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EARTH TO LUNAR CELSS EVOLUTION

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INTRODUCTION

Three decades ago, humankind 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 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 student enrollment 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 forty-first shuttle mission in 10 years have just been completed. This accounts for 249 days in space, 128 days more than the total of the three Skylab missions (Garret, personal communication, 1991). Two scientific observatories, the Hubble Space Telescope and the Gamma Ray Observatory, have begun making observations, and the Magellan spacecraft is completing its mapping of Venus. The Galileo and Ulysses spacecraft are currently en route 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. 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 base and a 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 among 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 these patterns are indicative of the space program's funding (funding peaked at 0.8% of the GNP in 1969, and fell to 0.2% of the GNP in 1975, where it has leveled 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.

Many of the above problems can be remedied using 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 dispelling 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 timescales 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 Earth's system. However, to understand how CELSS can be used as an investigative tool, the concept of a CELSS must be clearly defined.

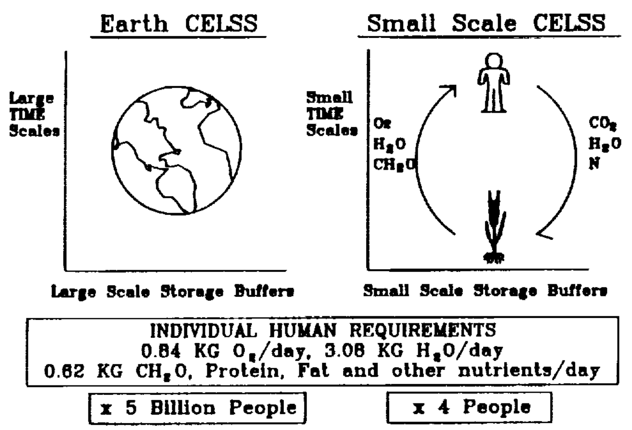

Fig. 1. Artificial ecosystems for space travel would operate on much shorter timescales and with much smaller buffer volumes than the only true closed ecological life support system, our planet Earth.

The best example of a CELSS is the one on 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 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 of other life forms, and vice versa (Fig. 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 timescales 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 nonbiological 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 that 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 LEDs, 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 does not 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 (Fig. 2). These functions can be defined as storage, monitoring, treatment, transport, collection, and use. For example, to maintain a chicken in CELSS, its 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.

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,

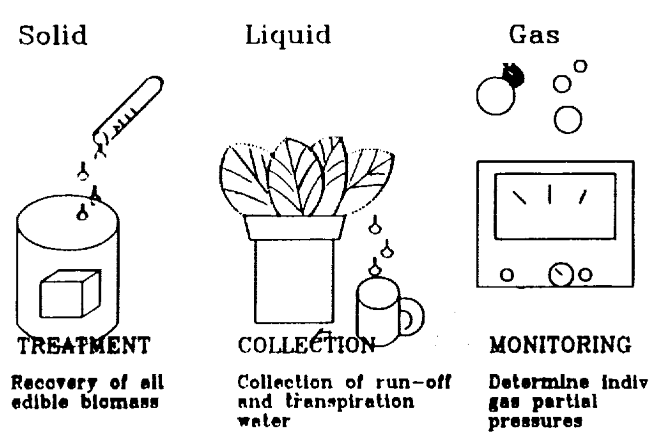

Fig. 2. Mass flows in a CELSS may be broken down into gaseous, liquid, and solid matter. For each loop, forcing functions move the matter between storage, treatment, collection, use, and monitoring locations.

contamination control, and conversion of all biomass into edible form must be overcome. But it is obvious that CELSS research has a tremendous potential to impact positively 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 weeks duration 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 U.S., 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 U.S. ranks behind other industrial nations in the average facility citizens have in mathematics and sciences. As during the Apollo program, this new initiative can inspire students to take an interest in these critical foundations of American education. Through development of a lunar base, a number of benefits 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 original 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 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 kilogram to the Moon can be estimated. Implementing a biological waste water treatment into an existing P/C resupply system alone reduces the cost from $22.6M to $3M for one person for two weeks.

Because of the merits of phasing described earlier, a phased implementation of biological elements was used, and a CELSS design group examined the strategy of phasing organisms into a baseline P/C system. All 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 control, 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 eliminate 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 needed to shelter and maintain it on the lunar surface. The first step is a CELSS for 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 recent droughts, leaving its water reserve at less than 20% of 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 this problem is already being addressed by a system that reuses all of the town's wastewater for municipal irrigation[(1)]. Currently, this critical area is being studied at Stennis Space Center: plants are used to recycle water and to remove air pollutants in the "BioHome" research project. A company in Boulder, Colorado, has already marketed and installed biological wastewater treatment systems (Purecycle) that recycle water in people's homes and have proven that the technology is achievable.

