similar to that of bricks, roughly 1/5 of water (Schwartzkopf, 1990). If the soil was used in heat transfer, a mass flow of 450 kg/h with a temperature rise of 100 K would be required in

order to dump 10 kW of heat (Schwartzkopf, 1990). This idea might be possible if the soil was mined for lunar resources, but only as a secondary system.

Probably the simplest form of radiative heat transfer is the use of radiative fin surfaces. Several surface areas exist including the rectangular, triangular, trapezoidal, and constant temperature gradient type fins (Donald Mackay, 1963) (See Figure 3-1). The rectangular fin is the heaviest, but is the simplest and easiest to make. It also has the highest effectiveness for a given profile number. (Note: The profile number is calculated from the configuration and thermal characteristics, and is the key to the design of an effective radiator.) Although a triangular fin having the same area would transmit roughly 12% less heat, it would be more mass efficient.(Donald Mackay, 1963) The trapezoidal fin would not be a good choice because it performs midway between the rectangular and triangular fins, thereby offering no great advantages. The best fin would probably be the constant temperature gradient fin. This type of fin distributes the surface area of the metal, making it the lightest of all the configurations. Although constant temperature gradient fins are the hardest to make, they compensate for this fact by reducing the weight by a greater percentage than the the loss in its heat transfer characteristics.(Donald Mackay, 1963) Although radiative fins by themselves do not offer the best solution when compared to the other methods, they are in fact used in other heat transfer concepts like the heat pipe.

The use of a mechanical refrigeration cycle for heat rejection is a second possibility for a heat rejection system. The basic concept is similar to that of a conventional refrigerator, with the ideal cycle being that of a reverse Carnot cycle. (See Figure 3-2) Two types of refrigerating cycles, the Simple Circuit Compression System and the Cascade System, were looked at. (See Figure 3-3) The Simple Circuit System is advantageous because it allows only a small amount of heat to be transferred out of the working fluid during intercooling and does not have the temperature stage differences characteristic of the Cascade System.(Donald Mackay, 1963) However, it is restricted to single fluid operation. In comparison to the Simple Circuit System, the Cascade system offers superior condenser areas and shaft power outputs.(Donald Mackay, 1963) Thus, since minimum power conditions are important, a multi-stage Cascade System is necessary. When the temperature ratio of internal to external temperatures is greater than 1.25, a Cascade System will reduce the required shaft power by 17%. A total savings of 20% may be obtained for a configuration factor of 0.8 (Donald Mackay, 1963). The configuration number is simply determined

by the shape and orientation of the involved surfaces. In any case, if a mechanical refrigeration system were used, the Cascade System would be the most advantageous.

Another type of refrigeration currently being developed is Pulse Tube Refrigeration (PTR). This fairly simple concept utilizes a piston to compress gas. As the gas is compressed, energy is removed while the gas warms up. Finally, when the gas expands, it cools down very rapidly to a temperature lower than the original temperature since energy was removed during compression.

Small PTR units are used in cooling infrared sensors, cryogenic refrigeration, and superconductivity. When used in cooling infrared sensors, a small PTR can cool up to a couple of Watts. Using a larger compressor, PTR's can provide up to 60 Watts of cooling. However, the increase in size of the compressor adds to the total weight of the PTR and smaller compressors capable of handling this same amount of cooling are very expensive. Since cooling the module will require a large amount of heat transfer, Pulse Tube Refrigeration is not the ideal choice for the lunar heat rejection system. (Information on Pulse Tube Refrigeration was obtained by Professor Klaus D. Timmerhaus and an associated graduate student at the University of Colorado, May 1991.)

The current state of the art in heat transfer systems is the heat pipe concept, used in conjunction with heat exchangers. The heat pipe is an effective thermal conductor, having a higher conductance than any given conducting metal.(Ebeling & Meyer, 1988) Waste heat from a heat source region is delivered via a heat pipe to a storage medium containing radiative fins, which then distributes the waste heat to the heat sink region (See Figure 3-4).

This system has several advantage over a liquid radiator for use in space systems. First, the heat pipe relieves the need for the heat exchanger to be connected directly to the radiating area (Ebeling & Meyer, 1988). The heat exchanger may then be better protected from micrometeorites. Second, although a heat pipe puncture from a micrometeorite would decrease overall heat rejection capabilities, the heat rejection system would not be totally destroyed since each heat pipe represents a closed system. However, since the standard heat pipe's conductance is fixed, the heat pipe must be designed to handle a constant specific heat load (Sheffield, 1986). This problem may be overcome through the use of variable conductance heat pipes, which allows for the control of the conductance through the use of a noncondensible gas at the condenser ends (Sheffield, 1986). The pipe

would therefore expand and contract with changes in the vapor temperature, thus controlling the effective condenser heat transfer area. In comparison to conventional liquid radiators, the heat rejection capability per unit area is inferior (Sheffield, 1986). However, heat pipes have a longer lifespan because of their setup. This offers a significant advantage when considering a heat transfer system for a relative long lunar mission duration. Another consideration for Heat pipes, is that they may be used under a low temperature gradient to obtain an almost isothermal heat source. The heat flux transformation can also be used to give a low heat flux density in the storage chamber, enabling large heat flows.(Sheffield, 1986) Finally, the heat pipe can act as a thermal diode by operating unidirectionally and can eliminate the need for additional heat exchangers.

There are two types of heat pipes, which are characterized as having either wet or dry connections (See Figure 3-5). Note that the required radiative finned area depends on whether an air or liquid medium is employed in the storage area (Sheffield, 1986). In a dry connection heat pipe, the cooling fluid and heat pipe are separated from each other. In contrast, in a wet connection heat pipe system, the fluid is in direct contact with the heat pipe. This method is preferred for several reasons. First, the separation of the fluid and pipe in a dry connection imparts an additional heat barrier as opposed to the wet connection. Also, in a wet connection type heat pipe, an additional temperature transfer may occur along the length and circumference of the pipe (Ebeling & Meyer, 1988).

The Moving Belt Radiator is a near term technology capable of fulfilling the Lunar Base heat rejection system requirements. In this concept, waste heat is transferred from an Interface Heat Exchange (IHX) Unit to a Moving Belt which is exposed to space. As the belt travels through space, heat is radiated from the belt to the background environment. The IHX, which contains a low vapor pressure fluid, then acts as the heat sink for the heat expulsion.(See Figure 3-6)

Several major advantages support the use of this method in space. First, this method offers the capability to radiate as much as 200 MW in a device that could fit within the shuttle bay.(Aguiler,1990) Although such requirements do not exist for a Lunar heat transfer system, the ability to stow it during transport is a major concern.

The main reason for using this type of system would be the fact that it weighs a great deal less than current heat pipes. It is estimated that the Moving Belt system would weigh as low as 1/5th to1/3rd that of current

heat pipes.(Aguiler,1990) Moving Belt radiators also have favorable micrometeorite survivability characteristics. Micrometeorite impacts would most likely impart only a small reduction in the belt surface.

There are three types of Moving Belt Radiators: Liquid, Solid, and Hybrid. With the Liquid Belt Radiator, a meniscus of the interface heat exchange fluid forms on the surface of the belt, and in fact in the mesh of the belt. This offers excellent heat transfer characteristics by utilizing the fluid's heat of fusion, thereby adding to the total emissivity.(Aguiler,1990) The emissivity for Liquid Belts can be as high as 0.8 if certain oils are implemented. Liquid metals may also be employed for higher temperatures, but the emissivity would be much lower, on the order of 0.1.(Aguiler,1990)

The Solid Belt Radiator may be drawn through either a solid-to-solid contact heat exchanger or a liquid bath type heat exchanger. In a solid-to-solid drive system, two rollers (aluminum or magnesium) would have the capability of varying the pressure applied to the belt (Aguiler,1990). The idea is that the belt will move in the direction of greatest pressure. The Solid Belt Radiator has an advantage over the Liquid Belt Radiator since no free liquid is exposed. Thus, problems in spillage or loss of fluid would be almost nonexistent. Solid Belts can be designed to have almost perfect black body characteristics with an emissivity of 1.0.(Aguiler,1990) Thus, the practical emissivities of the range 0.8 to 0.95 would significantly decrease the required belt area, thereby reducing the mass.

The Hybrid Belt is composed of a phase change material which is encased within the belt.(Aguiler,1990) The Hybrid Belt is unique in that it has the same high heat transfer characteristics of the Liquid Belt, but without the exposure of a free liquid surface. The Hybrid Belt also has a greater heat transfer ability compared to the Solid Belt, due mainly to the use of phase change materials. Phase change materials have extremely long lifetimes and can be used to maintain constant temperatures or store heat energy for later release through solid-liquid phase change processes (Sheffield, 1986). This has two important advantages. First, the latent heat of fusion of most materials is much higher than their normal heat (Sheffield, 1986). Therefore, a smaller amount of mass will be able to store/recover a given amount of heat. Second, since the thermal process is nearly constant, the heat rejection operation would be more efficient, which is also more desirable.

The Liquid Droplet Radiator (LDR) concept is the second advanced concept to be considered. An LDR works by generating thousands of sub-

millimeter sized droplets through space, which then radiate heat. The droplets are formed by a transducer and are collected by a droplet collector, which recirculates the fluid. The LDR is composed of a droplet collector, generator, orifice plate, and stimulator, which may be acoustically driven.

The cooling process begins at the droplet collector throat, where the fluid collects. It is then forced into the wide throat positive displacement gear pump by the pressure of the incoming droplet streams. From the collector pump, the silicon oil travels up to the high pressure boost pump for formation into droplets at the generator.

The generator is equipped with a laser alignment system. This is very important because it ensures that the collector is in the appropriate position to capture the silicon oil. If the alignment is off, the droplet stream may be corrected by motorized positioners. The ability to obtain straight stream jets is also important in controlling the droplet stream. This is influenced directly by the fluid properties, jet operating parameters, and the structure of the generator.

The fluid then passes through the orifice plate which controls the number of fluid droplets. The orifice plate on test models is 100 micrometers in diameter and contains 20 rows of 200 orifices (Pfeiffer, 1989). Experiments determined that above 300 K, the weight increases faster than the heat transfer when more than 20 rows are used (Pfeiffer, 1989). The orifice to orifice pitch is also an important consideration, especially when considering the ease of manufacturing and performance. At higher pitches, the manufacturing is easier. However, at low pitches, the weight and size are reduced while the strength increases. Thus, a pitch-to-diameter of 6 was selected (Pfeiffer, 1989).

One of the most important features of the LDR is the stimulator, which breaks up the stream into uniform drops. There are two types of stimulation possible, either structurally induced or acoustically induced. The structurally induced stimulation has several benefits. First, the motion induced components do not have to be compatible with the fluid. Also, the stimulator does not have to be sealed from the fluid while being coupled to it (Pfeiffer, 1989). Structurally induced generators are easiest to utilize when the frequency is low and when small drop generators are used. The acoustic stimulation, on the other hand, is very desirable since it imparts the energy of the transducer directly to the fluid. The transducer, which oscillates between 4 to 30 kHz, then generates droplet velocities of 2 to 10 msec (Pfeiffer, 1989). Slow velocities are desirable in order to impart the

optimum heat transfer. Variables that change the effectiveness include droplet velocity, droplet diameter, droplet pitch, and the number of droplet layers.

The original concept of the LDR was conceived of in 1979. Several configurations have originated since then and include the Spiral, Annular, Enclosed Disk, Triangular, and Rectangular. (See Figure 3-7) The last two, Triangular and Rectangular, are the most likely configurations for the use on a Lunar base. Note that the method of deploying and collecting the droplets gave rise to these names. The Rectangular type collector is most preferred for its simplicity and by investigations that have determined that it would weigh less than a similar triangular system. This type of LDR system is being most heavily pursued by Grumman, since it is felt that the Triangular type collector will have a decreased heat transfer capability resulting from fluid collisions (Pfeiffer, 1989). McDonnel Douglas has been working with the Triangular system, where the drops are focused an a single centrifugal collector. Initially it was felt that this type of system would be lighter in weight. However, an investigation determined that the fluid mass required in a triangular system is more even though its at a higher temperature and has more radiative area while using a lighter collector (Pfeiffer, 1989).

The main benefits of this system are its low mass, lack of moving parts, and ability to reject hundreds of kilowatts of heat. For instance, a total mass of 3500 kg for a Heat Pipe system that can expel 200 kW would be 7 times heavier than a comparable LDR system, which would weigh 500 kg (Pfeiffer, 1989). Also, unlike the heat pipe, the mass of the LDR also includes the weight of the generators, collectors, piping, and support structure. Thus, the LDR system is significantly lighter than other heat rejection system.

SPINOFFS

Many heat rejection systems used today utilize chemicals, such as Freon, that have been proven to damage the environment. Therefore, one benefit of the CELSS heat rejection technology would be to provide a small, lightweight, yet environmentally safe, thermal control system for use on Earth.

RECOMMENDATIONS AND CONCLUSIONS

The Moving Belt Radiator and Liquid Droplet Radiator are very close to weighing the same amount and weigh significantly less than any other heat transfer system. (See Figure 3-8) Current heat pipe radiators are the state of the art for now, but weigh roughly 62,700 kg and 50,600 after

enhancements.(Pfeiffer, 1989) However, the Liquid Droplet Radiator is estimated to weigh 28,600. This is very comparable to the Moving Belt which will weigh roughly 30,600 kg.(Pfeiffer, 1989) The Moving Belt Radiator most likely to be selected would be the hybrid system. This is because of its excellent heat transfer characteristics and because it has no free liquid surface. It will probably utilize a boom structure deployment, as long as the weight is kept down, in order to control the system more accurately. In the case of the Liquid Droplet Radiator, a Rectangular system setup will most likely be the desired choice.

3.5 SAFETY

RATIONALE

The space environment is very hazardous to mankind. Extreme temperatures, radiation, lack of atmosphere, and the low gravity are some of the problems that must be considered when designing the structures and supporting equipment for a Lunar Base. Also, if an emergency were to develop, it would take roughly 3 days before anyone would be able to make it back to Earth. Thus, considerations must be made to take this into account. Some safety problems may be averted by placing the module in a permanently shaded area. This will at least eliminate many of the radiation and thermal expansion problems associated with being in direct solar light. However, this solution does not provide answers for everything and further demonstrates the need to quantify all possible safety problems and solutions. The purpose of initiating a safety criteria is to identify all possible sources of danger and to assess strategies that may be implemented in their occurrence. Thus, in the advent of an emergency, a step by step solution may be carried out in order to obtain the best possible solutions and minimize the damage.

REQUIREMENTS

The Lunar Base must be able to protect and shelter up to 4 people for several weeks, even in the case of an emergency. It is very important to note that the safety of the crew, as well as the base, is of utmost importance. Thus, the development of a Lunar Crew Safety Threat List is very important and will greatly help in the process of determining a problem solution strategy. From the threat list, a more detailed solution will be provided for selected threats. However, one should note that there is a limit to the amount of safety possible.

TRADE STUDIES

Crew safety threat considerations were developed from our group and from observations taken from the "Space Station Crew Safety Alternative Study." In order to develop solutions for any emergency, three key points must be understood. First, "How much safety is necessary?" (Peercy, et al, 1985) This may seem like a vague question, but it stresses the need to consider that there are limits to the amount of safety that is humanly possible. Space Exploration is dangerous, it's as simple as that. The next thing that needs to be considered is, "What are the threats the program is prepared to deal with?" (Peercy, et al, 1985) If the threat is simple or repairable, it will probably be worth the time and effort to fix it. However, there comes a time where it might be better to just start over, and if this were the case, the problem would have to be very severe. Finally, "What are the strategies and interdependence of these strategies to meet the criteria developed to deal with the threats?" (Peercy, et al, 1985) There are many different solutions to many different problems. However, many of the problems have not even been recognized. Thus, the following list will attempt to list as many as possible.

Lunar Module Crew Safety Threat List:

A) *Radiation	B) *Meteoroid Penetration
C) *Explosion	D) *Biological/Toxic Contamination
E) *Injury/Illness	F) *Loss of Pressure
G) *Fire	H) Loss of access to hatch
I) Corrosion	J) Inadvertent Operation
K) Grazing/Collision	L) Mechanical Damage
M) Electrical Shock	N) Lack of Crew Coordination
O) Leakage	P) Abandonment of Base
Q) Intrusion/Attack	R) Temperature Extremes
S) Structural Erosion	T) Consumables Depletion

Note: * denotes 7 "driver" threats

There are several methods that may be initiated that would help reduce many of these problems. The first way is through the use of new technologies. One can assume that modifications and changes are constantly being made to improve products and ideas, as well as making them safer. Next, the development of safety methods, escape plans, and rescue operations based on the threat list would further help. This will ensure that the risk and danger will be minimized.

Fire is considered to be the most critical threat. Not only is it a very destructive force, but its emissions will severely effect the module

atmosphere. Its a good example of where the strategies that may be undertaken to preclude its occurrence actually compound the problems of other threats, such as toxic contamination and explosions (Peercy, et al, 1985). The use and selection of nonflammable and non-toxic material for Lunar components is the first step. Isolating fuels, oxidizers, and flammable materials is another important step, as well as providing adequate containment vessels (Peercy, et al, 1985). The installation of warning and extinguishing systems would also be necessary. In the worse case scenario, the Lunar Module's atmosphere could be evacuated into space.

Radiation contamination is also another major problem. On Earth, our atmosphere shields us from most of the harmful solar and cosmic rays. However, on the moon we do not have this advantage. Initially, the Infrastructure Group looked into utilizing Lunar regolith and Kevlar blankets for shielding purposes. This would involve a substantial increase in payload and the requirement that a method be developed for deploying the shielding. The best solution to this problem, however, would be to place the module in a permanently dark area. This would solve both radiation and temperature fluctuation problems. It is estimated that slightly less than 2% of the Lunar surface fits this description. This will solve the problem of direct radiation from the sun, which is normally 50 rem per year, and its resulting flares, which average 100 rem per event and occur on an average of three times a year (Schwartzkopf, 1990). Cosmic radiation, which averages 20 rem per year, will still be a problem. Observable effects may be seen in humans at 25 rem, with death resulting from a dosage of 450 rem (Schwartzkopf, 1990). Thus, radiation shielding is still important, especially since the accumulation of radiation is also harmful. Secondary radiation effects will also be decreased by being in a permanently shaded area.

Leakages, although they do not necessarily have to be life threatening, can also be a problem. The careful selection of seal material for longevity and faying surfaces is important (Peercy, et al, 1985). Hatches will probably be the prime location for leaks, barring punctures created by micrometeroids or improper use of equipment. Proper seals will help alleviate this problem. Note, Lunar dust may also prove to be a problem in obtaining a proper seal. Lunar dust adheres to suits, camera lenses, and other exposed surfaces. Thus, the accumulation of dust at the hatch seals may result in small leakages and difficulty in closing the hatch. Several methods have been looked at including a brush - blower method (Harrington, et al, 1990). However, it was felt that the use of a of a passive electrostatic brush would

serve the same purpose without loosing precious gases. Note, the adhesion and cohesion of the dust is attributed mainly to electrostatic forces.

Micrometeoroid impacts is another consideration that has to be looked into. The Lunar Module will be located on the near side of the moon, which is definitely less cratered than the far side. Based on an evaluation of the strike frequency of various meteorite sizes, it was determined that the frequency of a meteoroid 0.1 cm in diameter would occur roughly once every 20 years (Schwartzkopf, 1990). This was for an area of 10 m by 60 m. For a slightly larger meteoroid of 0.2 cm, the frequency of occurrence increases to 200 years (Schwartzkopf, 1990). Thus, although micrometeoroids may pose a problem, there occurrence would be "once in blue moon."

In the event of a real emergency on the moon, the Infrastructure Group contemplated several ideas. The first would be to have an emergency launch vehicle and a backup power supply. If something were to happen to the module, the emergency vehicle would be able to function as a temporary safe haven. Emergency supplies of food, water, and air would also be made available. These backups would be able to supply 4 people with basic necessities for a period of several weeks. The Lunar Module itself would have a node connected on both ends in order to offer two modes of egress/ingress. In addition, all hatches would have the capability of being operated manually. Another idea that has not been quite develop is a transfer vehicle that would be connected directly to the module. This would allow the crew the ability to leave the module without having to pre-breathe first.

