LIFE SYSTEMS FOR A LUNAR BASE

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Biosphere II is designed to be a materially closed and informationally and energetically open system capable of supporting a human crew of eight. Currently under construction by Space Biospheres Ventures near Oracle, Arizona, Biosphere II is scheduled for full closure and an initial two-year operation with a crew of eight beginning in the fall of 1990.

INTRODUCTION

The Biosphere II project is pioneering work on life systems that can serve as a prototype for long-term habitation on the Moon. This project will also facilitate the understanding of the smaller systems that will be needed for initial lunar base life-support functions. In its recommendation for a policy for the next 50 years in space, the National Commission on Space urged, "To explore and settle the inner Solar System, we must develop biospheres of smaller size, and learn how to build and maintain them" (*National Commission on Space,* 1986). The Biosphere II project, along with its Biospheric Research and Development Center, is undertaking work to meet this need. In this paper we will give an overview of the Space Biospheres Ventures' endeavor and its lunar applications.

BIOSPHERE II: OVERVIEW AND SCALE

The total airtight footprint of Biosphere II is about 137,416 sq ft or 3.15 acres, with a volume of 7.2×10^6 cu ft (see Table 1). Of this area, the main structures of the Biosphere II, which house rainforest, savannah, desert, marsh, ocean, intensive agriculture, and human habitat areas, are 98,000 sq ft with a volume of 5.4×10^6 cu ft. On its longest side, it measures approximately 550 ft from the rainforest to the desert area.

TABLE 1. Dimensions of Biosphere II.

Area Footprints	Feet	Meters	Acres	Hectares
Intensive Agriculture	24,020	2,232	0.55	0.22
Habitat	11,592	1,077	0.27	0.11
Rainforest	20,449	1,900	0.47	0.19
Savannah/Ocean	27,500	2,555	0.63	0.26
Desert	14,641	1,360	0.34	0.14
West Lung (Airtight Portion)	19,607	1,822	0.45	0.18
South Lung (Airtight Portion)	19,607	1,822	0.45	0.18
Total Airtight Footprint	137,416	12,766	3.15	1.28

Volumes	Cubic Feet	Cubic Meters
Intensive Agriculture	1,336,012	37,832
Habitat	377,055	10,677
Rainforest	1,225,053	34,690
Savannah/Ocean	1,718,672	48,668
Desert	778,399	22,042
Lungs (At Maximum)	1,770,546	50,137
Total	7,205,737	204,045
Soil, Water, Structure, Biomass	671,635	19,019
Air	6,534,102	185,026

Two variable volume chambers, or lungs, will be sealed from the outside atmosphere and be continuous with the atmosphere of Biosphere II. These lungs cover 39,200 sq ft, with a volume of about 1.7×10 cu ft. Because air expands and contracts with changes of temperature, these increases or decreases in its internal air-volume pressure would cause the glass or seals to break due to differential pressure if such an expandable chamber were not provided.

Biosphere II will be primarily solar powered—in terms of solar radiation for photosynthesis. Electrical generation is primarily by natural gas, with diesel generators for back-up. Waste heat from the generators will be used to chill or heat water used for temperature control, thus reducing resource needs by about 20%.

The hydrosphere of Biosphere II will contain approximately 1.3×10^6 gal of water, 1.1×10^6 in the ocean area and about 200,000 gal of freshwater. In Biosphere II the surface proportion of ocean to land will be 15:85. The productivity of Biosphere II's marine systems is expected to be high because coral reef and marsh ecosystems are included.

Logistical constraints, e.g., the collection or acquisition of full-sized plant specimens, dictate that the plant biomass at the commencement of closed-system operations will be considerably less than those anticipated at equilibrium. To accommodate the transformation of this immature, or growing, system requires the provision of reservoirs of material for uptake and conversion to organic tissue during this equilibration of the system.

The anticipated equilibrium biomass of Biosphere II is 70 tons. With a relatively small mass of atmosphere, hydrosphere, and geosphere to act as buffers, the biogeochemical cycles will operate rapidly (see Table 2). For example, CO_2 will cycle daily compared to an estimated cycle in our global biosphere of 10 to 12 years. The persistence of biospheric systems will be measured in numbers of the various cycles it sustains, as well as in calendar years. The percent availability of elements in the biotic cycle and their distribution in component parts will be important measurements, as this has been a major concern in previous closed ecological systems (*Hanson,* 1982; *Starikovich,* 1975; *Fong et al.,* 1982).

TABLE 2. Atmospheric system of Biosphere II.