The major stumbling block for attaining a CELSS is closure. It is essential to CELSS research to be able 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 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 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, P/C systems are the technology used for total resupply missions such as 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 P/C systems fall short when considering safety and compatibility issues. For instance, the Sabatier CO_2

reduction process creates 0.33 kg of methane, a hazardous byproduct for plants and animals, per person/per day. P/C 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 used to reduce wastes in sewage treatment. For example, municipal sewage plants used 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, microorganism 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 turnaround 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 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 (Fig. 3). The *functional* level considers the inputs and outputs over an organism's 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 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.

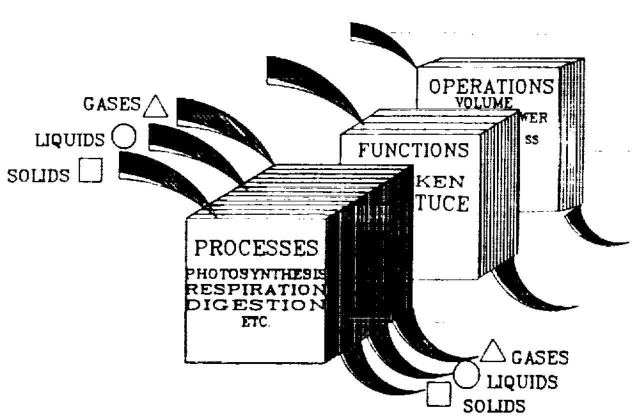

Fig. 3. A systems engineering approach, treating each organism as a "black box", has been chosen to describe and characterize possible candidates for a controlled ecological life support system.

Using 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. 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 from 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, 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 to ascertain the best candidate based on parameters like mass, power, volume, safety, cost, and reliability.

To achieve the goal of a lunar base with a CELSS 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 spaceflight they also implemented proven technologies, as well as using 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 is flexible to variable economic and political support. The approach that was determined for a lunar base was also a phased approach that 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 whether if the entire mission is realized or not.

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 (Fig. 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-

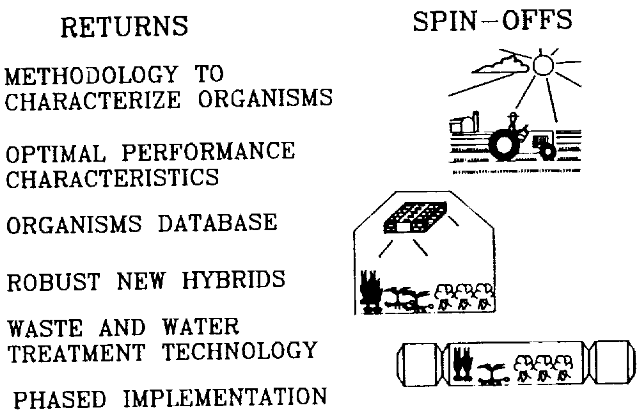

Fig. 4. Numerous spin-offs for Earth applications may be derived from CELSS research.

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 the Antarctic, desert and 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 P/C 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 P/C 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 Fig. 5.

In a previous design effort[(2)] 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 II 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 used to partially tend the CELSS, freeing astronauts to further pursue 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 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 CELSS, 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.