RECOMMENDATIONS AND CONCLUSIONS

The development of a threat strategy is probably the most important thing that can be done prior to the launching of a mission. This would help identify all possible threats with a corresponding step by step solution to minimize damage and avert further dangers. Material selection is another extremely important criteria, as this will help reduce or even alleviate threat possibilities. The selection of a permanently shaded area will also help counter the effects of extreme temperature fluctuations and radiation effects. Finally, in the case of a real emergency, the crew would be able to use the emergency launch vehicle. This would be able to provide the needed food, water, air, power, and other survival necessities needed in a safe haven with the added ability of functioning as a launch vehicle.

3.6 LUNAR SITE

RATIONALE

The first element needed for the space based phase is a lunar site. To implement a bioregenerative system on the moon, a location must be found that takes advantage of all inherent possibilities available on the moon. A Lunar Base site will need to be chosen prior to the first launches and several considerations deserve attention.

REQUIREMENTS

The surface temperature drives many considerations and can range from nearly 40 Kelvin(K) (Mendell, 1985), in permanently dark locations, to 385 K (Bell, et al., 1988). The thermal environment can pose several problems for lunar structures, mostly due to the large difference between these extreme temperatures, i.e. the more constant the temperature the less stress on the structure. Critical materials storage, for hydrogen, oxygen and water, in liquid or solid form, allowing for simpler storage, remains another factor. Analysis of local heat rejection properties becomes necessary to examine dissipation of excess heat possibilities, if necessary.

Solar activity also plays a vital role in site selection. Solar light, used for simple lighting or plant growth, can also represent an inexhaustible power source that can deliver deadly amounts of radiation. In addition to these Solar Energetic Particles (SEP) radiation, which can deliver an average of 85 rem per year (Bell, et al., 1988), there exists Galactic Cosmic Rays (GCR), which come from outside of the solar system, that deliver 20 to 50 rem per year (Bell, et al., 1988). A rem is the measure of dosage acquired due to radiation exposure and the Radiobiological Advisory Panel suggests, for astronauts, that 38 rem per year is allowed (Bell, et al., 1988). Therefore, toleration of GCR could occur, but the SEP would require some kind of lunar protection shelter.

Evaluation of the local scientific value, including in situ materials resources and astronomical viewing, orbital access and communications needs must also take place. The ability to perform daily operations in and around the site represents the final consideration.

TRADE STUDIES

Five options exist for possible sites, two mid-lunar locations, two dark polar sites and a lighted polar area. All considerations will be addressed for each possible location.

A mid-lunar location describes basically any site between the poles that experiences distinguishable days and nights. Two possibilities exist in the

mid-lunar regime, the moon's near side and the moon's far side. The only real difference will come in the communications with the near side having the greater advantage.

Mid-lunar temperatures will range between 100 K and 385 K (Bell, et al., 1988), a 285 K difference. This large temperature flux, unequaled on Earth, will put high thermal stress on any lunar structures and will require high pressured vessels for materials storage. The low temperatures will help heat rejection but the high ones will pose difficult problems and extensive systems.

Solar light and power will see day and night phases that may last up to 14 days, requiring artificial lighting and mass-intensive batteries when night hits. With both SEP and GCR, a radiation protection structure becomes necessary.

Scientific value may depend on in situ materials because astronomical viewing is the best at a polar location. Unfortunately, little information, regarding the materials available on the lunar surface, exists and further research must take place. Lastly, orbital access becomes easier at a polar location, as mentioned above, communications will depend on the selected side of the moon and daily operations will do well half the time.

A lighted polar site would be located near a pole and would receive solar activity nearly all of the time. The moon's axis tilts, 1.5 degrees (Mendell, 1985), to allow for nearly permanent daytime and nighttime near the poles, which will allow for a lighted polar site as well as a dark polar location.

In a lighted polar scenario, the temperature flux would be less than that of a mid-lunar location, but due to the infrequent periods of darkness it would still see fairly large changes. The lunar structures would do better here because of the smaller flux, but the overall average would be warmer than a mid-lunar location which would make it more difficult for heat rejection and critical materials storage.

This location represents the optimal site for access to solar light and power with nearly constant amounts. With this availability comes the problems associated with radiation, both SEP and GCR, therefore requiring a radiation protection scheme.

The scientific value does better than mid-lunar because of the access to a larger portion of space for astronomical viewing. Materials data, like at

any lunar location, remains fairly unknown and orbital access becomes better at a polar location because a polar orbit would pass over the site about every two hours (Mendell, 1985). Communications remains the same, but daily operations become easier due to the nearly constant sunlight provided.

As explained above, the possibility for a polar location that receives nearly complete darkness exists, and near the poles, the possibility of a completely dark area exists which could happen in a large crater's shadow, see Figure 3-9. Two possibilities can be examined, a dark polar site and a dark polar site that has nearby solar light access. The only difference between these will becomes just that, having no solar light or having nearby access.

The temperature dependent considerations do extremely well at a polar location. The temperature flux and average temperature will be smaller than any other lunar locations. The lunar structures would see less stress due to smaller thermal fluctuations and these would ease the storage of vital materials. And with this low average temperature, heat rejection problems will be greatly reduced and possibly even eliminated.

Solar activity would not be present in the dark location unless, as mentioned above, it was nearby and accessible. SEP would pose no radiation problems in the dark regions and only the GCR would cause concern. Because of GCR toleration, radiation shielding protection becomes unnecessary.

The scientific value increases slightly because the cold temperatures would ease the operation of more powerful, cryogenic telescopes. Orbital access and communications remain exactly the same as a lighted polar location. Unfortunately, the consistent darkness would greatly hamper daily operations.

After examining the advantages and disadvantages of each location, the considerations were scored on a scale of ten. A weighted scaling factor was used to emphasis the more important aspects and then overall scores were calculated. The reasoning behind the low solar weights is due to the later recommendation for nuclear energy to provide base power. Figure 3-10 shows the weights, scores and overall totals and Figure 3-11 better displays the final evaluation. Both dark polar locations scored better than the other three possibilities.

A polar location that receives no solar light or radiation is the site selection for the Lunar Base. The best scenario, referred to above as Figure 3-12, remains the shadow of a large crater that could provide the darkness and allow for nearby solar access.

Lunar remote sensing becomes the first stumbling block facing the site selection process. High resolution sensing must be accomplished to determine the most suitable location. In conjunction with the mapping for navigation, a satellite with optical, infrared and radar capabilities that can resolve objects and formations on the order of one meter will suffice.

After completion of the remote sensing, possible sites will need to be chosen and then verified. Lunar probes (robots), sent to the lunar surface, can further survey the locations before the final selection occurs. Once compiling and analyzing all information, a final decision will select the site of the first lunar habitat.

SPINOFFS

The lunar remote sensing will provide added insight to better understand the moon, especially in the fields of geology, astronomy and materials science. Satellite technology can only see further advancement and the verification robots introduced to the lunar surface could produce several promising technologies applicable to Earth based uses.

RECOMMENDATIONS AND CONCLUSIONS

A polar site in the permanent shadow of a large mountain or crater would provide both radiation and meteorite protection, as well as eliminate thermal expansion and contraction. Since 2% of the lunar surface is under permanent shadow several possible sites will be available. Unfortunately, little is known about the polar regions of the moon. Therefore, remote sensing and mapping will be needed, followed by robotic site verification, to determine the optimum location.

3.7 COMMUNICATIONS

RATIONALE

The second element needed for the space based phase is a communication network between the Earth and the lunar surface. This link will enable various transmissions to take place including teleoperation command of the robots, system status data of every item landed on the surface, audio/video transmissions, and experimental data transfer.

The communications system will be designed to provide as close to a constant link as possible. This will allow the crew of the base to keep in contact with the earth at almost any time. The system should allow real-time (with delay time accounted for) communication for day to day activities, as well a higher signal reliability for more sensitive communications including experimental data that will be downlinked to earth for processing. The system performance will be restricted by the location of earth-based tracking stations, satellite orbits, and by the north polar position of the Lunar Base.

REQUIREMENTS

In order to function in the desired fashion, the communications link must meet several requirements. First, the combination of satellites used and the number and location of tracking stations on the earth must be optimized to provide maximum coverage time for minimal cost and mass deployment. The system must also be reliable and require little or no maintenance. Regarding the signal structure used, it will be necessary to have a high data rate for high transmission reliability, and also to have high signal quality, at least for more delicate data transmissions, such as computer information and experimental results.

CRITICAL TECHNOLOGIES

A communications system to link the earth to the Lunar Base will not require any great discoveries. It will be more an application and extension of existing technologies. The best system would utilize existing technologies as much as possible, while necessary new technologies will benefit earth based communications systems.

Current communication systems use a wide range of frequencies, one type of which yields wavelengths in the millimeter range. This millimeter wave (MMW) area has been used extensively already in communications satellites that occupy geostationary orbits (Conley, 1986). The systems using MMW have proven to be durable and relatively efficient. Drawbacks of MMW communications systems include frequency congestion due to the large number of satellites operating in this region, atmospheric attenuation, and mass intensive antennas.

One method for reducing interference and increasing signal reliability is to use a spread spectrum signal format. This format involves processing the signal before it leaves the transmitter, and after it is received. Before it is transmitted, the signal's carrier is spread from its narrow frequency spike configuration to a wider, spread out signal. This spreading can be as much as 20 MHz. This wide bandwidth carrier allows the signal to occupy the

same space in the electromagnetic spectrum with other signals and noise, while being completely unaffected by those signals. Spread spectrum signals are being used by the military and by the Global Positioning System (GPS) satellites.

Three technologies need be developed beyond their present capabilities to enable the optimal configuration of an earth-moon communication link. Their importance is relative to the final configuration of the system. First, it has been suggested that lasers be used to transmit and receive signals. A study was done comparing MMW technology with current optical communication technology (Conley, 1986) that describes some of the advantages and shortcomings of an optical system. The main advantage is increased signal reliability (on the order of 1 lost bit in 1012), greatly increased bandwidth capabilities, lighter weight and less volume, immunity to radio frequency interference (RFI) and greater resistance to solar activity.

The greatest weaknesses in the present level of technology are efficiency and lifespan. Current commonly used lasers are only 8 to 15% efficient compared to MMW efficiencies of up to 30%. A typical laser lifetime will extend up to five years. Developments are being made, however, and free electron lasers (FEL) may be available within the required time period for use in the communications link. This newer type of laser has demonstrated increased efficiency possibly up to 25%, with 50% efficient lasers being expected in the future. The second technology involves the reduction of mass of a useful MMW antenna. Current antennas with gain considered adequate mass up to 700 kg. Since antenna configuration is largely dependant on the signal it is designed to receive, the main area of improvement would be in the materials used.

The third and perhaps most critical technological problem involves a satellite designed to stay in orbit around the moon for an extended length of time. Lunar orbits are highly unstable due to the influence of the earth's gravitational field. Even the low orbits used during the Apollo missions would only last a maximum of three to four weeks before becoming too unstable to be useful. The only obvious way of keeping a satellite in lunar orbit for extended periods of time would be to make the satellite "smart". This would involve having attitude control thrusters and a processing unit on board the satellite to compensate for any decay in the satellite's orbit. Normally, satellites are equipped with no attitude control system, or with control jets and enough fuel to make only small, initial adjustments.

A smart satellite will have to have a larger supply of fuel, and must constantly calculate or receive data on its orbit. The more frequent the orbit monitoring, the easier it will be to correct for any deviations. The longer the satellite waits to make corrections, the bigger and more fuel consuming those corrections will have to be.

TRADE STUDIES

Several options are available to meet the requirements of the system. These include different satellite configurations, no satellites, an all optical system, an all MMW system, or a hybrid system, with or without the use of spread spectrum technology.

A description of the options for satellite configurations follows.

Option 1 - Using no satellites, a system could be implemented using direct communications between the earth's surface and the lunar surface. The main difficulty with this is that since our Lunar Base design calls for a site near the north pole in the permanent shadow of a crater or other formation, the receiving angles at the base will always be very low. This system would be composed of antennas in multiple sites on the earth, and one at the Lunar Base, possibly on a ridge to facilitate the reception of the low angle signals. Advantages include needing no satellites, lower deployment mass, and low cost.

Option 2 - Using at least two satellites in geostationary orbits, a system would feasible that allowed less tracking stations to be used on the earth. This would de-emphasize the atmospheric effects, since the ground stations could e directly under the satellites allowing the signals to pass through the atmosphere perpendicularly. The drawback is again the fact that the Lunar Base will only see signals coming in at very low angles on the horizon.

Option 3 - Requiring more satellites, a system would be possible that transmitted from the earth surface to satellites in GEO, which relay the signal to smart satellites in a high-eccentricity orbit around the moon, which would finally relay the signal to the Lunar Base. The biggest problem with this system is the large number of satellites involved. At least two would be needed in GEO, with at least three in orbit around the moon. The lunar satellites could be the same ones used for remote sensing and mapping (which must be done early on), which would make this configuration more realistic. The biggest benefit of this configuration is the high angles at which the signals would reach the Lunar Base. This makes the signal easier to track, and reduces the risk of multipath interference.

Option 4 - Using the same satellite configuration around the moon, but relaying the signals directly to the earth's surface will decrease the number of satellites and consequently the cost and mass. The biggest disadvantage of this system is the need for sufficient tracking stations on the earth, as well as needing a communications structure that is able to penetrate the atmosphere with sufficient reliability. The main advantage of this system is that assuming the remote sensing satellites are in place and designed as smart satellites, then most of the system will already be in place before construction of the base begins, and with minimal additional cost, mass, or construction. Again the vase would see the signals coming in at a high enough angle (up to 60°) to be useful, and with a high-eccentricity orbit, only a small number of lunar satellites will be needed since each one will remain in line-of-site with the base for lengthy periods of time.

Option 5 - The only way to have satellites close to the moon and be independently stable would be to have satellites orbiting around the L1 Lagrange point. The L1 point lies between the earth and the moon, closer to the moon. Three satellites in orbit around the L1 point would act as relays from the earth's surface to the Lunar Base. The advantages of such a configuration are its stability, and its increased angle of incidence on the lunar surface. The main drawback of this scenario is the complexity involved in getting the satellites in the correct orbit around the L1 point. Also, even though the lunar incidence angle is fairly high (up to 30°), it is still not as high as either option 3 or 4.

The actual signal structure of the communications system could have several different forms. Using a combination of optical, MMW and spread spectrum technology, an optimal configuration should be possible. The system would need two main modes. The first is a medium quality mode that would be used for everyday communications and for monitoring the station when no crew are there. This mode would be facilitated by using current levels of technology, with the exception of possibly using an optical link between the satellite and the Lunar Base to increase the signal accuracy and reduce any risks of interference from lunar topography.

The medium quality mode requires a data rate on the order of 10-100 kilobits per second with a bit error rate of around 1×10^{-5}. This is all that is needed for most data transmissions including system evaluation and audio communication.

Another way to increase the signal reliability would be to use a spread spectrum format. Spreading the signal over a wide bandwidth makes it harder for the signal to become distorted or influenced by interference. A spread spectrum MMW signal would have fairly strong immunity to distortion, and would serve well as a medium to high reliability signal.

The second mode would be a high reliability mode for transmitting highly detailed or sensitive data. Relatively low data rates will be sufficient to produce the required reliability. A compressed data rate of approximately 20 Megabits per second with a bit error rate on the order of 1×10^{-9} is required for robotic tele-operation. This is within the current capacity of either optical or spread spectrum MMW technology.

To use a laser system through the earth's atmosphere may be possible if it is only used occasionally. The times when it is used could correspond to the best atmospheric conditions, as well as the best satellite positions (i.e. the closer to vertical the signal is, the less effect the atmosphere will have).

After considering the options, the optimal system for a Lunar Base communication system might be as follows:

The satellites used for remote sensing and mapping of the moon would be equipped as smart satellites with both MMW and laser communications systems. They would be in high-eccentricity orbits that placed them over the north pole for most of their orbital period, allowing long periods of coverage with high incidence angles. The signal would then by relayed to geosynchronous satellites and then transmitted to an Earth receiving station. For everyday communications a spread spectrum signal broadcast on the MMW system would be used. For the times when high accuracy signals are sent, the laser system would be used (possibly also using a spread spectrum format) at times when the earth's atmospheric conditions were optimal.

SPINOFFS

Each year of the ten year plan new spinoff technologies will bring advancements to earth based research, scientific, military and civilian alike.

The development of smart satellites will involve the use of low level artificial intelligence (AI). This technology will be useful in many applications that will benefit many people. For example, low level AI could be used for such things as making more efficient houses. Houses that are able to maintain their internal environment better will be more energy

efficient. Tasks such as regulating the internal temperature of a house can be done automatically on a level not currently in common use. Instead of using a simple thermostat located in one or two places in the house, an AI system could receive input from several key locations through out the house and use not only the heating system, but also drapes, blinds, window tinting, and solar energy to keep the house at the desired temperature without the major fluctuations experienced with a thermostat system.

The development of laser communications systems will be useful initially to the military. The characteristics of lasers are such that data transmitted along the beam will be very secure. In order to tap into that data, the beam must be intercepted somewhere along its narrow path. Line of sight communications would be useful satellite communications, covert missions, ground to air communications, and ship to air communications. Secure channels will allow the transmission of information that would previously needed coding before and decoding after transmission.

Later civilian uses for FEL communications will include satellite communications for telephone and television. Laser systems in conjunction with fiber optic systems should allow the transmission of very high quality signals over phone lines and television channels.

RECOMMENDATIONS AND CONCLUSIONS

Having a communications system in place before the installation of a Lunar Base is of major importance. A link to earth will be necessary not only for survival, but also to gain scientific knowledge and for psychological reasons. Benefits from the development of a viable system will affect many aspects of life on earth as well as the future in space.

This paper has described several options and suggested the best from those options. Further research may yield more options, especially in the area of type of communications links (i.e. MMW and FEL). The scenario mentioned above involving lunar satellites, geosynchronous satellites, FEL's, and MMW systems is one choice that would meet the requirements of the Lunar Base communications system at least as an initial system.

3.8 TRANSPORTATION

RATIONALE

A transportation system is one of the critical technologies that must be developed before a Lunar Base may be established. Indeed, not a single kilogram of mass may be placed on the lunar surface without some means

of transporting it there. Therefore, a transportation system capable of hauling payloads from the Earth to the lunar surface is an essential part of the Lunar Base infrastructure.

REQUIREMENTS

As illustrated in Figure 3-12, there are three separate stages in the transportation of payloads to the lunar surface: 1) from Earth to low Earth orbit (LEO), 2) from LEO to low lunar orbit (LLO), and 3) from LLO to the lunar surface. A transportation system must be developed that can operate efficiently over all three of these regions. This efficiency would be manifested in the system's ability to provide not only safe, reliable transport of both crew and cargo to and from the lunar surface, but to do so in as cost effective a manner as possible.

TRADE STUDIES

The Earth to moon transfer may be accomplished by the use of either a single, multi-staged vehicle or by several separate vehicles. For crew transport to and from the lunar surface, the single vehicle concept is definitely a viable option. Indeed, the Apollo missions were accomplished using just such an approach. However, for the transport of large, mass-intensive payloads, vehicular mass and volume requirements are prohibitive for the single vehicle option. Therefore, the multiple vehicle option was determined to be the best choice for a lunar transportation system.

Three vehicles would be needed for this option, one for each stage shown in Figure 3-12. A heavy lift vehicle (HLV) is needed for the first region, an orbital transfer vehicle (OTV) for the second region, and a lunar lander for the third. Since the size and payload capabilities of each vehicle is dependent upon the mass of the vehicle or vehicles operating in later stages, the lunar lander must be designed first, followed by the OTV and finally the launch vehicle.

There are several requirements that must be met by a lunar lander design. First, the lander must be able to transport the largest single piece of cargo needed for the Lunar Base. This was determined to be a habitation module and an emergency node. The node could be eliminated, but then pressurized module access could not be obtained until a node was delivered by a later mission. This is not desirable, since termination of the program at this point would result in the module being wasted on the lunar surface. The mass of the module and a small node/airlock was estimated using data for a slightly larger module (Capps, et al., 1989). A

total payload capacity of 20,000 kg was determined to be sufficient to accommodate both the module and the node.

A lander must also be capable of transporting a four person crew module form LLO to the lunar surface and then back. The mass of such a module was estimated using Apollo data (Reichert, 1989) and work done by Eagle Engineering to be approximately 6,000 kg.

Another requirement is that the lander must allow for easy cargo removal. This is especially important for the first landing since no cargo handling equipment will be in place on the lunar surface. Since the first payload will partially consist of this equipment, some method must be available for the equipment to unload itself. Ease of payload removal is also important for all subsequent landings, so that the mass of the payload handling equipment may be minimized.

The final requirement is that the lander be able to land on a surface of up to 12 degrees slope , since a prepared landing site will not be available for the initial landing (Eagle Engineering, 1988c). Although some sort of prepared landing area will be available for all subsequent missions, for safety reasons it is still important that the lander have the capability of landing under less than ideal conditions.

In the design of a lander that will fulfill these requirements, there are several design options that must be examined. These include reusability, parking orbit altitude, number of stages, propellant type, as well as the option of designing separate manned and cargo landers.

It was determined that initially the lander would be expendable but would have the capability of operating in a reusable mode in the future. In the early stages of lunar development there would be no way of inspecting, servicing, or refueling the lander either on the moon or in low lunar orbit, and it would not be practical to return the lander to the space station even if the facilities existed there. As these facilities do become available, however, it will be more cost effective to operate the lander as a reusable vehicle (Eagle Engineering, 1988d).

The altitude of the lunar parking orbit is another consideration that must be addressed. As the parking orbit altitude is increased, the mass of the lander also increases due to the need for more propellant. This directly translates into an increase in LEO stack mass, mass to be transported to low Earth orbit. Therefore, the lowest possible orbit is desirable.

Unfortunately, as LEO stack mass decreases with orbital altitude, so does orbital stability. There is also a lower limit, relating to abort concerns, of approximately 93 km above the lunar surface. An orbit of 93 km was determined to be unstable over the period of a few months (Eagle Engineering, 1988d). This would not pose a problem since the expected stay time in orbit for the early phases of the Lunar Base is on the order of days rather than months. Therefore, 93 km was chosen as the parking orbit altitude for the lunar lander.

The number of stages that a craft needs is directly related to the total ΔV that it must achieve. As a general rule of thumb, one stage is needed for every 3 km/s change in velocity (Eagle Engineering, 1988d). Since the ΔV from LLO to the lunar surface is approximately 2.1 km/s, the lander would operate most efficiently with a single stage.

Propellant type is another major concern in the design of a lunar lander. For the initial lunar lander, advanced propulsion methods, such as nuclear or ion power, were ruled out. After further study and development, these technologies may be appropriate for a second-generation lander, but for now conventional chemical propulsion is the best choice.

There are two basic types of liquid propellants used today: earth storable, such as nitrogen tetraoxide/Aerozine-50 (N_2O_4/Aer 50) or nitrogen tetraoxide/monomethylhydrazine (N_2O_4/MMH); and cryogenic propellants, such as liquid oxygen/liquid hydrogen (LO_2/LH_2). The main advantage of LO_2/LH_2 is that its specific impulse (Isp) is significantly higher than either of the earth storable propellants; 450 s as compared to 330 s and 300 s, respectively (Eagle Engineering, 1988d). Since Isp is a measure of the propellant efficiency, this translates into far less propellant mass needed to achieve the same ΔV and , consequently, into a lower gross lunar lander mass. The mass difference is not as large as might be expected, though. This is due to the low density of hydrogen which leads to a higher lander structural mass. There are also major problems relating to pumping and long term storage of cryogenic propellants. However, research is presently underway to overcome these stumbling blocks. Assuming that this can be done, LO_2/LH_2 is the best choice for the lunar lander propellant.

The final trade study to be made involves whether to build separate manned and cargo landers as compared to a single multi-purpose lander. It has been estimated that it will cost in excess of $1.5 billion to design a lunar lander (Eagle Engineering, 1988d), putting the development costs of the dedicated lander option at over $3 billion. This option will also incur

additional costs due to the fact that it will undoubtedly require separate manufacturing and assembly facilities. However, it can be seen from Table. 3-13 that the multi-purpose lander used in a cargo capacity would have a far greater mass than a dedicated cargo lander. Since this 8,700 kg of additional mass directly translates into an extra 22,000 kg required in LEO (Eagle Engineering, 1988d), it is clear that there is a severe mass penalty associated with the multi-purpose lander. With current launch costs ranging from $6,600 to over $10,000 per kg to LEO (U.S. Congress OTA, 1990), the cost of launching the additional mass would quickly offset the development costs of a second lander. Therefore, it would be more cost effective to develop separate manned and cargo landers.

Once the trade studies have been completed, it is possible to estimate the mass of the landers using Apollo data and scaling equations developed by Eagle Engineering. This results in a gross mass of 50,000 kg for the cargo lander, including 22,500 kg of propellant, and 7,500 kg of inert vehicle mass along with the 20,000 kg payload. The slightly less massive manned lander includes 30,900 kg of propellant, 9,000 kg of vehicle mass, and a 6,000 kg payload for a gross mass of 45,900 kg. A more detailed mass breakdown for each lander is shown in Figure 3-14. Since the cargo lander is the more massive of the two, it defines the payload requirements for the orbital transfer vehicle.

The second vehicle needed for payload transfer to the lunar surface is the orbital transfer vehicle, which would operate between LEO and LLO. The requirements for such a vehicle are that it be able to transport 50,000 kg, have reusable capability, and have a maximum one way trip time of under a week to facilitate crew transfer.

The design options for an OTV are nearly identical to those for a lunar lander; however, some of the conclusions derived from them are not. Like the lunar landers, the OTV should begin operation in a expendable mode with the capability to later become reusable. It should also use LO_2/LH_2 to minimize the mass required in low Earth orbit. However, the required ΔV of 4.1 km/s for the LEO-LLO transfer means that the orbital transfer vehicle would operate most efficiently using two stages. Also, since the OTV payload requirements for manned and cargo missions are nearly identical, a single multi-purpose transfer vehicle would be more cost effective. Human rating for the OTV could be obtained after it has proven its reliability on cargo missions. Since several cargo missions would be required before the first manned mission, there would be ample time for it to show that it is safe for the transport of humans. Therefore, it was

determined that the OTV would be a double stage, multi-purpose vehicle using cryogenic propellant and have the capability to be used in an expendable mode.

Once these design choices have been made it is possible to estimate the mass of the orbital transfer vehicle. This was done using the mass of an OTV designed to transport a lunar lander and a 25,000 kg payload to LLO (Petro, 1989). The total mass of this lander was calculated by Petro to be 109,000 kg, resulting in a total LEO stack mass of 168,000 kg. Since the LEO stack mass is related to the mass to be delivered to the lunar surface by a factor of 5.2 (Eagle Engineering, 1988d), a decrease in payload size to 20,000 kg results in a LEO stack mass of only 142,000 kg. From these masses the orbital transfer vehicle mass is estimated to be 92,000 kg including 83,500 kg of propellant and 8,500 kg of inert vehicle mass.

The LEO stack mass of 142,000 kg is the total payload to be delivered to LEO by the heavy lift vehicle for each lunar mission. It is not required to transport the entire mass with one launch; however, the number of launches needed for each mission should be minimized. The HLV should also be designed to provide reliable, efficient, and cost effective payload transport to LEO. Several designs are currently under study that might meet these requirements, such as the Titan IV expansion, the Shuttle C, the Advanced Launch System, several forms of advanced propulsion techniques, and an in-line Shuttle Derived Vehicle.

The main benefit of the Titan IV evolution option would be its low development costs. Such a vehicle would basically be a Titan IV with a larger core stage and different solid rocket boosters. This would allow a payload increase from the current 17,750 kg (U.S. Congress OTA, 1990) to 46,000 kg (Shelton, 1987). Unfortunately, this figure still is not feasible for a lunar mission since it would take at least four launches to assemble all of the components in LEO needed to land a large payload on the moon.

The Shuttle C is essentially a cargo version of the Space Shuttle. It would use many of the Shuttle components, such as the solid rocket motors, the main engines, and the external liquid propellant tank. However, in place of the orbiter would be a 4.6 m diameter by 25 m long cargo bay. This arrangement would allow the Shuttle C to carry up to 71,000 kg to low Earth orbit. The Shuttle C could also carry a larger payload bay, allowing payloads of up to 7.6 m by 27.4 m to be transported. Although this configuration would allow for only 61,000 kg to be transported to LEO, it would be better for volume intensive payloads (Shelton, 1990). In either

case, however, three launches would be needed to transport all of the lunar elements into LEO. Although this is better than the Titan IV evolution option, it still far from optimum.

There are several different forms of an Advanced Launch System (ALS) presently being studied. A common denominator of all of these designs is the low operational costs. The ALS is being designed to launch payloads at a cost of approximately $660 per kg to LEO (U.S. Congress OTA,1990). This is at least a factor of ten lower than current launch systems like the Space Shuttle or the Titan IV. The ALS could also have a 13 m diameter by 36 m long payload bay and be capable of lifting over 140,000 kg to LEO (Shelton, 1990). This could possibly allow for an entire lunar mission to be launched using a single launch vehicle. Despite having a low operational cost and high payload capacity, the ALS was not chosen as the heavy lift vehicle for the Lunar Base. The development costs will be very high and the final design of an Advanced Launch System is years in the future. Therefore, the ALS could be a viable option for a second-generation HLV but is not appropriate for the initial Lunar Base.

Several types of advanced launch methods are also being examined, including mass drivers and nuclear rockets. Although mass drivers would have very low operational costs, they are not suitable for launching large payloads. Therefore extensive, time consuming in-orbit assembly would need to be done. The major drawback to rockets using nuclear propulsion is the political problems surrounding any type of nuclear power. Judging from the public's opinion of nuclear reactors, it is doubtful that enough support could be generated for a nuclear powered rocket.

The final option considered for a heavy lift vehicle is the in-line Shuttle Derived Vehicle. This is similar to the Shuttle C concept except that instead of mounting the payload bay on the side of the external tank, it would be above it. Such a vehicle would be over 80 meters tall, thus requiring new launch and assembly facilities. However, by using three Space Shuttle Main Engines, two Advanced Solid Rocket Motors, a Shuttle derived core stage, and a 7.6 m by 27 m payload bay; a 95,000 kg payload could be launched to low Earth orbit (Shelton, 1990). This would allow an entire lunar mission to be transported to LEO with only two launches. Through the extensive use of Space Shuttle components, development costs would be kept low, as would the time needed to complete the design. Therefore an in-line Shuttle Derived Vehicle is the best choice for a heavy lift vehicle to be used for the establishment of an initial Lunar Base.

SPINOFFS

The knowledge gained from the research done on solving the problems associated with the use of liquid oxygen/liquid hydrogen as a propellant could also have some Earth-based applications. Because the only combustion bi-product of hydrogen is water, it is an extremely clean source of energy. It is also provides more than double the energy per kilogram as compared to conventional fuels (Brown, 1987). Therefore, hydrogen is an ideal choice to replace fossil fuels as our primary energy source.

Unfortunately, there are several problems associated with using hydrogen as an energy storage and transport medium, many of which are identical to difficulties that must be overcome before LO_2/LH_2 may be used for space applications. Probably, the largest problem to be solved involves the handling, transfer, and bulk long term storage of hydrogen. Research is currently being done being done by NASA in an attempt to solve these problems. If these obstacles can be overcome effectively, then using hydrogen for such things as automobile fuel is definitely in the foreseeable future.

RECOMMENDATIONS AND CONCLUSIONS

A lunar transportation system is one of the critical technologies that must be developed before a Lunar Base may be established. An efficient, cost effective method of transferring cargo and humans to the lunar surface is of vital importance to the establishment and continued support of a Lunar Base. A determination of the requirements for a such a lunar transportation system was made and the design options that would fulfill these requirements were examined.

It was determined that a three part lunar transportation system should be developed. This system would include separate manned and cargo landers, an orbital transfer vehicle, and a heavy lift vehicle. The landers and the OTV would use cryogenic propellant , operate from a 93 km lunar parking orbit, and would be designed to be reusable. While the lunar landers would have a single stage, the orbital transfer vehicle would operate most efficiently with two stages. The heavy lift vehicle to be developed is an in-line Shuttle Derived Vehicle capable of transporting up to 95,000 kg to low Earth orbit, allowing all components needed for a lunar mission to be assembled in LEO after only two launches.

3.9 NAVIGATION

RATIONALE

Now that systems can transit to the moon and vehicles can land cargo on the surface, a need for a method of navigation exists. The employment of a navigation system will permit safe and accurate landings on the lunar surface while providing vehicle location at any instant of time.

REQUIREMENTS

A more detailed requirement list includes an accurate landing capability, with less than five meters of error, and the ability to give instantaneous vehicle location, relative to the lunar surface. The operation of such a system will require low maintenance, high survivability in the severe space environments, a long operational lifespan and small amounts of power. Two other necessary considerations include simple and timely system implementation coupled with minimal development and deployment costs. A low transport mass from Earth will help minimize launch costs and system redundancy will provide increased landing safety.

TRADE STUDIES

Several options, used today for Earth navigation, exist that can meet all or most of these requirements. All of these systems have different advantages and disadvantages, and these will have to be weighed to determine the best option. Two systems could use the current Earth Global Positioning System (GPS) and operating Earth-based radars. Another two methods would apply these previous two systems to the moon, Lunar GPS and lunar-based radar. TACAN-type (Tactical Air Navigation) and LORAN-type (Long Range Navigation) systems as well as Instrument and Microwave Landing Systems (ILS and MLS) could aid lunar surface navigation. The final possibility includes a terrain-following radar, and then a discussion of transponders, more of a navigational aide, will follow.

The Earth GPS system, consisting of several satellites in geosynchronous orbit around the Earth, gives location to any receiver on the globe, and these satellites, with proper adaptation, could give location in space and on the moon's near side. The advantages include: low cost, a system exists and works, implementation, operations, and safety. The system's accuracy on Earth reaches 16 meters in two-dimensions (Eagle Engineering, 1988c), however, unknown accuracy on the lunar surface would most likely be worse. Finally, navigation on the moon's far side would not be possible and the third, missing dimension would have to be accounted for.

An Earth-based radar system would use current large radars located on the Earth's surface to track lunar vehicles. Using powerful transmitters and sensitive receivers, good determination of location could occur, but landing accuracy would suffer. Like Earth GPS, utilization of existing

systems on Earth will minimizing operational requirements, cost, implementation and safety factors. Two disadvantages would include only near side navigation and employment of a cumbersome large system, with both large amounts of people and equipment.

A Lunar GPS system would model the Earth GPS system as it would deploy several lunar orbiting satellites which would provide constant surface coverage. Lunar GPS would give excellent landing accuracy and precise location, but, it would also require increased costs, large transport mass from Earth and detailed implementation. The system would provide safety redundancy, but difficult operational problems could occur.

A radar near the Lunar Base, another possibility, would allow for on-the-horizon navigation. Burdensome requirements include delivery, implementation and testing of this lunar-based radar before complete operation. Though once in place, these complex, expensive radars would provide desirable landing accuracies and adequate location, near the base. Safety and operations would depend on the number of radars installed.

Ground-based transmitters, including TACAN or similar systems, provide adequate location and landing precision. Unfortunately, the frequencies used require for line-of-site transmissions that give only range and horizontal azimuth information. Other cons of TACAN-type systems include: difficult implementation because of the need for several transmitters, heavy mass penalties with numerous, large units, subsequential costs and high operational maintenance.

LORAN-type systems, much like TACAN, use beacons to transmit receiver location. Furthermore, LORAN utilizes low frequencies that allows for over-the-horizon transmission, and hence, fewer transmitters. LORAN will give adequate location but cannot give necessary landing assistance. These low frequency systems would fare better, than similar TACAN systems, in several categories. Less cost, transport mass, implementation and operations represent these categories, while safety would slip slightly because of fewer units.

Another system, used by current aircraft, uses high frequency transmitters to provide highly accurate landings. Known as Instrument or Microwave Landing Systems (ILS or MLS), these systems, while assisting landing, would give little sense of location. The relatively small size of these ground-based transmitters helps to lessen mass, cost, implementation and operational requirements. Safety could come with additional or redundant units.

The final possibility comes from existing technology that guides cruise missiles to their targets and flies fighter/bomber aircraft at low altitudes, known as terrain-following radar this system can provide excellent landing and navigation accuracies. A radar would map the lunar surface, as well as determine altitude, and mathematically compare this map to another highly-defined map stored in the system's computer, to provide extremely accurate navigation. Obviously, the system's computer will require the availability of an accurate lunar surface map. The only deficiency lies in safety where if the system failed there would no means of navigation left. Installation of redundant or multiple terrain-followers could alleviate this problem. Implementation and cost would be minimal given the current technology. Systems, built directly into the landers, would require less operational maintenance and present smaller weight penalties.

A transponder, more of a navigational aide than a navigation system, deserves discussion along with this section. A transponder is a fixed beacon that automatically transmits a signal over a short range. These transponders, once activated in the immediate landing area, could enhance any landing system to provide increased safety and accuracy. Transponders would require little maintenance, cost and weigh little while allowing for easy installation. Transponder location will be addressed further when looking at landing/launch pads.

After looking at the pros and cons of every system, each requirement for the individual system received a score out of ten. These score were then multiplied by a weighted factor, because some important requirements needed more emphasis, to give an overall assessment. The requirement weights, system scores and overall scores, seen in Figure 3-15, and the final evaluation, displayed in Figure 3-16, show these calculations. Although Earth-based radar, Earth GPS and lunar-based radar score well, the clear winner is a terrain-following radar system.

The final recommendation is for an initial redundant terrain-following system. When possible, this system should see augmentation with first transponders and then a lunar-based radar for increased accuracy and enhanced safety.

The accurate mapping of the lunar surface remains the major stumbling block for the terrain-following radar system. For the landing accuracies of less than five meters, a mapping accuracy of less than two meters will be sought. More lunar remote sensing information will follow in the section discussing site selection.

Adaptation and development of current terrain-following systems to meet lunar navigation requirement will provide the only other hurdle for this navigation system. The possibility of meeting the requirements, given the current abilities displayed by the U.S. military and with some fine tuning, exists and the availability of a system could happen in less than a decade.

SPINOFFS

The further development of terrain following radar would not only allow safe landings on the lunar surface, but would also benefit the commercial airline industry where it could be used to improve landing safety in bad weather and at night.

RECOMMENDATIONS AND CONCLUSIONS

Mission planning for the lunar remote sensing probe should begin immediately followed by the launch and data collection found under Phase A of the previously outlined mission scenario. With further development of terrain-following systems and maps generated from the lunar surface, production and testing of a lunar terrain-following system can begin. Time should allow for easy system integration with the landers before the first launches.

3.10 LANDING SITE

RATIONALE

With a site located and a navigation system to land, the next puzzle piece to implement is a landing and launch pad. Initial landings at the site will have certain requirements, but it will soon be necessary to provide a landing/launch pad that will allow for safer landings which will include humans. These requirements will be examined in order to design a landing/launch pad for future missions.

REQUIREMENTS

The initial landings will occur with little or no site preparation, depending on the versatility of the verification robots. The requirements for these landings are fairly lax to allow vehicles to land in the desired locations. The landing surface should have a grade less than twelve percent and no large rocks, ones larger than 1.5 meters, should exist in the area. With the one meter resolution of the remote sensing satellite, the determination of local obstructions can happen. A safe landing zone should exist up range and downrange, and no large landing hazards should exist in the near vicinity (i.e. large mountains and cliffs).

Once a site preparation robot has been landed, further improvements can be made to the landing/launch area. The robots should improve the average surface grade to less than three percent and the surface can be compacted for increased strength. The simple and reusable pad should be located a safe distance from the module to minimize blast effects, which will be detailed later. Landing errors of 100 meters will be allowed for large errors and a landing ellipse (one kilometer by three kilometers) will be established for extreme navigation errors. The pad should be within walking distance of the module, less than one kilometer which will allow for walking times of less than 20 minutes. Transponders, and a subsequent lunar-based radar system, with markers will need proper placement for increased landing accuracies and enhanced safety.

For the permanent pad design, several of these requirements need consideration. The major problem becomes the blast effects, of landings and launches, on the module and other lunar structures and vehicles. Objects less than 50 meters from ground zero receive severe damage, while objects from 50 - 400 meters away see fairly significant pitting and objects between 400 meters to two kilometers show little or no damage, but long-term damage can occur after many exposures (Eagle Engineering, 1988c). Another serious factor comes from particles that can be thrown from the lunar surface and then lobbed onto lunar structures. These particles can reach a height of approximately twelve meters (Eagle Engineering, 1988e).