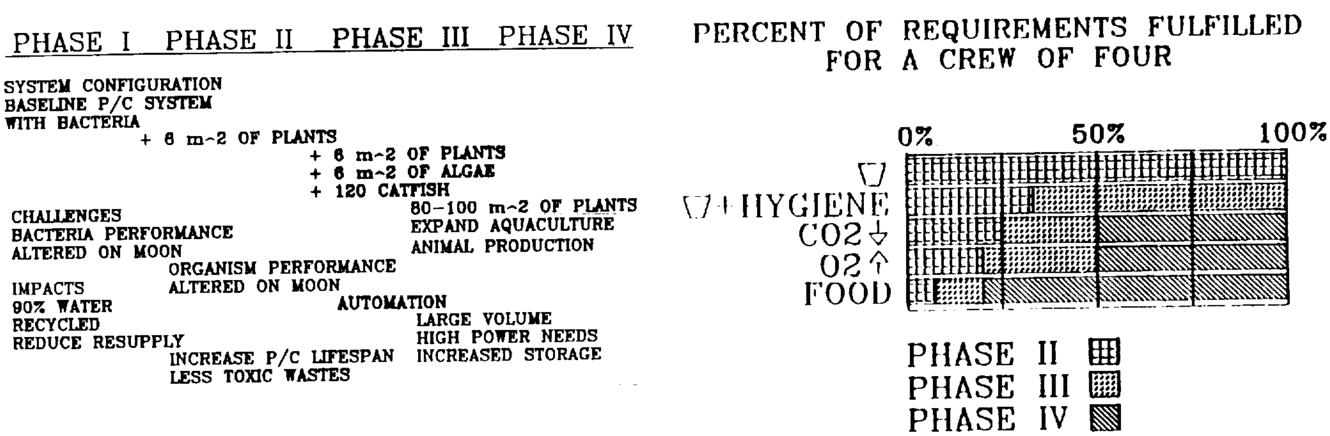

Fig. 5. Phased evolution of a balanced bioregenerative life support system. For each integration step, impacts on the existing life support system, as well as challenges, can be derived. The amount of consumables provided by the bioregenerative part of the life support system are shown for each phase.

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 used 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 used by the materials processing industry and others in which gas purity levels are important. The attainment 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 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 Table 1.

The third ground-based element needed is a small, self-contained power system 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 systems, and advanced methods such as solar windmills and the use of thermal gradients. Although RTGs have been used extensively for other purposes, the integration of hundreds of 500-W RTGs into a single power system would present a formidable challenge. The advanced methods are ruled out because there are 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 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 of 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, a nuclear reactor, like the SP-100, is the best alternative.

TABLE 1. Approximate volumes and facilities for a human habitat on the lunar surface for a crew of four.

Facilities	Volume (m^3)
Personal quarters	18.8
Galley	6.4
Hygiene/waste	4.5
Health maintenance	4.5
Dining/recreation	4.8
Data management/ com.	2.7
Exercise	varies
Maintenance	2.7
EVA storage	12.0
ECLS	9.5
Storage (90 days)	22.6
CELSS (through phase III)	15.2

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 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 use 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 use 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.

Once the ground-based phase has been completed (Fig. 6), 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 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.

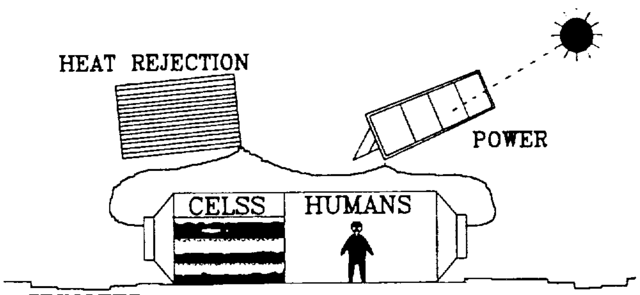

Fig. 6. Possible spin-off technologies from the ground-based research in CELSS infrastructure.

Some of the major threats to crew safety on the lunar surface include radiation, meteorite strikes, fires, loss of power, and illness or 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 90-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 these requirements and provide a constant thermal environment for the base, eliminating the expansion and contraction associated with thermal fluctuations. Since approximately 2% of the lunar surface (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 transmission 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 Mbps (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 that will in turn send the signal to an Earth receiving station.

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

The final infrastructure element needed for the space-based phase is a transportation system capable of transferring all the base elements to the lunar surface and placing the communication satellites in orbit. The most efficient method to achieve this is the use of a three-part system, using 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 HLV to be used is an inline shuttle-derived vehicle capable of delivering 95,000 kg to LEO, allowing an entire lunar mission to be delivered to LEO with only two HLV launches.

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 used 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 (Fig. 7). Due to workload and safety concerns, robots will be used 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

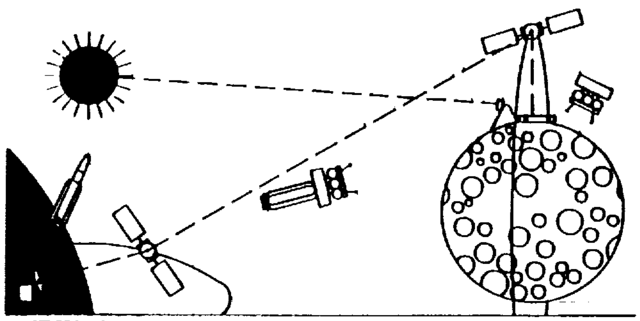

Fig. 7. The required lunar base infrastructure elements show high potential for Earth-based spin-offs.