TRADE STUDIES

Three types of protection exist for blast effects: distance, barriers and shielding. Following the given numbers above, the module should be placed at least 400 meters from the pad. Barriers include erected fabricated barriers, which would require extra mass brought from Earth, and natural barriers. Grading or piling of lunar regolith can provide a natural 'wall' against the blast effect, see Figure 3-17. Small crater rims may exist that will provide another source of natural barriers. Shielding could be provided with some type of blanket to cover lunar structures, but like a erected barrier it would require extra mass from Earth.

The three other numbers that factor into the design include the 100 meter landing error, less than one kilometer walking distance and the one kilometer by three kilometer safe landing ellipse up and down range. Adding the landing error to the blast effect radius gives the minimum distance the module will be located from pad's ground zero, or 500 meters.

Transponder/marker location represents the final part of the design. Seven transponders/markers will be located in the pad area. Two will be located up and down range, at the furthest points on the ellipse, and two cross-range from the landing point, placed on the landing ellipse. The last three transponders will be 'buried' on the landing error circle in a triangular-like fashion. The completed design can be seen in Figure 3-18.

SPINOFFS

The only major stumbling block will entail preparing the landing and launch pad, which will done mostly by robots. However, natural formations on the lunar surface may exist that will minimize these problems. The benefits of this task will come from the robots, which will be examined later.

RECOMMENDATIONS AND CONCLUSIONS

The initial landings will be at the mercy of the natural terrain, but lunar mapping should provide excellent areas. After the robots land on the surface and a with the establishment of a communications network, true landing/launch pad construction can begin. These communications will be examined in the next section.

3.11 INFRASTRUCTURE RECOMMENDATIONS AND CONCLUSION

The harsh environment of space will require that a module and its supporting equipment be immune to Lunar and space temperature fluctuations, radiation effects, and micro-meteoroid collisions. It will also have to support an initial crew of four for relatively short periods of time. During this time, it will function as a safe haven and place of study. The Lunar Base will also have to be capable of averting and dealing with emergencies. This can be done by using specialized materials in construction, developing contingency plans to deal with specific emergencies, and implementing the project carefully. Backup systems and supplies will also help divert disaster. In case of extreme emergencies, an escape launch vehicle can be used as a temporary safe haven and as means of leaving the moon.

There are several required technological advances necessary in order to accomplish this mission. The first of these is a comprehensive transportation system from the Earth to the Moon. A navigation system, a means of selecting an adequate module site, and the preparation of an actual landing/launch site will also be required in the first steps of developing a permanent base. Once on the Moon, communications

technologies will be utilized to support manned and unmanned operations. Power will also be a necessary first step to support the continually upgraded functional operations. Heat rejection from the module, as well as the design and development of the module and nodes, will also play a key roles in the development of a permanent base. Safety requirements will further guarantee the prosperity of the habitants, as well as the base itself.

All in all, the Lunar Base will have to meet operation and safety standards in order to provide the best possible means of living on the moon, while still providing useful scientific and social returns.

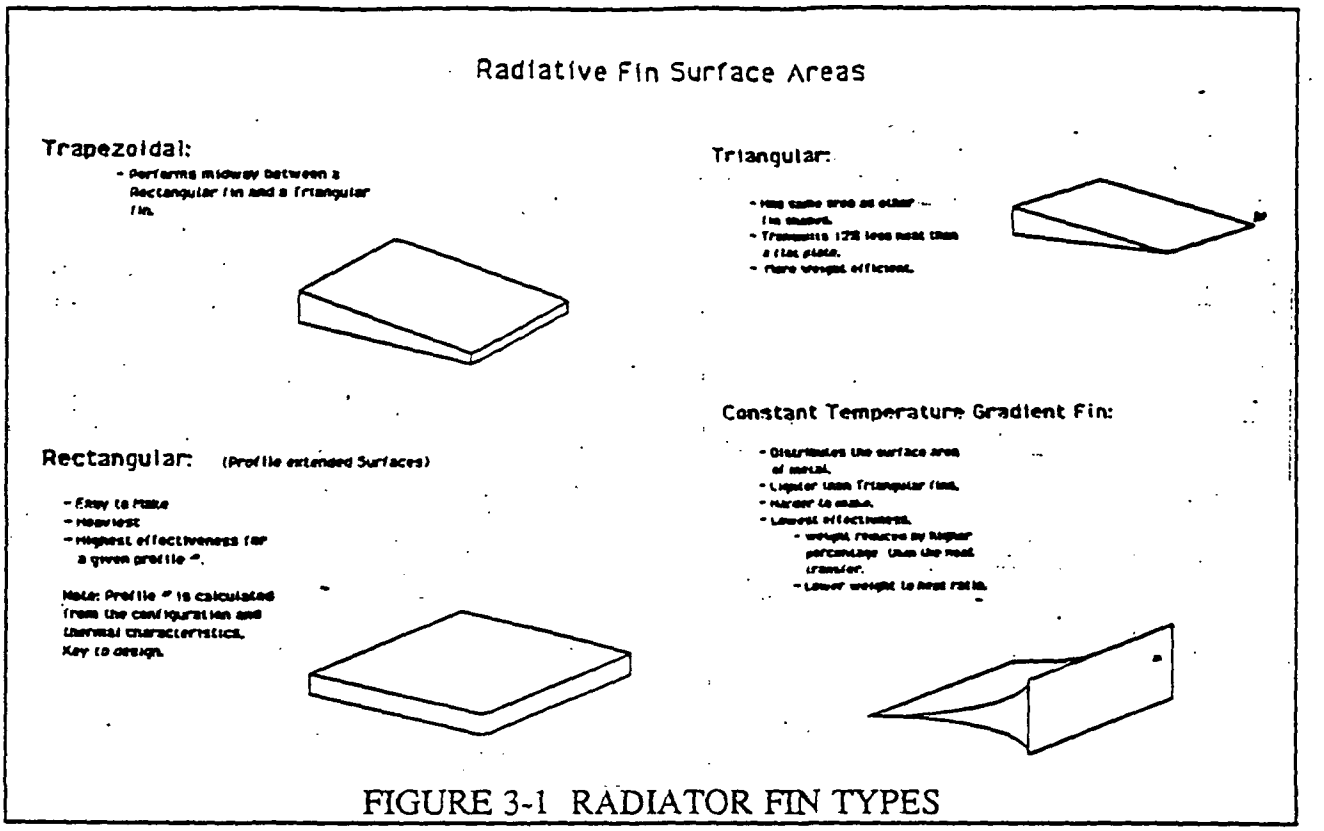


FIGURE 3-1 RADIATOR FIN TYPES

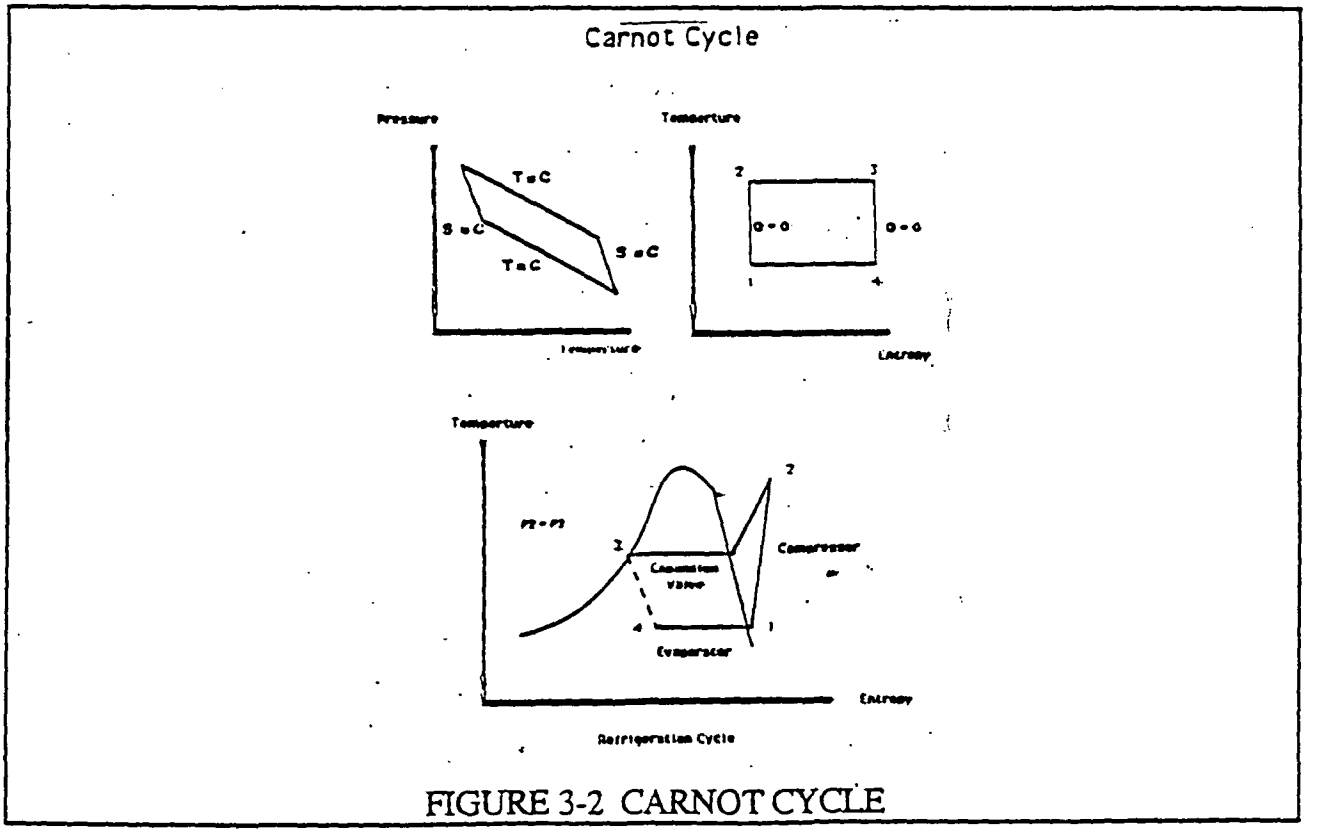


FIGURE 3-2 CARNOT CYCLE

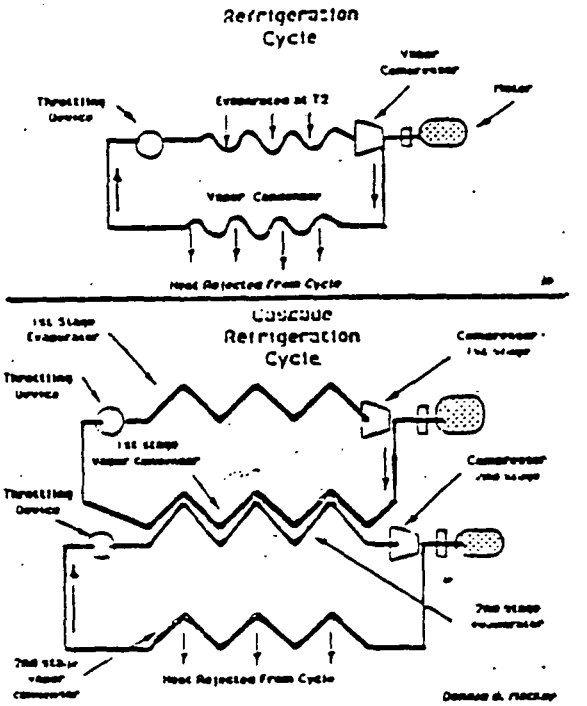
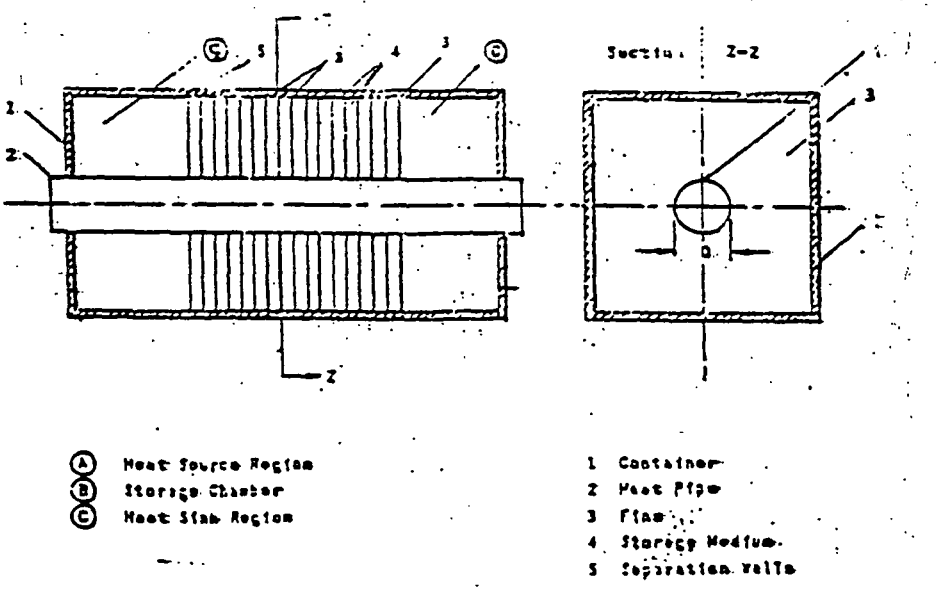
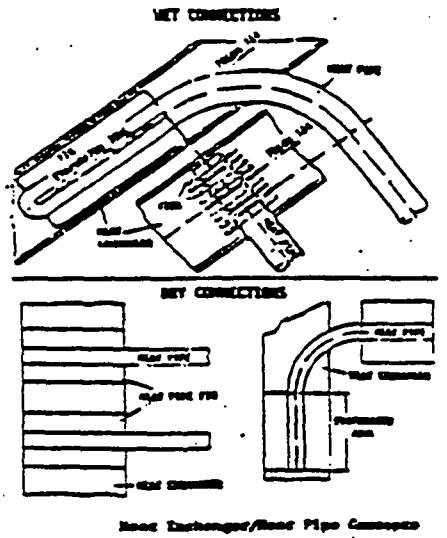


FIGURE 3-3 REFRIGERATION CYCLES



Obtained from the "Thermal Aspects of Future Spacecraft Thermal Management Systems." By J. W. Sheffield at the University of Missouri (1984)

FIGURE 3-4 HEAT PIPE

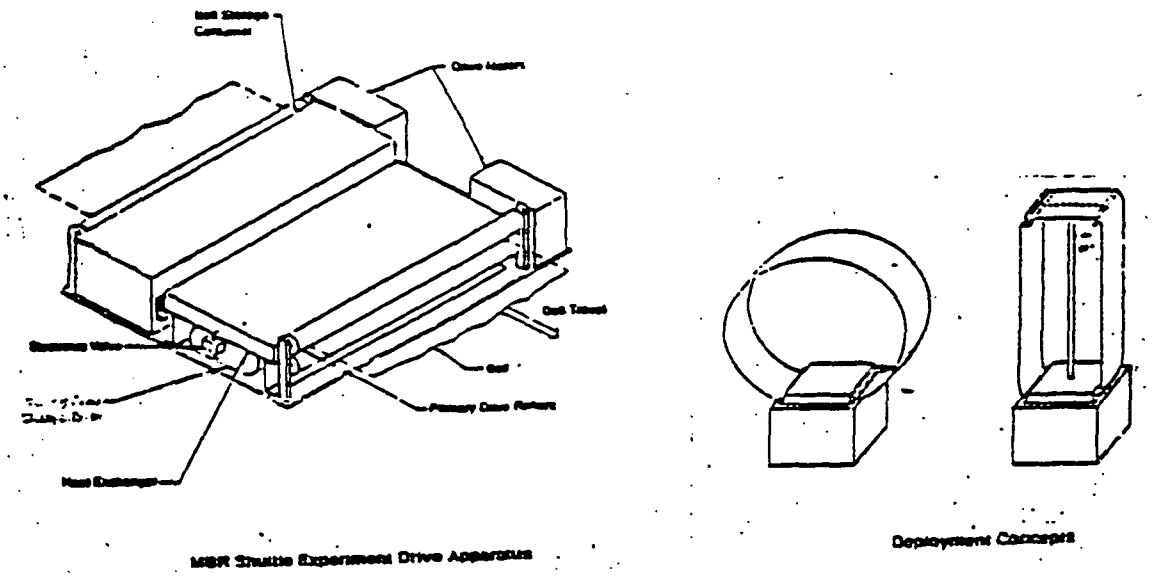


Heat Exchanger/Heat Pipe Concepts

Obtained from the "Theoretical and Experimental Investigation of Heat Exchangers for Columbus Hybrid Radiators."

By W-D Ebeling & K Meyer
Proceedings of the 3rd European Symposium on Space Thermal Control & Life Support Systems (October 1988)

FIGURE 3-5 WET AND DRY HEAT EXCHANGERS

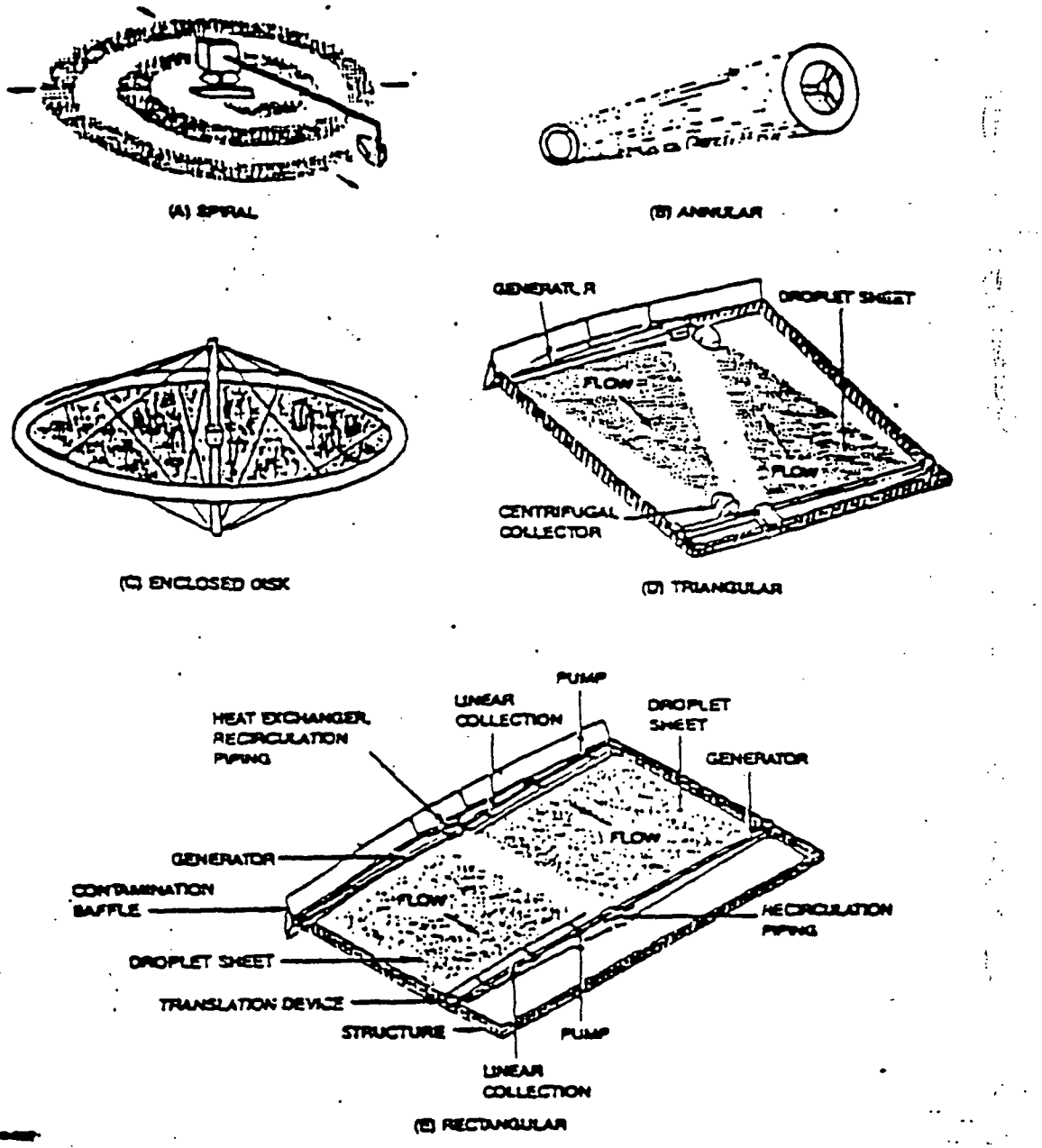


MSR Shuttle Experiment Drive Apparatus

Deployment Concepts

Obtained from the "Conceptual Design of a Moving Belt Radiator Shuttle-Attached Experiment."
By Jerry L. Aguilar (1990)

FIGURE 3-6 MOVING BELT RADIATOR



Obtained from the "Conceptual Design of Liquid Droplet Radiator Shuttle-Attached Experiment".

By Shlomo L. Pfeiffer (October 1989)

FIGURE 3-7 LIQUID DROPLET RADIATOR CONFIGURATIONS

	Heat Pipe Radiator	Enhanced Heat Pipe Radiator	Liquid Droplet Radiator	Moving Belt Radiator
Radiator	47,863	36,824	12,903	14,933
Structure	11,240	10,450	6,371	13,017
Transport Loop	1,484	1,484	7,008	2,507
TES	2,086	2,086	2,086	0
Other	0	0	211	0
Total	62,673	50,844	28,579	30,557
(Weights in kg)				

FIGURE 3-8 RADIATOR MASS COMPARISON

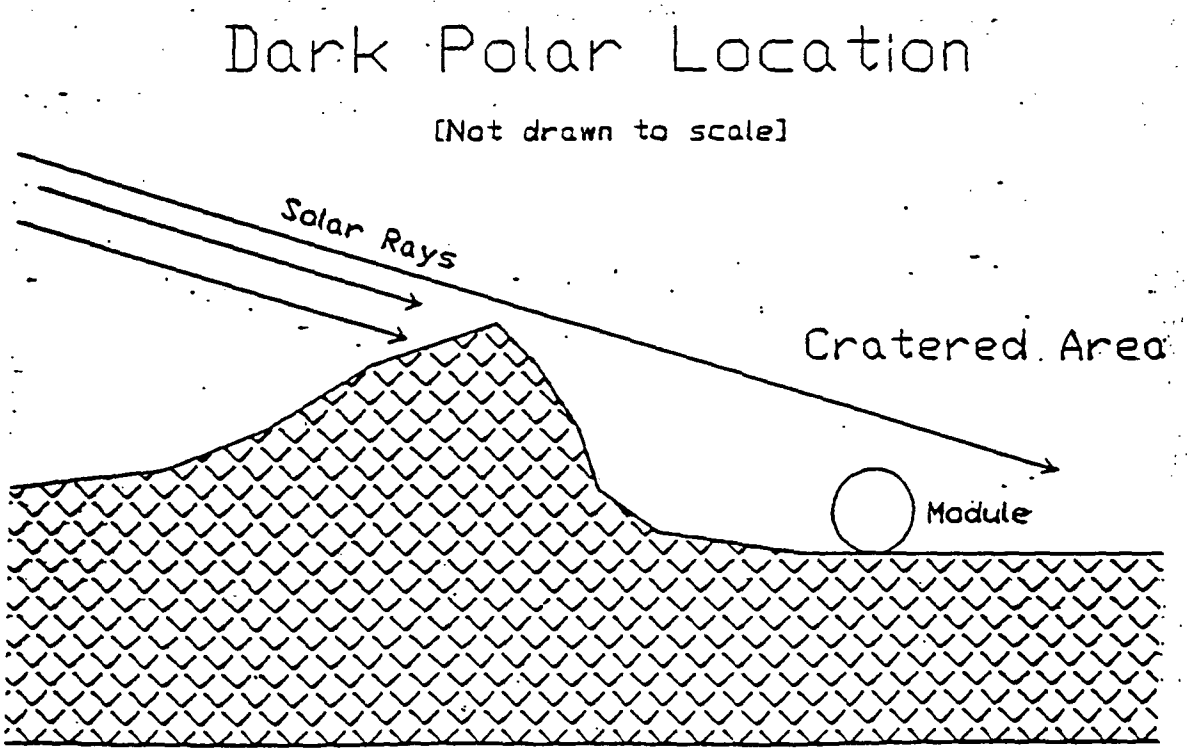


FIGURE 3-9 PERMANENTLY SHADOWED POLAR SITE

Site Concerns	Weight	Mid-Lunar Score	Mid-Lunar Weight	Mid-Lunar on Backside Score	Mid-Lunar on Backside Weight	Lighted Polar Score	Lighted Polar Weight	Dark Polar Score	Dark Polar Weight	Dark Polar near Solar Score	Dark Polar near Solar Weight
Thermal Environment	1.1	4	4.4	4	4.4	6	6.6	8	8.8	8	8.8
Storage	0.9	6	5.4	6	5.4	5	4.5	9	8.1	9	8.1
Heat Rejection	1.4	7	9.8	7	9.8	5	7.0	10	14.0	10	14.0
Solar Light	0.5	5	2.5	5	2.5	9	4.5	0	0.0	5	2.5
Solar Power	0.7	4	2.8	4	2.8	10	7.0	0	0.0	8	5.6
Radiation Shielding	1.7	5	8.5	5	8.5	5	8.5	10	17.0	10	17.0
Scientific Value	0.9	4	3.6	4	3.6	8	7.2	9	8.1	9	8.1
Orbital Access	1.0	8	8.0	8	8.0	9	9.0	9	9.0	9	9.0
Communications	0.9	9	8.1	5	4.5	7	6.3	7	6.3	7	6.3
Daily Operations	0.9	6	5.4	6	5.4	9	8.1	2	1.8	2	1.8
Total:	10.0	58	**58.5**	54	**54.9**	73	**68.7**	64	**73.1**	77	**81.2**

FIGURE 3-10 LUNAR SITE TRADE STUDY

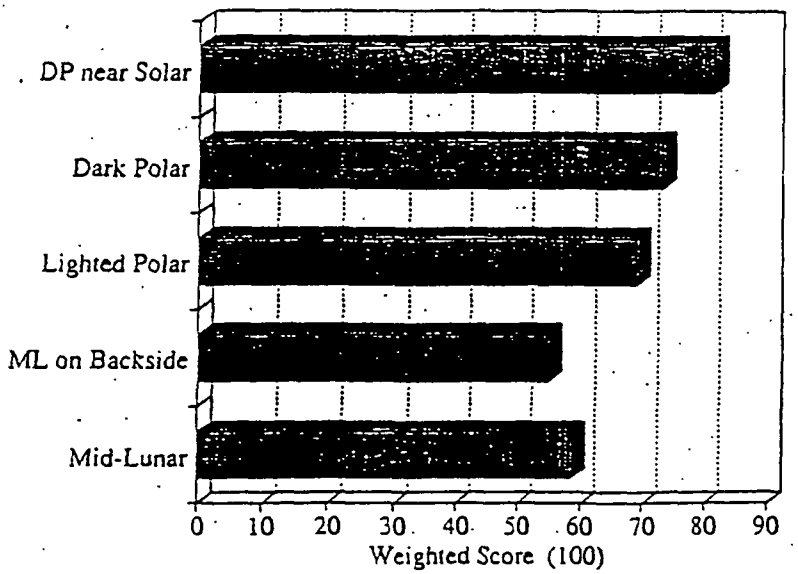


FIGURE 3-11 LUNAR SITE COMPARISON

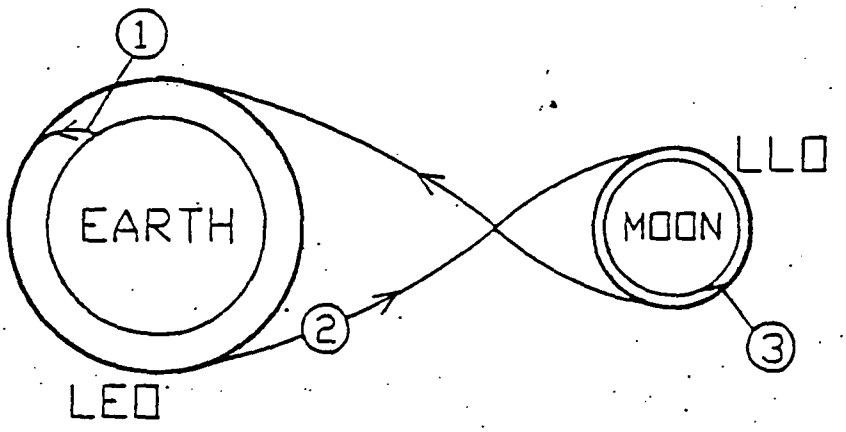


FIGURE 3-12 EARTH TO LUNAR TRANSPORTATION

Dedicated cargo lander

Payload mass:	20,000 kg
Vehicle mass:	7,500 kg
Propellant mass:	22,500 kg
Total mass:	50,000 kg

Dedicated manned lander

Payload mass:	6,000 kg
Vehicle mass:	9,000 kg
Propellant mass:	30,900 kg
Total mass:	45,900 kg

Dual purpose lander

Mission:	Cargo	Manned
Payload mass:	20,000 kg	6,000 kg
Vehicle mass:	9,000 kg	9,000 kg
Propellant mass:	29,700 kg	30,900 kg
Total mass:	58,700 kg	45,900 kg

FIGURE 3-13
LUNAR LANDER MASS COMPARISON

all masses are in kgs, all ΔV's are in km/s

	Cargo*	Manned**
ΔV, ascent	0	2.28
Payload, ascent	0	6,000
ΔV, descent	2.1	2.1
Payload, ascent	20,000	6,000
Total Inert Mass	7,500	9,082
Structure	1,011	1,322
Engines	704	646
RCS dry	332	323
Landing Systems	672	617
Thermal Protection	1,471	2,017
Tanks	2,207	3,025
DMS / GN & C	150	150
Electrical Power	478	478
Airlock	455	455
Total Propellant	22,500	30,838
Ascent Prop.	0	10,838
Descent Prop.	20,134	17,265
Unusable Prop.	608	842
Reserve Prop.	810	1,122
Usable RCS	758	656
Unusable RCS	38	33
Reserve RCS	152	131
Gross Mass	50,000	45,900

* Estimated from mass breakdown of a cargo lander designed for 25,000 kg by Eagle Engineering, Lunar Lander Conceptual Design, NASA-CR-172051, 1988

** Masses taken directly from Lunar Lander Conceptual Design

FIGURE 3-14
LANDER MASS BREAKDOWN

Navigation Systems	Landing	Location	Operations	Implementation	Mass	Redundancy	Cost	
Weight:	2.0	1.6	1.5	1.3	1.2	1.2	1.2	
Earth GPS	4	4	7	9	9	10	9	Total
Weighted:	8.0	6.4	10.5	11.7	10.8	12.0	10.8	70.2
Earth Radar	4	4	8	9	10	10	9	
Weighted:	8.0	6.4	12.0	11.7	12.0	12.0	10.8	72.9
Lunar GPS	9	10	6	2	2	9	2	
Weighted:	18.0	16.0	9.0	2.6	2.4	10.8	2.4	61.2
Lunar Radar	9	8	7	5	6	8	4	
Weighted:	18.0	12.8	10.5	6.5	7.2	9.6	4.8	69.4
TACAN System	6	7	6	3	3	8	4	
Weighted:	12.0	11.2	9.0	3.9	3.6	9.6	4.8	54.1
LORAN System	3	7	7	5	6	7	5	
Weighted:	6.0	11.2	10.5	6.5	7.2	8.4	6.0	55.8
ILS or MLS	9	1	6	6	7	5	6	
Weighted:	18.0	1.6	9.0	7.8	8.4	6.0	7.2	58.0
Terrain-Following	10	9	8	10	8	4	7	
Weighted:	20.0	14.4	12.0	13.0	9.6	4.8	8.4	82.2
Transponders	8	0	8	8	8	9	8	
Weighted:	16.0	0.0	12.0	10.4	9.6	10.8	9.6	68.4

FIGURE 3-15 NAVIGATION SYSTEM TRADE STUDY

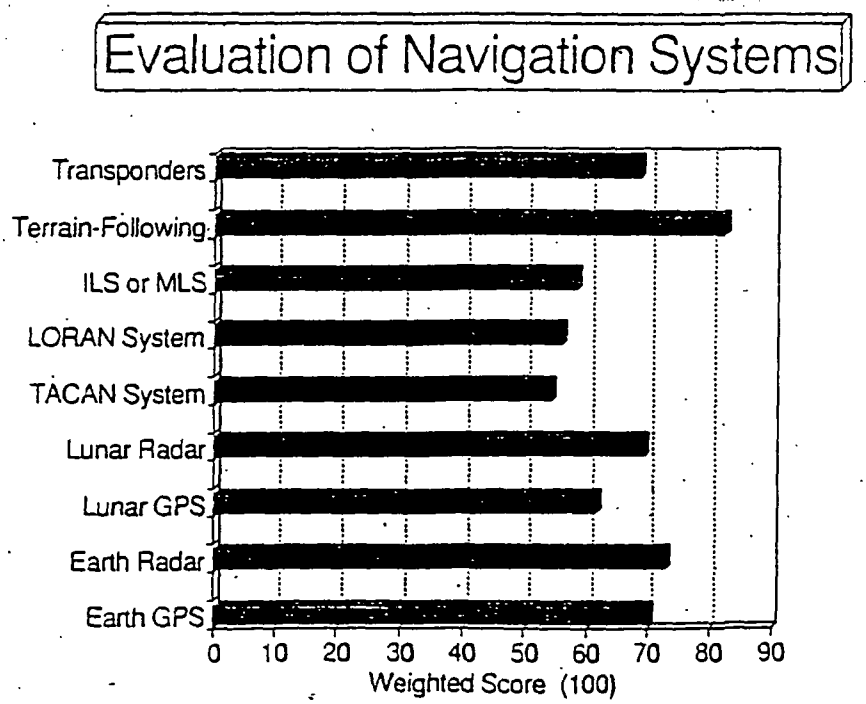


FIGURE 3-16 NAVIGATION SYSTEM COMPARISON

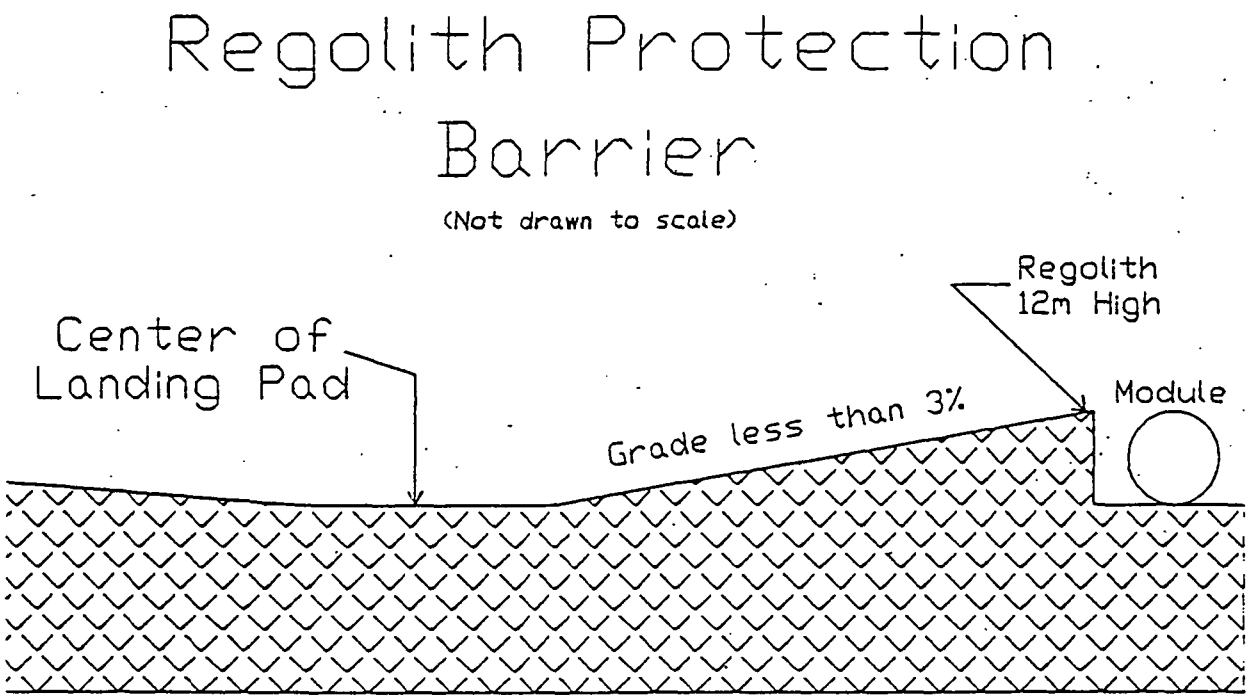


FIGURE 3-17 LANDING SITE BLAST BARRIER

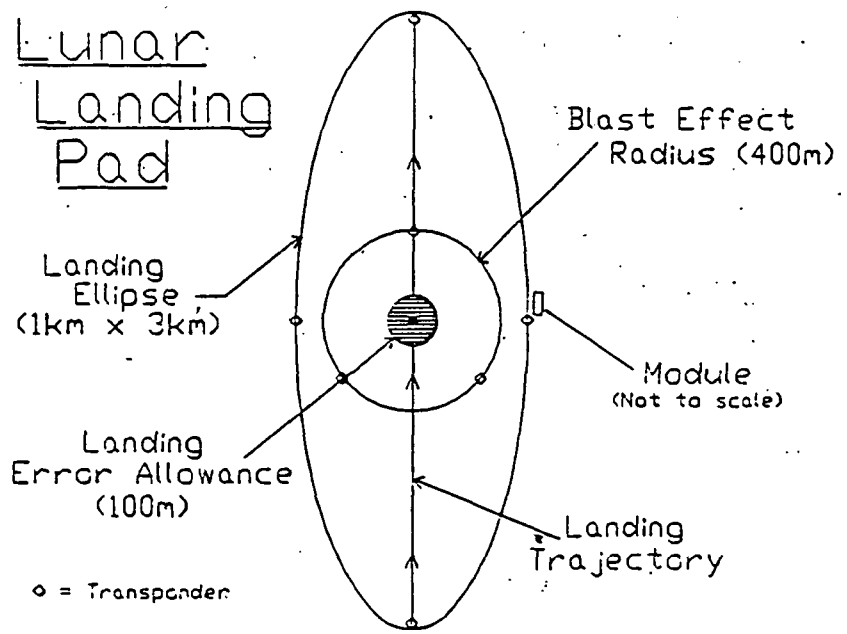


FIGURE 3-18 LANDING SITE DIAGRAM

4.0 ROBOTICS

4.1 INTRODUCTION

The Space Habitation Robotics Group study addresses the application of automation and robotics for emplacing, activating and maintaining an early lunar base. It is the goal of this paper to develop a general methodology for analyzing the uses of automation and robotics for any lunar base. This study has been fashioned in a manner similar to Boeing's Robotic Lunar Surface Operations Study, to the University of Colorado Center for Space Construction's analysis of the Boeing study and to previous Space Habitation Robotics studies.

The general methodology has the following elements:

- Develop rationale for lunar robotics
- Determine the lunar base requirements and assumptions
- Develop a list of functions to describe the necessary lunar tasks
- Apply necessary functions to a specific task
- Break each function down into required technologies for robotics
- Identify technological stumbling blocks
- Formulate recommendations

4.2 RATIONALE

Duplicating the physical capabilities of man has been the long term goal of all those involved in the creation and development of robotic systems. But to those involved duplication sometimes is not enough. Extending and improving the physical capabilities of humans would be a much higher goal, especially if it was performed by machines. The development and implementation of these types of automated systems is vital to the future of the United States space program. In the past automation and robotics has found its most critical and successful applications in repetitive, remote, or hostile environments; in factories, on land, under the sea, and in space; in hazardous terrain, or settings lethal or inaccessible to humans. If the U.S. space program plans to develop a permanent surface space habitation system on the Moon, it will be imperative to development and implement robotic systems to perform this task. In addition to other tasks, robotics could be used for site preparation, digging, instrument installation and placement, reactor placement, mining, and landing site establishment. But why use robotic systems for these tasks? Why develop expensive

machines that can perform the same tasks that humans can, and why on the Moon?