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 hr of prebreathing and gearing. This time can be better used 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 codevelop robotics, costs can be further reduced, and benefits can be brought back to Earth.

Automation and robotics are a mechanical workforce designed for a wide array of tasks. In the last decade, the robot population has exploded to approximately 350,000 units worldwide[3]. Machine production industries control the largest share, with some automobile manufacturing corporations employing more than 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 extraterrestrial 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%[3].

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 Table 2. 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 Table 3. Likewise, a vital infrastructure requirement, retrieving cargo from a lunar lander, is developed in Table 4. 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

TABLE 2. Establishing a lunar base and maintaining a lunar CELSS requires many labor intensive tasks.

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

TABLE 3. Replacing a failed LED breaks down into specific labor and technology needs.

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

TABLE 4. Retrieving cargo sent from the Earth is a very labor-intensive, yet simple task.

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

needs. For redundancy and costeffectiveness, the components will be modular with respect to a central power and control unit, much like a tractor. So, in the tradition of Mr. Potatohead, the innovative MPH lunar robot (Fig. 8) was conceived.

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 Tables 5 and 6). 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 Table 7, 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.

Ongoing research and development will not only overcome some of these roadblocks, but will 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 has considerable implications for auto and aerospace industries. Developing titanium-aluminum alloys will reduce the mass of aircraft by 60%[6]. 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 industrial productivity and improved work safety and health with just a 0.02% increase in unemployment[7]. Currently, teleoperated robots are being employed for nuclear plant maintenance, offshore 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.

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

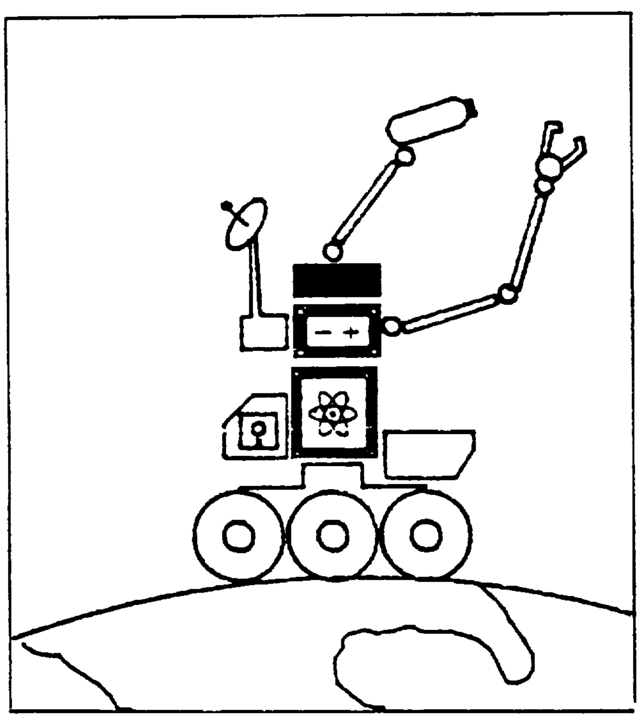

Fig. 8. The MPH lunar robot (Mr. Potatohead).

TABLE 5. The trade study of nuclear power generators[4] reveals DIPS as the economic technology choice. RTG: =Radio-Isotope Thermal Generator; DIPS = Dynamic Radio-Isotope Thermal Generator; P_{max} = peak electric power output.

Generator Type	P_{max} (kW_e)	P_{spec} (W_e/kg)	Efficiency (W_e/W_{th})	Lifespan (years)
RTG	0.5-5	5.2	4.2-6.6%	10
DIPS	1-10	>6.5	18-24%	7
Nuclear Reactor	0.5-1	80		

TABLE 6. 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 [5]. All other data[4].

Storage Type	P_{spec} (W_e-hr/kg)	Lifespan (years)
RFC	20-35	
Ni-Cd Battery	20	15-20
Ni-H_2 Battery	30	10-20
Pb-acid Battery	25	10-20
S-Na Battery	100	
Zn-air Battery	200	

TABLE 7. The MPH lunar robot can accomplish a variety of tasks with a small set of utility components.

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

and space shuttle environments to provide improvements during the second stage. The MPH will aid in the lunar site selection process, and three 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 database. From this knowledge, we may tackle a variety of other problems, such as using 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 the role of plankton 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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