Robotics will provide for a cost effective means of establishing a lunar base. Some of the main reasons for this are: (1) Man rated vehicles are more expensive to develop (3-10 times more) than a vehicle that would be coined as "robotic" rated. (2) Robotics will alleviate the costs of on-site human support while the base is being constructed. I.e. food, water, and supplies will be needed to support humans, and thus in cost-to-mass terms, the price of transportation will get extremely expensive. In the beginning the cost to transport these robotic systems will be high, but in the end, will be far cheaper than developing a mission that will involve the launch and support costs of humans. It is necessary to note, however, that there will be initial costs for the development and production of these robotic systems.

More likely than not, Industrial firms and other departments of the government will be very interested in the use of these robotic systems. By convincing industry that such a development would be beneficial to them in profits and safety, their support and combined research efforts will enable both the U.S. space program and industry to lower the costs distribution of development and production. Eventually, Earth-based applications and development of robotic systems will expand.

In addition, the development and launch of Robotic missions will take less time than similar manned missions. Man rated launching vehicles simply take more time to develop than those that would transport robotic machines to the moon. This is mainly due to the time it takes to approve vehicles for human safety factors and support.

The final reason for using robotic systems is safety. By using robots for construction, base maintenance and repairs, and various lunar surface tasks such as soil sampling, mining, digging, etc., the risks of over exposure to high levels of radiation, meteor impacts to humans, and simple construction accidents that would be far more lethal on the lunar surface, would be greatly reduced. Such robotic support when in the permanent presence of humans on the lunar surface, and when humans are not their in the beginning construction stages, will greatly improve human safety. In addition, the use of robotics in some of the previously mentioned, time consuming tasks, will enable crew members to spend much more time performing more valuable tasks such as lunar research.

Automation and robotics has been used with great success for initial scientific investigations on other planets, as well as previous Apollo missions on the lunar surface. Industry has also felt the impact of present automated systems with great success in areas of costs, time consumption, and safety. In the end, Robotics and automation will be seen as strictly necessary for lunar base installation and support.

4.3 HISTORY

It has already been mentioned that automation and robotics has been used with great success for initial scientific investigations in space, as well as industry. From the Mercury/Gemini programs, through current applications of automation and robotic techniques in industry and the military, baseline models, with known reliability, have been provided to assist future designs of operating systems on land and in space.

The Mercury/Gemini program utilized automation and robotics to control guidance systems, re-entry system sequences, as well as escape systems. These automated systems provided greater safety for the crew, and freed them to perform other activities such as research and experimentation. Continued success followed with the Apollo program, and improvements were made on the guidance and control systems, as well as the development of automated Lunar surveyor probes. The functions of these probes included quantification of landing sites, soil density, and slope inclination. Lunar rover vehicles were also used during the last three Apollo missions and provided greater mobility and load-carrying capacity for the astronauts. And although they were manually operated, their use can provide for future designs of robotic LRV's for use on a Lunar base.

Three years after the conclusion of the Apollo missions (1975), two Viking probes were sent to the surface of Mars. These landers utilized automation to control their radar altimeters, three-gyro internal guidance systems, and three accelerometers. In addition, computers controlled the throttleable hydrazine landing engines which were automatically ignited prior to landing. Additional automated advancements provided for the landers ability to utilize a robotic arm to retrieve soil samples. These samples were gathered from underneath the landers, and were then deposited through sieves for future experiments. The collector head could back-hoe at 20 pounds, dig at 30 pounds, and lift at 5 pounds, while the arm could extend 10 feet and rotate 302 degrees. Other booms were used to measure temperature, pressure, and wind conditions.

Today the Space Shuttle, in addition to it's other systems, utilizes automation to control it's internal control systems and guidance systems, as well as an arm that is used to launch and retrieve satellites. This arm is remotely manipulated and controlled, and has been used with great success. In industry, high speed tasks, efficiency, reliability, and cost-effectiveness are all provided to car manufacturers through the use of automation and robotics. Some of these tasks include painting, welding, fabricating, and precision tooling. Throughout the history of industrial robotics, robots have been used as manipulators handling materials, parts, tools, and other specialized devices. In addition, these systems have provided for job safety by alleviating the use of humans in hazardous working environments. The military also uses automation extensively in areas that include internal guidance systems, terrestrial navigation systems on missiles and aircraft, aircraft attitude adjustments, as well as prototype vehicles which can negotiate roadways, construct three-point maps of their surrounding, utilize vision systems that determine object nature, and navigation systems that utilize triangulation.

4.4 BASELINE REQUIREMENTS AND ASSUMPTIONS

After developing a strong rationale the next consideration is the lunar base design (Figure 4.1). The base design is derived from the base mission statement, the ground rules and assumptions the base operates under, the requirements derived from the mission statement and outside influences and essential base subsystems. The ground rules, assumptions and base requirements will effect the choice of construction methods and thus influence the application of automation and robotics for a lunar base.

As defined by the Structures group the early base will have some specific subsystems such as habitat, thermal control, power, communications, cargo hauling, and landing pads. These subsystems have certain requirements and are as follows:

Habitat- Emplacement of a pressurized living and working space that is able to support four humans. Activities such as unloading the habitat model from the lander and transporting it to a prepared site will be required.

Power- A source of power that can meet the desired needs of the habitat module and support equipment, such as rechargeable batteries for robotic vehicles, will need to set up. As with the habitat module the power source will require being unloaded and transported to a prepared site. The power

source will however require more intricate operations such connecting cables and deploying radiators.

Thermal control- Although the structures group concept for placement of the habitat module in a shaded area would nullify the need for shielding from solar radiation future early base designs may require the use of lunar regolith to provide thermal control and shielding from the sun. If used regolith would need to be either bagged or piled over the habitat module.

Communications- On the early lunar base the communication needs will be supplied by the lunar lander and orbiting satellites and thus there will little need for robotic assistance in the set up and operation.

Cargo hauling- In order to efficiently transport equipment and supplies on the lunar surface, a system of stakes and cables will need to be utilized. Transporting cargo will be a very labor and power intensive operation that will require a strong cable and an efficient winch.

Landing pads- In order to reduce the amount of lunar dust that is generated when landing on the lunar surface, landing pads will need to be created. Like roads, large amounts of lunar soil will need to be moved and compacted.

4.5 ROBOTICS TASK DESCRIPTION

The second step in the methodology is to define a set of functions which encompasses all the necessary tasks for emplacing, activating and maintaining an early lunar base. In some cases the base design requires the use of certain methods of construction for a particular task, but in most cases the choice of construction methods are wide. Thus, a list of functions and their requirements were derived.

Note: information extracted from CSC Systems Cluster Report #18

ASSEMBLE

- Method of assembly (riveting, bonding, welding, etc.)
- Masses of individual parts
- Sizes of individual parts
- Number of parts
- Force required
- Precision required
- Mass of finished assembly

Size of finished assembly
Maneuvering space available

CONNECT
Type of connection
Number of connections
Force required
Precision required
Maneuvering space available

DEPLOY
Method of deployment
Force required
Precision required
Number of deployments
Maneuvering space available

DISASSEMBLE
Method of disassembly
Mass of object
Size of object
Masses of individual parts
Sizes of individual parts
Maneuvering space available
Proximity/fragility of surrounding structures

DISCONNECT
Type of disconnection
Number of disconnections
Force required
Precision required

DUMP
Type of material (size, cohesion, etc.)
Amount of material
Precision required Dust limitations
Maneuvering space available
Proximity/fragility of surrounding structures

EMPLACE
Type of object
Mass of object

Size of object
Quantity of object
Precision required
Fragility of object
Proximity/fragility of surrounding structures
Maneuvering space available

EXCAVATE

Geometry of the starting surface
Regolith constituents (particle size, rock distribution, etc.)
Regolith densities
Depth of excavation
Area of excavation
Total volume to be moved
Finished surface variance
Proximity/fragility of surrounding structures
Maneuvering space available

GRADE

Regolith constituents (particle size, rock distribution, etc.)
Finished surface variance
Area of graded surface
Depth of grading
Regolith density
Proximity/fragility of surrounding structures
Maneuvering space available

OFFLOAD

Relative sizes of cargo and transport
Relative masses of cargo and transport
Size of cargo
Mass of cargo
Height of object on transport
Fragility of cargo
Proximity/fragility of surrounding area
Maneuvering space available

PACK

Required density
Type of material to pack
Surface area to be packed
Depth to be packed
Height of upper surface

Proximity/fragility of surrounding structures
Maneuvering space available

STOW

Method of stowage
Force required
Precision required
Number of stowages
Maneuvering space available

TRANSPORT

Type of cargo (loose, containerized, etc.)
Amount of cargo
Mass of cargo
Size of cargo
Distance to be transported
Frequency of transport
Surface over which transported

As indicated in the list of functions there are specific requirements for each function that must be considered. In the case of offloading, transporting and emplacing the main requirements are mass, size and amount of payload. In the case of the deploy, assemble and connect functions the main requirement is precision. These sets of requirements have an obvious difference in the level of specificity ie. the level at which the needed technologies are analyzed is different.

4.6 REQUIRED TECHNOLOGIES

The three functions, offload, transport and emplace, can be analyzed at an integrated technology level. This means that specific earth based systems such as cranes, trucks and forklifts can be examined as to there ability to perform the functions (Figures 4.2 - 4.5).

This level of description however, is inadequate for an accurate technology evaluation. The description of the offload, transport, employ, deploy, assemble and connect functions require a more in depth analysis of specific technologies. To achieve this level of specificity individual subsystems of robotics were identified. These subsystems and their requirements are defined as follows:

MANIPULATORS

Motor torque requirements
Degrees of motion
Length of reach

SENSOR
Position, velocity and acceleration
Pressure, force and torque
Inclination and temperature
Ranging and proximity sensing

END EFFECTORS
Dependent on job task
Precision needed
Room to maneuver

TELEMETRY
Communications
Control

POWER
Type of power system
Power requirements

THERMAL CONTROL
Temperature limits
Type of power system

STRUCTURAL
Mass of robot
Size of robot
Materials used for robot
Load capacity

LOCOMOTION
Tracks or wheels
Drive train
Braking
Suspension

The subsystems were then defined as the needed technologies. With the robotic subsystems defined as technologies the whole functional flow for the set up of the nuclear dynamic power system was rewritten. Under

each function, specific robotic actions were identified and the main technologies used to perform the activity were listed.

4.7 TECHNOLOGICAL ADVANCES

A careful overview of Robotic technology will reveal three areas that require particular attention in the development of new/improved technology, in order for a Lunar Robotic System to operate effectively. These are Manipulators, Sensors, and Telemetry, with Effectors being more or less a subsection of Manipulators.

MANIPULATORS

The choice to concentrate primarily on Manipulators is because, 'without multi-directional wrist-like motion a Robot is little more than a miniature crane.' (Rosheim,M. 1989) In assembling a Lunar nuclear power system, precise and careful teleoperator controlled manipulation will need to be developed. Successful implementation of many initial Lunar systems will not only rely on this type of precise Robotics, but also on manipulation and handling of objects on a much larger physical and weight scale.

A key element in Lunar Robotic technology development will be the involvement of commercial industry at the earliest possible stage. A primary driving force of Lunar Robotic technology should be the idea of immediate benefits to commercial industry. An alignment of technical development with industry needs should be implemented. A 1988 JILA survey (Figure 4.6) indicates greater degrees of freedom and more compact size were the most desired improvements in industrial Robots. These industry needs align very well with Lunar Robotics technology development needs.

Creating higher-performance Robotic and Teleoperator Systems demands advances in wrist actuator technology. 'Correct kinematic and structural design of wrist actuators will determine the Robot designs versatility.' (Rosheim,M. 1989) The wrist is located at the end of a robot arm as the human wrist, manipulating the End- Effector and thus the work piece. Three degree of freedom wrist joints are essential in teleoperator Robots for high dexterity, precision and simpler master/slave interfacing (Figure 4.7). Lunar Robots must be able to perform in complex three-dimensional environments that humans do. There are two types of wrist actuators: the Roll-Pitch-Roll, and the Pitch-Yaw-Roll wrists (Figure 4.8).

Current state of the art wrists include the Remote Manipulator System (RMS)wrist used on the Space Shuttle, and the Triple-Axis Common-pivot arm wrist (TACPAW). Problems with the RMS wrist include; weight and bulkiness,
axes are widely separated making control more difficult. The TACPAW wrist
addresses the RMS problems by its compactness, and is designed to combat "weak wrist syndrome". The TACPAW wrist is also 'back-drivable', meaning the wrist allows for walk-through programming due its low friction drive, singularity free axis and low reduction transmission ratio (The RMS ratio is 740:1, making it not back-drivable) (Figures 4.9 and 4.10).

IMPORTANT DESIGN CONSIDERATIONS

-Maximum degree-of-freedom operation.
-Singularity free operation.
-Back-drivable
-Compact design for better sensor integration.
-Matching precision/load requirements.
-Integration from/to possible industrial use.

SENSORS

Robot sensors can be divided into four somewhat distinct areas; Vision sensors, Scene illumination, Force sensors and Tactile sensors. The interdependence of manipulators and sensors is seen in Figure 4.11. A control system is used in the sensor feedback loop to control the robots manipulations. In determining the sensor system needed, the four areas mentioned must be addressed to the specific tasks to be performed. Implementing real-time sensory feedback will be a difficult and challenging task.

Vision Sensors- While it is generally believed that vision sensors are readily available to support Robotics, vision sensors are often confused with electronic cameras designed for the television industry. There are currently no vision systems specifically designed for robotic applications. Some examples of vision systems and their applications.

VISION SENSORS

TYPE	APPLICATION	RESOLUTION
LASER/CAMERA	RANGING	VARIES
CCD CAMERA	GREY SCALE IMAGING	LOW
VISION IN HAND CCD	OBJECT GRASPING	0.5mm @10cm
LASER SCANNING	3-D INFORMATION	HIGH
FIBER OPTIC	VISION IN HAND	0.1mm @ 14cm

PERFORMANCE ABILITIES OF LASER RANGEFINDING

Operating range = minimum (cm) to maximum (km)
Range accuracy ~ 1 percent of the distance for long range and mm for short range
Range rate accuracy (radial velocity) = mm/sec to cm/sec
Field of view = 30 X 30*
Small in size, light-weight and low power draw
Simplicity and reliability

Placing the vision sensor on the end-effector of the Robot , as opposed to a remote location, greatly simplifies the problems of parallax, coordinate transformation and resolution.

Scene Illumination-The need for controlled illumination in image recovery is to combat lack of contrast in the object being scanned. Unstable illumination conditions will lead to greater signal processing complexity, hence the importance of locating illumination sources in effective locations on the Robot.
Types of illumination can include: front lighting in the visible spectrum, structured lighting with photodiode arrays and diffuse illumination.

Force Sensors- Force sensing can be either active or passive. An active force feedback system can provide real-time sensory feedback, in order to allow complex operations to be performed automatically. Force sensors can consist of six-component strain gauges to give three dimensional feedback. Passive force sensing is accomplished by mechanical means, and is used in assembly operations where precise alignment is needed. The device derives its 'sensing'
properties from geometry and elasticity of its parts, therefore within certain angular and lateral displacements successful assembly can still be obtained. No true force sensing feedback is input to the system hence the term 'passive'.

Tactile Sensors-Shape recognition through touch, along with the sensing of pressure applied while gripping, is a simplified concept of tactile imaging. The ability of the tactile sensor to correctly feedback force of grip information can't be understated, hence selection of a suitable material to perform the transduction is the most critical aspect of tactile sensing. Response time, settling time along with recovery time, often are too long for real-time feedback in a highly sensitive sensory pad. The various systems employed to date include: carbon-loaded rubbers, which change resistance with pressure; Piezoelectric polymers, measure change in the acoustic propagation constant of a material under pressure; etched silicon substrate separated by active and passive metallic electrodes with a carbon-loaded skin placed over it.

END-EFFECTORS

End-effectors can be very task-specific, and thus without specific assembly requirements available can't be adequately addressed.

TELEMETRY

An inherent problem of any teleoperated Lunar Robotic system will be the communication link with an earth-based operator. The nature of this problem is two-fold: 1) Continuous communication from any single point on earth to a lunar location can be logistically difficult to maintain; 2) A 2.5 to 3 second delay in roundtrip communication times makes real-time operation of a teleoperator Robotic system more difficult.

Methods and options of maintaining communication links have been addressed in the structures section, and therefore will not be re-addressed here. It should be noted that , Robotic activities will need to be scheduled around times when communication links are securely available.

POWER

There are various ways to power a Robotic system, key to determining a power source is the duration of intended the mission or task. Another determinant in power supply selection is the total amount of wattage needed to operate the systems involved in the task. An assumption is made that all motors and auxiliary systems are strictly electric.Various internal power sources available or under development could be used to power the Robotic system.

NUCLEAR POWER SYSTEMS

TYPE	WATTS/Kg	TEMP(K)	COOLANT	COMMENTS
Hg Rankine	200	980	NaK	Operated for one year, had fuel swelling
Turboelectric				
Thermo-electric	250	1600	heat pipe(Na)	SP-100
Thermionic	to 900	1675	heat pipe(Na)	Under development
Thermo-electric	30	980	NaK	Advanced SNAP

Source: Advance Nuclear Systems for Portable Power in Space, 1983, National Academy Press, Washington DC.

Another option is to power the robot by a rechargeable battery system. The advantages of a battery system over an active power generating system are reliability and simplicity. The disadvantages are , the need for an external power source for recharging the battery system, and the unavailability of the Robotic system during recharging.

BATTERIES

TYPE	CELL VOLTAGE	W-HR/Kg	COMMENTS
LEAD ACID	1.95	30	FOR COMPARISON ONLY
NICKEL-CADMIUM	1.25	38	INEXPENSIVE
NICKEL-HYDROGEN	1.25	50-100	HIGH CYCLE LIFE
SODIUM-SULFUR	1.25	66-154	DELIVERS HIGH POWER

Source: Proceedings of the 25th Intersociety Energy Conversion Engineering Conference, 1990, Nelson, P.A., Schertz, W.W., and Till, R.H. (ed.), American Institute of Chemical Engineers

Regenerative fuel cells and Solar voltaic are two other possible power supplies. Fuel cells have an excessive weight penalty along with the problem of dealing with cryogenics. Solar voltaic would be impractical in a Lunar polar base site.

THERMAL CONTROL

Thermal control is dependent on the type of power supply system chosen, and because of this interdependence will influence which type of power supply is chosen. An internally powered Robotic system will inherently require more radiation surface for thermal control than most battery systems. This increase in radiator surface adds weight and complexity as well as reducing the possible locations for manipulator placement on the Robot. A thermal flow chart for the robot can be seen in Figure 4.12.

STRUCTURES

The structure of the robotics vehicle will be determined by the load carrying capacity needed and the environmental conditions, such as terrain and radiation. The materials used in the structure will need to be light, durable and radiation resistant. Some material which might be chosen are titanium, magnesium, beryllium, steel and aluminum. Each material exhibits both advantages and disadvantages.

Titanium- Although it is light weight and very strong the cost is economically impractical.

Magnesium- When exposed to a vacuum it suffers appreciable evaporative losses. To counter the effects of sublimation, magnesium requires a protective coating

Beryllium- Vulnerable to particle damage and cracking due to vibrations.

Steel- Although very strong, it is too heavy to be used for space structures.

Aluminum- It is light weight, strong and does not suffer appreciable evaporative losses.

RADIATION PROPERTIES

Material	Solar absorb.	IR emissivity	Temp Equilibrium

Aluminum*	0.2	0.031	631 K
Titanium*	0.448	0.129	540 K
Silvered teflon	0.08	0.66	234 K
Fixed silica	0.805	0.825	393 K
White paint	0.252	0.853	292 K
Black paint	0.975	0.874	407 K

LOCOMOTION

In the lunar environment, there are a variety of choices for locomotion. These forms of locomotion include conventional wheels, conical wheels, tracks, walking/trailer combination and a tri-star assembly (Figures 4.13 and 4.14).

Conventional wheels- They have a simple design using proven technology and are suitable for use on the lunar surface. They are also difficult to repair and subject to puncture

Conical wheels- These wheels provide a wider wheel base than conventional wheel, but are not as structurally sound as conventional wheels.

Track- Tracks are capable of covering rough terrain, but have a complex design. They have many moving parts affected by lunar dust and are difficult to tow due to friction caused by the many moving parts.

Tri-star assembly- A tri-star assembly is capable of covering rough terrain, but is complex in design.

Walking/trailer combination- This combination is capable of operating on rough terrain, but requires a separate system to control movement of support legs.

RECOMMENDATIONS FOR TECHNICAL DEVELOPMENT

1. Precision Manipulators with 6-degrees-of-freedom
2. Vision/ranging devices that are 'vision in hand'.
3. Precision Tactile/Force sensors with feedback.
4. Back-drivable Manipulators for precision motion programming.
5. Advanced battery designs.

4.8 RECOMMENDATIONS

The robotics group developed a methodology for designing lunar robotic systems. The general methodology is as follows:

- Develop rationale for lunar robotics
- Determine the lunar base requirements and assumptions
- Develop a list of functions to describe the necessary lunar tasks
- Apply necessary functions to a specific task
- Break each function down into required technologies for robotics
- Identify technological stumbling blocks
- Formulate recommendations

The final step in the methodology, the formulation of recommendations, develops from an analysis of current technologies. Initially, research is done to determine the capabilities of each required technology. If the technology is not developed enough to perform a desired function, this is deemed a stumbling block. Once all the stumbling blocks for each individual technology are discovered, recommendations can be made concerning the advances that need to occur in that technology. In this paper, manipulator technology was investigated, stumbling blocks found and recommendations offered.

4.9 TEN YEAR PLAN

Once technological recommendations have been made, a time-line (Figure 4.15) can be drawn depicting the evolution of a robot capable of performing desired tasks. The evolution involves a stepwise implementation of necessary technologies starting with a terrestrial research and development to reduced gravity and space applications. The given time-line shows a conceptual implementation of technologies required for a remote construction robot. This time-line is not a ten year plan, but a visual representation of how required technologies can combine over time to form a final robotic product. A more in depth investigation of necessary technologies would have to be undertaken to develop a concise ten year robotic design.

This time-line shows one of several possible implementation schemes derived from the methodology. Initially, each of the desired technologies has a starting point. These technologies then advance individually over time. Once a technology advances to the point where it can be used in conjunction with another technology, they merge. Technologies that are

specifically designed for use with another technology merge together before merging into the whole. One example occurs in the given time-line. In this case, transportation was deemed to be energy intensive. The power was therefore developed to conform to the transportation specifications, and hence merged together before merging into the whole. Also, the less critical technologies were not merged until the end of the time line. In this case, the final desired material was not needed until a final prototype was to be built. Once all essential technologies have merged, the desired product is completed.

Useful advancing technologies can be assimilated, refined and implemented by industry. An example would be combining visual sensors with robotic manipulators for possible grasping tasks in harsh environments. Since the technologies advance individually, they can be applied to industry even if a final robot is not completed. This way, even if a project ends prematurely, technological advances will still have other applications.

For lunar robotics, technological designs must accommodate the lunar environment. Design specifications for an earth based robot and a lunar based robot may be quite different even though the tasks may be similar. For this reason, a complete task description is needed as a precursor to robot design. Additionally, the time line may merge differently depending on where the robot is designed to work. As an example, materials research may be critical to the robots operation in a lunar environment. The materials may be implemented earlier in this robots evolution or also designed to conform with another technology.

4.10 ROBOTICS GROUP CONCLUSION

There are numerous designs for proposed lunar robots (Figure 4.16 and 4.17). Each of these robots was designed for a specific task on a lunar base with a conceptualized design. If the lunar base design changes, these robots may become totally useless or subject to severe change. Instead of designing another robot for an unknown base, the robotics group devised a methodology for developing robots. Subsequently, a robot can be designed once a base design is known. If base design changes, the methodology can be implemented to find a new robotic design. By implementing this methodology, lunar or even earth based robotics can be easily developed.

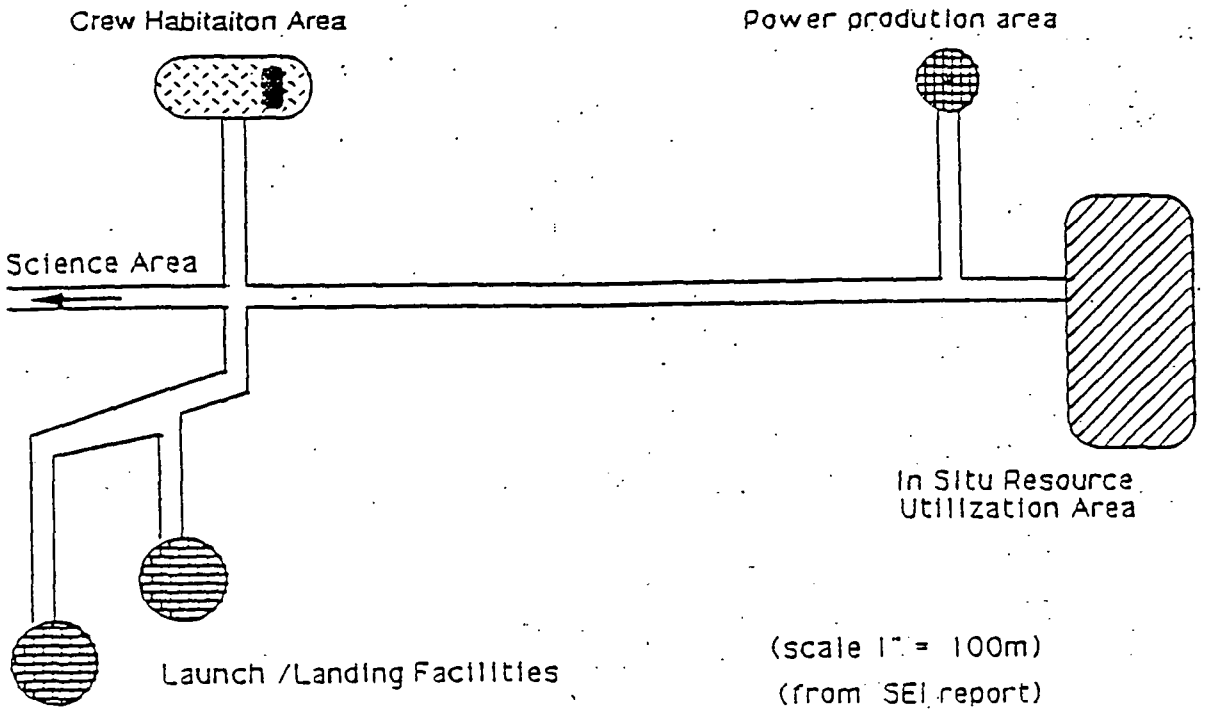


FIGURE 4-1: LUNAR BASE DESIGN.

	A	B	C	D	E
1	Offload	Score	Performance	Complexity	Versatility
2	Mobile boom-crane	6.0	3.0	1.0	2.0
3	Hybrid: bridge assisted boom crane	3.7	2.0	0.7	1.0
4	Forklift	3.7	1.7	1.0	1.0
5	Gantry Crane	3.3	2.0	0.7	0.7
6	Erectable crane	3.0	1.7	1.0	0.3
7	Ramp with winch/cable system	4.0	2.7	1.3	0.0
8	Chute with winch/cable system	4.0	2.7	1.3	0.0
9	Lift cargo with erectable structure: move land	2.7	1.7	0.7	0.3
10					
11	Transport	Score	Performance	Complexity	Versatility
12	Off-road truck (flatbed)	5.3	2.7	1.0	1.7
13	Pull on wheeled cradle or trailer	4.0	1.3	1.0	0.3
14	Forklift	3.7	1.7	1.0	1.0
15	On-road truck	3.7	2.3	1.0	0.3
16	Gantry crane	3.0	1.7	0.7	0.7
17	Rail System	3.0	2.0	1.0	0.0
18					
19	Lift and Position Loads	Score	Performance	Complexity	Versatility
20	Mobile boom-crane	6.0	3.0	1.0	2.0
21	Forklift	3.7	1.7	1.0	1.0
22	Gantry crane	3.3	2.0	0.7	0.7
23	Erectable crane	3.3	2.0	1.0	0.3

FIGURE 4-2: OFFLOAD, TRANSPORT, AND POSITION TRADES.

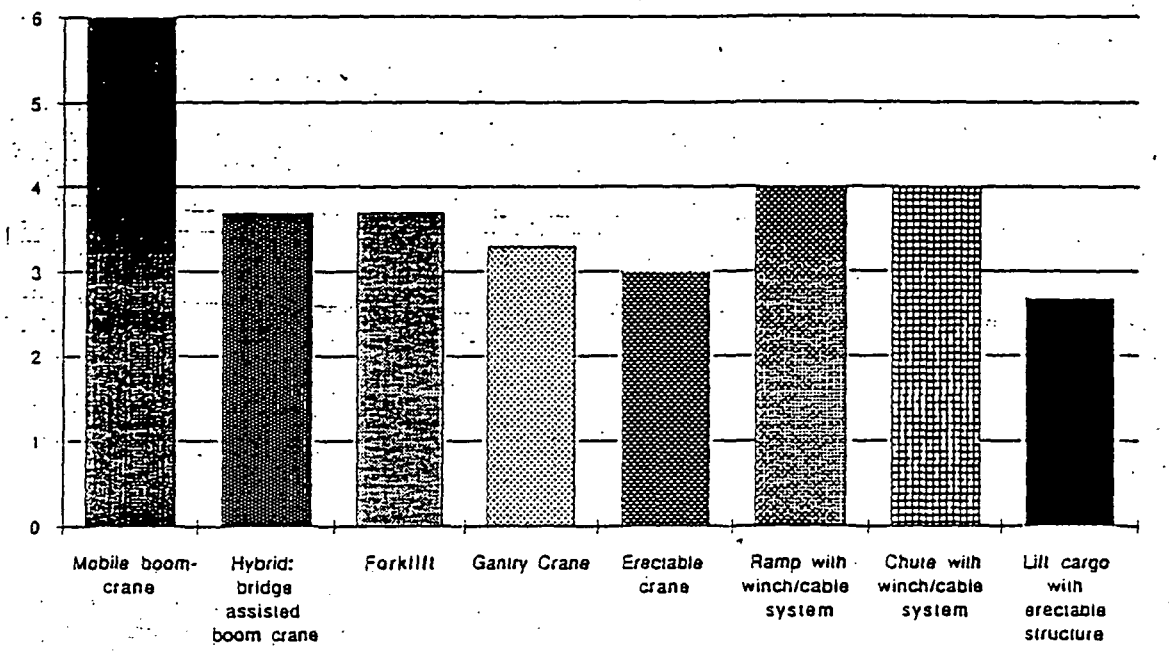


FIGURE 4-3: OFFLOAD SCORE TABLE.

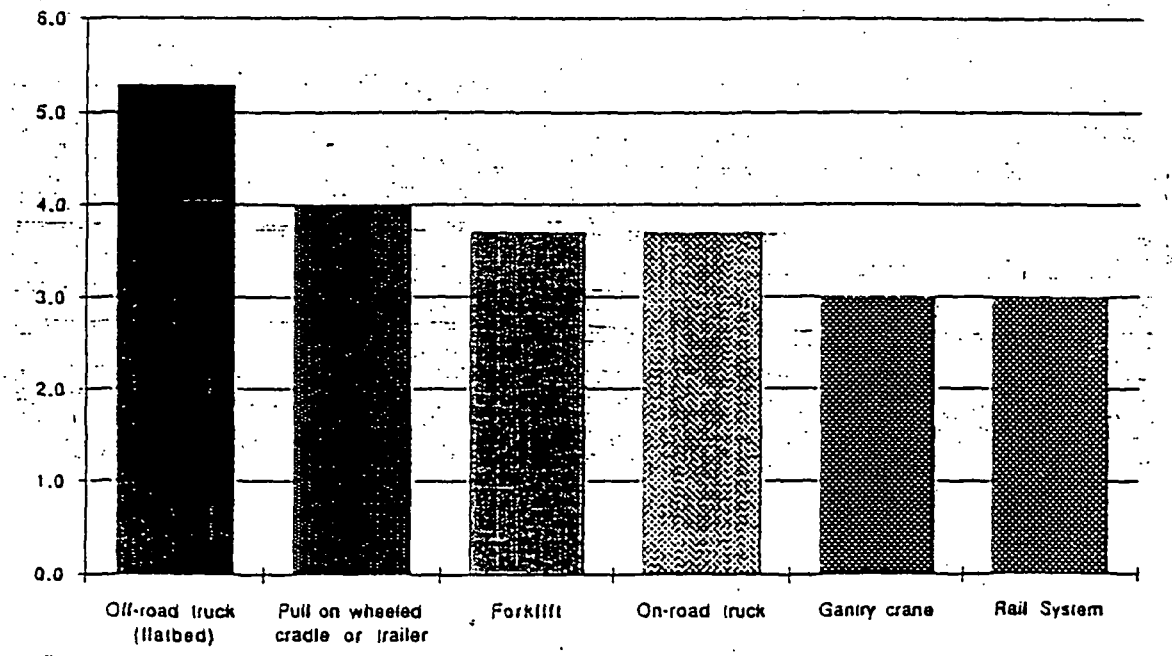


FIGURE 4-4: TRANSPORT SCORE TABLE.

	A	B	C	D	E
1		Front-end			Belt
2		Loader	Scraper	Truck	Conveyor
3	Capacity (mt/hr)	to 725	to 1100	to 2300	to 4500
4	Distance (m)	15-300	150-1500	300 and up	1800 and up
5	Grades (deg.)	to 7	to 7	to 6	10 15
6	while loaded				
7	Avg. Speed (km/hr)	8 16	24-40	30-55	10 23
8	while loaded				
9	Reliability	medium	medium	medium	high
10	Crew	1	1	1	none
11	Handeling large	good	poor	good	poor
12	blocky material				
13	Flexibilty for	excellent	excellent	excellent	fair
14	length change				
15	Flexibility for	excellent	excellent	excellent	poor
16	route change				
17	Haul road	prepared by	prepared by	graded	none
18	condition	loader	scraper		
19	Capital costs	medium	medium	medium	medium/high
20	Operating Costs	high	high	high	low

FIGURE 4-5: TRANSPORTATION VEHICLE TRADES.

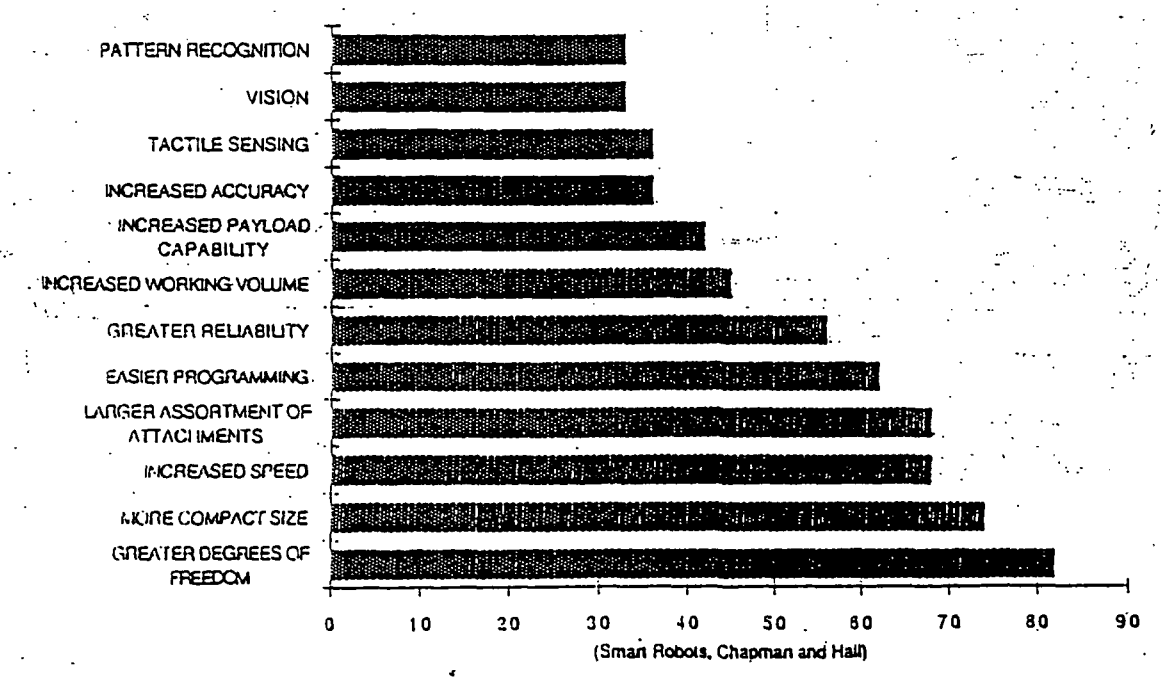
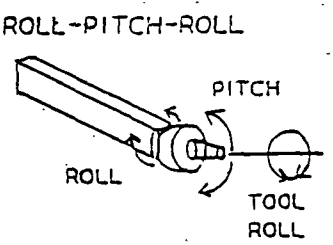


FIGURE 4-6: USER SURVEY OF DESIRED IMPROVEMENTS IN INDUSTRIAL ROBOTS.

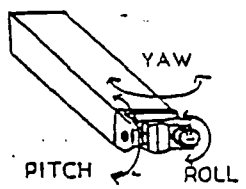
	A	B	C	D	E	F	G	H	I	J
		Under Development	In Current Use	Roll-Pitch-Roll Design (Singularity)	Pitch-Yaw-Roll Design (No Singularity)	Direct-Drive Hydraulic	Load Capacity (lb)	Low Precision (.025 - 1.02 cm)	High Precision (.0013 - .025 cm)	Anthropomorphic Robot Applications
1	Ex-Cell-O HYD-RO		X		X	X	150	X		
2										
3	Cincinnati Milacron T3		X	X			150		X	
4										
5	Deviliss TR 3500 Wrist		X		X		15	X		
6										
7	Graco OM 5000 Slim Wrist		X		X		15	X		
8										
9	Martin Marietta Metr Wrist	X			X		22		X	X
10										
11	Moog type A Wrist		X		X	X	17		X	
12										
13	Ross-Hime Omni-Wrist		X		X		25		X	X
14										
15	Tokico Armstar Type E Wrist		X	X				X		
16										
17	Thermwood Paintmiser Wrist		X		X		15	X		
18										
19	Therwood PR Series Wrist		X		X		15	X		
20										
21	Unimation Puma 762 Wrist		X	X			44		X	
22										
23	Yaskawa Motoman-L60		X	X			130		X	

FIGURE 4.7: THREE-DEGREES-OF-FREEDOM WRIST TABLE.



Advantages:
- Simple construction
- Compact wrist

Disadvantages:
- Singularity reduces work-space
- Straight-line movement difficult
- Pitch to yaw involves rolling wrist



Advantages:
- No singularities
- Complete range of motion

Disadvantages:
- Difficulty when axes too far apart
- Gimble lock when axes aligned
- More complex.

FIGURE 4-8: THREE-DEGREES-OF-FREEDOM WRIST VARIATIONS

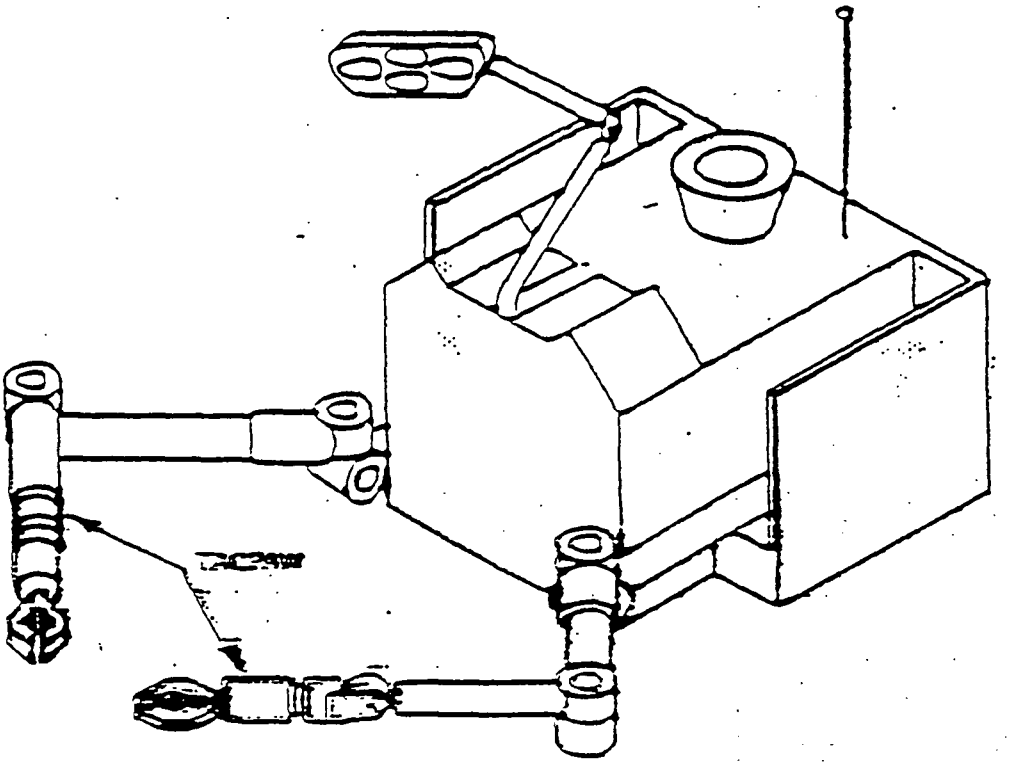


FIGURE 4.9: TRIPLE-AXIS COMMON-PIVOT ARM WRIST (TACPAW).

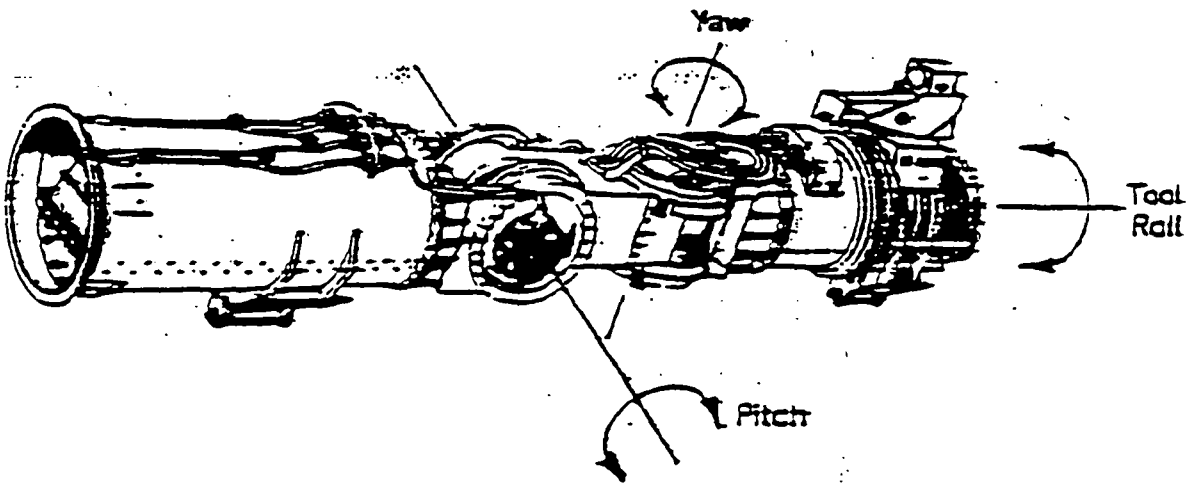


FIGURE 4.10: REMOTE MANIPULATOR SYSTEM WRIST.

VISION SENSORS —— LASER/CAMERA FOR RANGING

SCENE ILLUMINATION - LASER SCANNING PROVIDES 3-D INFO.

FORCE SENSING —— 3-D STRAIN GAUGE ON WRIST.

TACTILE SENSING —— PIEZOELECTRIC POLYMERS MEASURE CHANGE IN MATERIAL UNDER PRESSURE

EXAMPLE— EYE-IN HAND ROBOT VISION

LOCATION - END-EFFECTOR
INFORMATION - POSITION
DISTANCE
ORIENTATION

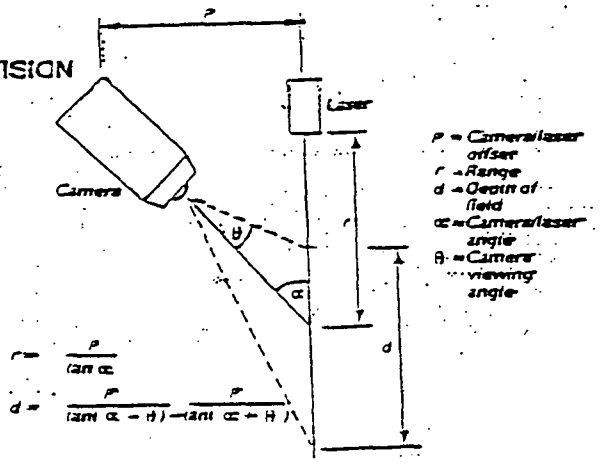


FIGURE 4.11: SENSOR VARIATIONS.

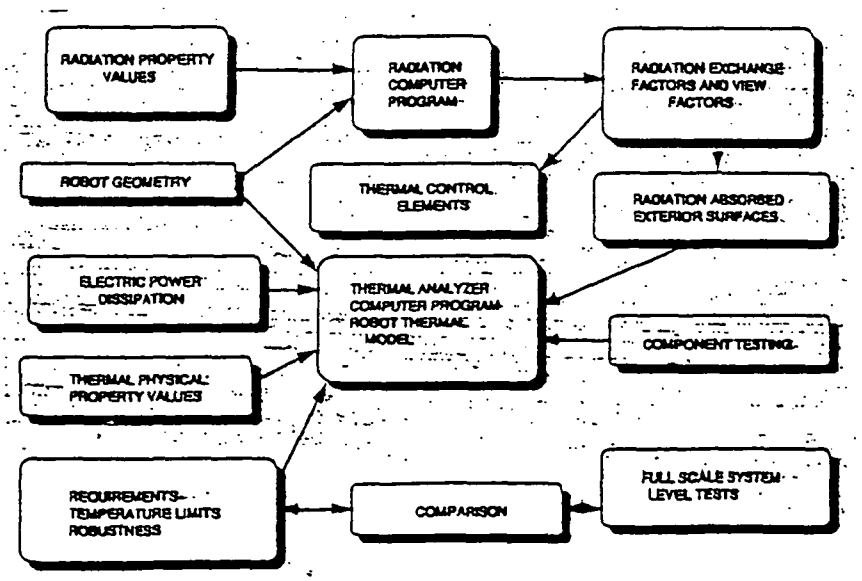


FIGURE 4.12: THERMAL FLOW CHART.

		Design Parameters				
DESIGN CRITERIA / WEIGHTING FACTORS / ALTERNATES →		CONVENTIONAL	CONED	TRACK	WALKING/TRAILER	TRISTAR
RELIABILITY	.178	1.42 / 8.0	1.42 / 8.0	.534 / 3.0	.890 / 5.0	1.25 / 5.0
COMPACTNESS	.022	.200 / 9.0	.200 / 9.0	.111 / 5.0	.133 / 6.0	.155 / 7.0
WEIGHT	.111	1.00 / 9.0	1.00 / 9.0	.222 / 2.0	.556 / 5.0	.778 / 7.0
SAFETY	.200	1.60 / 8.0	1.60 / 8.0	1.60 / 8.0	1.4 / 7.0	1.40 / 7.0
SIMPLICITY OF DESIGN	.022	.200 / 9.0	.200 / 9.0	.200 / 9.0	.889 / 4.0	.200 / 9.0
SIMPLICITY OF OPERATION	.067	.600 / 9.0	.600 / 9.0	.400 / 6.0	.467 / 7.0	.534 / 8.0
ENERGY EFFICIENCY	.022	.178 / 8.0	.178 / 8.0	.178 / 8.0	.155 / 7.0	.178 / 8.0
DURABILITY	.089	.711 / 8.0	.711 / 8.0	.533 / 6.0	.622 / 7.0	.711 / 8.0
VERSATILITY	.133	.933 / 7.0	.933 / 7.0	.933 / 7.0	1.2 / 9.0	1.07 / 8.0
REPAIRABILITY	.156	1.09 / 7.0	1.09 / 7.0	.778 / 5.0	.934 / 6.0	1.25 / 8.0
SUM OF PRODUCTS	1.000	7.935	7.935	5.469	6.445	7.513

FIGURE 4.13: DECISION MATRIX CRITERIA WEIGHTING FACTORS TABLE.

	A	B	C	D
1	Criteria			
2	Considered	Tally Marks	Total	Weighting Factor
3	Reliability	********	8	8/45 = 0.1778
4	Compactness	*	1	4/45 = 0.0222
5	Weight	*****	5	5/45 = 0.1111
6	Safety	*********	9	9/45 = 0.2000
7	Simplicity of	***	3	3/45 = 0.0667
8	Operation			
9	Simplicity of	*	1	1/45 = 0.0222
10	Design			
11	Energy	****	4	4/45 = 0.0889
12	Efficiency			
13	Durability	*	1	1/45 = 0.022
14	Versatility	******	7	6/45 = 0.1333
15	Repairability	*******	6	7/45 = 0.1556
16			45 total	SUM = 1.00

FIGURE 4.14: TRANSPORT MEDIA DECISION MATRIX TABLE.

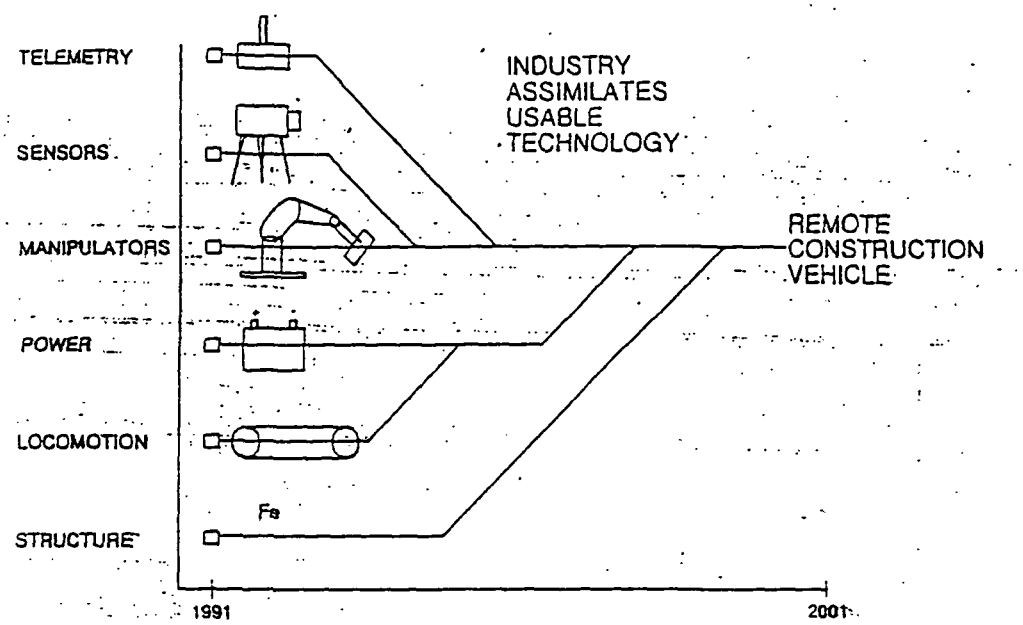
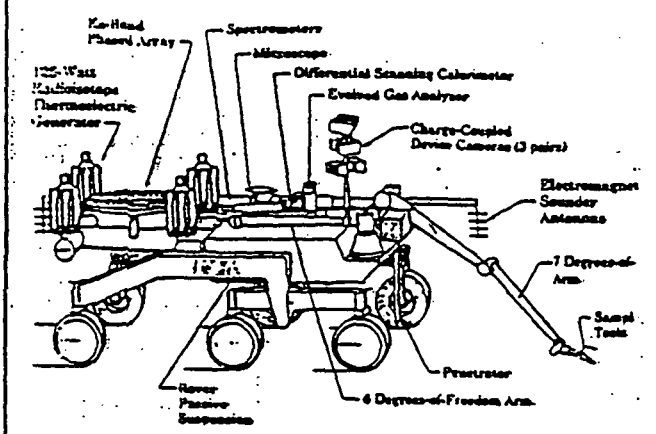
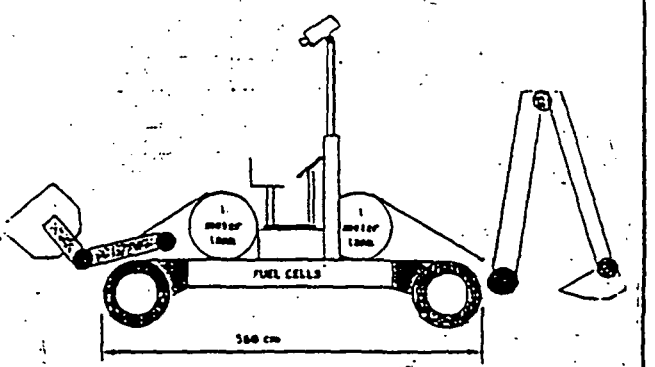


FIGURE 4.15: TECHNOLOGY PROGRESSION TIMELINE.



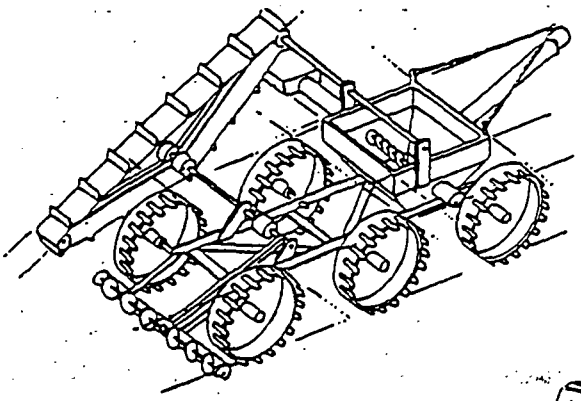
NASA 90-Day Study, November, 1989



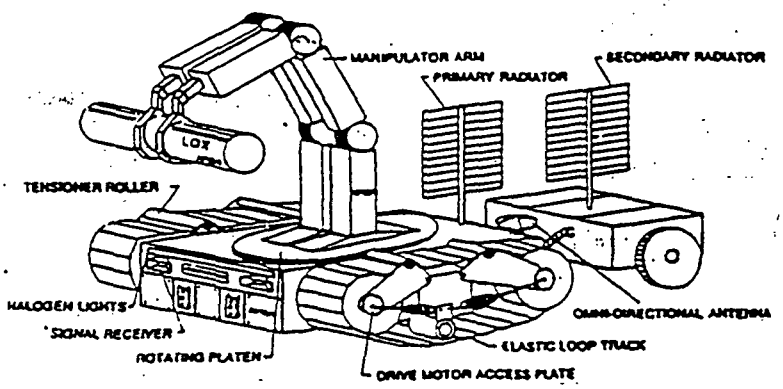
Combi for Space Construction, CSC System Cluster Report #18, University of Colorado, August 1990

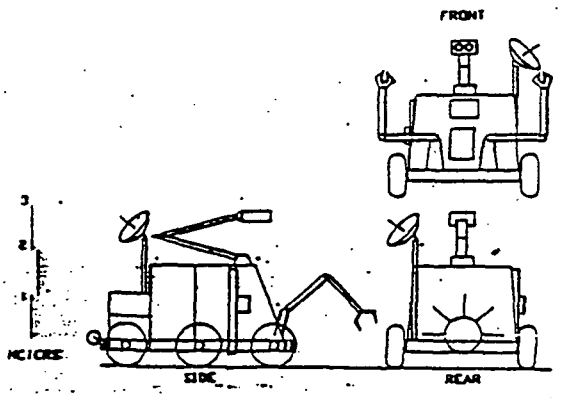
FIGURE 4.16: PROPOSED LUNAR ROBOT DESIGNS.

NASA Lunar Base Construction Team, "Lunar Outpost," Lyndon B. Johnson Space Center, Houston, TX, 8/89

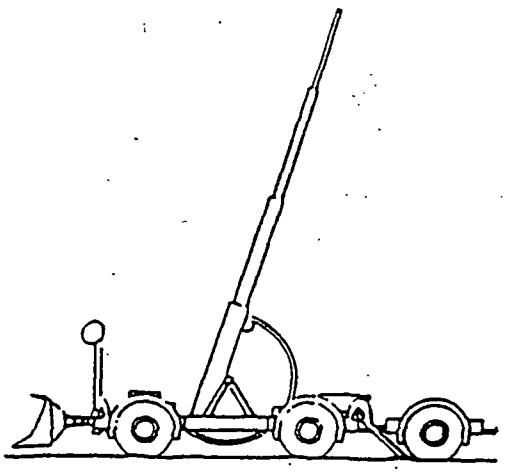


Old Dominion University, "Lunar Construction Utility Vehicle," July 1989





W. Feller, et al., "Cis-Lunar Space Infrastructure Lunar Technologies," University of Colorado, Boulder, Summer 1989



Center for Space Construction, CSC System Cluster Report #18, University of Colorado, August 1990

FIGURE 4.17: PROPOSED LUNAR ROBOT DESIGNS.

5.0 OVERALL CONCLUSION

By taking a careful look at the history of the Space Program and much of the literature that has been published in an attempt to remedy problems with it, the Spring and Summer1991 Space Habitation Class were able to make draw conclusions that directly affected our design methodology. These results were applied to four areas of the current Space Program, including Mission From Planet Earth, Mission To Planet Earth, Launch Systems and Technology Base. We selected a goal of a First Phase Implementation of a Lunar Base with a Bioregenerative Life Support System because it fit into and supported the overall Space Program. We then formed three groups, based on critical technologies identified in the reports we read, and also that had significant spin-off potential. These groups were Structures, Robotics and CELSS. Then the same methodology was used by each group: Identifying requirements, identifying options, conducting a trade based on these two and other new technologies, choosing a system and identifying critical technologies and their spin-offs. Phasing and synthesizing schemes were applied at each step leading to the design conclusions.

The Structures group outlined a launch scenario, and recommended an Inline Shuttle Derived vehicle for its heavy lift needs. In addition, requirements for transfer vehicles were determined and a terrain following navigation system was chosen for lunar landings. A dark polar sight was picked for the site of the base, and a SSF module with one all-purpose airlock and one scaled down airlock was selected as the first phase housing of the base. Lastly, design requirements and recommendations were made for communications, thermal control, safety, interior volume specifications, and nuclear power was chosen as the base power supply.

Because of the expense savings, earth applications, safety, and savings in launches, robotics was chosen as a key technology to investigate. General functions were examined based on tasks predicted as needed for our base design. The Robotics Group focussed on the set-up of a nuclear power generator, with an emphasis placed on the methodology for picking a manipulator for tele-operation from earth, including immediate applications this may have in industry.

The CELSS Group investigated the implementation strategy of phasing between a physical/chemical and bioregenerative life support system. Human requirements are met initially by a physical/chemical-bacteria system to attain a high degree of closure from the beginning. This is further improved by biological elements being phased into the system.

The advantages of this phasing process was explained, and the impact and challenges of each step outlined. Lastly, critical technologies such as Hydroponics and Lighting were also explored.

The benefits of our Lunar Base design include both short and long term returns (see Figure 5-1). In the near term, spin-off technologies from the base design can enhance U.S. economic prowess, inspire a revitalization of the educational system, especially in mathematics and sciences, and demonstrate the abilities of American engineering capabilities. Farther along, the base will represent the encouraging proof that human life can be maintained in a closed system far from earth. Also, the base will provide a platform for scientific observation, and a stepping ground of enabling technologies for other missions.

After the culmination of this semester's work, we have concluded that not only is the establishment of a First Phase Lunar Base with a Bioregenerative Life Support System in the next 25 years a challenging goal. but if the Nation and the Space Program truly maintain a commitment to this objective, it is a realistic one too.

Conclusion

The establishment of a 1st phase Lunar Base with a Bioregenerative Life Support System in the next 25 years is a realistic and challenging goal, with both long term and immediates returns.

Short term:

Spin-off technologies enhance US economic prowess

Educational inspiration, especially in mathematics and sciences

Demonstration of US engineering ability

Long Term:

Proof that Human life can be maintained far from the Earth

A platform for scientific observation

A stepping ground of enabling technologies for other missions

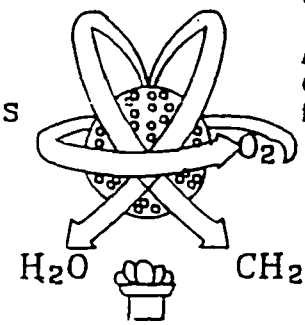


FIGURE 5-1 CONCLUSION

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