	Pressure			Total Mass
	MM-HG	PSI	KPA	Kilograms
Oxygen	136.1	2.63	18.13	31,800
Nitrogen	507.6	9.82	67.67	103,775
Carbon Dioxide	0.21	0.004	0.028	67
Water Vapor	13.4	0.26	1.79	1,761
Argon	6.1	0.12	0.83	1,782

Pressures do not total standard 760 mm Hg or 14.7 psi because at 3900′ elevation at project site, atmospheric pressure is about 663 mm Hg (18.8 psi).

BIOSPHERIC DESIGN: INTERPLAY OF BIOMES

In designing man-made biospheres for stability, diversity, and persistence, biomes have been used as the key structural elements. The term "biome" is here used in a sense analogous to its usual definition in global ecology: "the biota are organized into geographically distributed classes called biomes, which are types of ecosystems" (*National Research Council,* 1986); or systems ecology: "Regional climates interact with regional biota and substrate to form layers, easily recognizable community units ... in a given biome the life forms of the climatic climax vegetation is uniform" (*Odum,* 1971). The biomes, or major ecosystem areas, of Biosphere II will be controlled to different temperature and humidity regimes, and be dominated by characteristic vegetation and soil types as are the natural biomes of the Earth. The biomic areas of Biosphere II interact in its gas and mineral cycles.

In Biosphere II there are seven biomes, five modeled on wilderness biomes (rainforest, savannah, desert, marsh, and ocean) and two modeled on the major anthropogenic types of land use (intensive agriculture and human habitat) (Figs. 1 and 2). All the biomes are tropical. With the project's location in southern Arizona with its mild winters, hot summers, and great year-round sunshine, to do otherwise would have incurred a great price in energy required for cooling. The selection for various analog Earth biomes for the areas in Biosphere II has been coupled with the inclusion of species that can play a role in providing food, fiber, pharmaceuticals, and aesthetics, as well as functioning in the maintenance of atmosphere and completion of natural cycling processes. Indicator species are also included to assist in monitoring key variables such as pH, temperatures, and trace gas contaminants.

The tropical rainforest structure is approximately 90 ft tall. From the "cloud forest" ecosystem a stream flows down a waterfall, across the forest floor, and into the adjoining savannah. Dr. Ghillean Prance, now director of Kew Gardens, and the Institute of Economic Botany, New York Botanic Garden, were the rainforest design consultants. The Amazon rainforest was used as the analog for Biosphere II. Design of such a small area to provide the function and long-term genetic viability of a rainforest parallels important questions of research in the planet's rainforests (*Myers,* 1979).

The stream then flows through the savannah biome located at the top of rock cliffs. The savannah biome will include several habitat areas: a gallery forest, grassland, and a periodically flooded ecosystem. Dr. Peter Warshall of the Office of Arid Land Studies, University of Arizona, designed the savannah using plant species from Africa, Australia, and South America. The savannah will house about 150 species and 5000 organisms at closure, not including termites and other arthropods. The thorn scrub forest marks the ecotone or transition area between the savannah and the desert biome.

Next, the stream enters the marsh biome, which includes a freshwater area that grades up in salinity to a saltwater marsh. This estuarine marsh is modeled after the Florida Everglades. The oceanic system is 25 ft at its deepest point and includes a coral reef ecosystem and lagoon at one end. Wave action, required for the ecological maintainance of the coral reef, will be supplied mechanically through vacuum pumps. Dr. Walter Adey of the Marine Systems Laboratory, Smithsonian Institution, is design consultant for the marsh and ocean systems.

The desert biome is patterned after a coastal fog desert, such as the Vizcaino Desert in Baja California, and is populated with species adapted to low rainfall but high humidity. Dr. Tony Burgess of the Eco-Hydrology Project, USGS, Tucson, desert biome consultant, has designed five major habitat regions in this biome that will provide econiches for about 100 species, and a population that will vary between 50,000 individuals in the flowering season of the desert annuals to 900 individuals during the desert's inactive season.

The atmosphere is one continuous system throughout Biosphere II. Air circulation will be accomplished by convection and by technical means. Differences in elevation, temperature, and in some cases structural, diversions of air-flow have been built into the design. Air circulation is an important factor in pollination for those plants that utilize wind pollination, and air circulation sometimes affects the extreme temperatures some species can tolerate. Air handling units in all the biomes will ensure the circulation of air and coupled with heat-exchange water systems can provide cooling or heating as required.

The white steel-clad space frame domed building, the human habitat, is analogous to an urban center, and will include apartments, laboratories, computer and communications facilities, workshops, libraries, recreation, and similar facilities for the eight resident researchers. The human habitat is designed to be fully informationally linked to the outside via computer teleconferencing, television, video, radio, and telephone. A mission control building overlooking the project will receive data coming from the more than 2000 sensors inside Biosphere II. In addition,

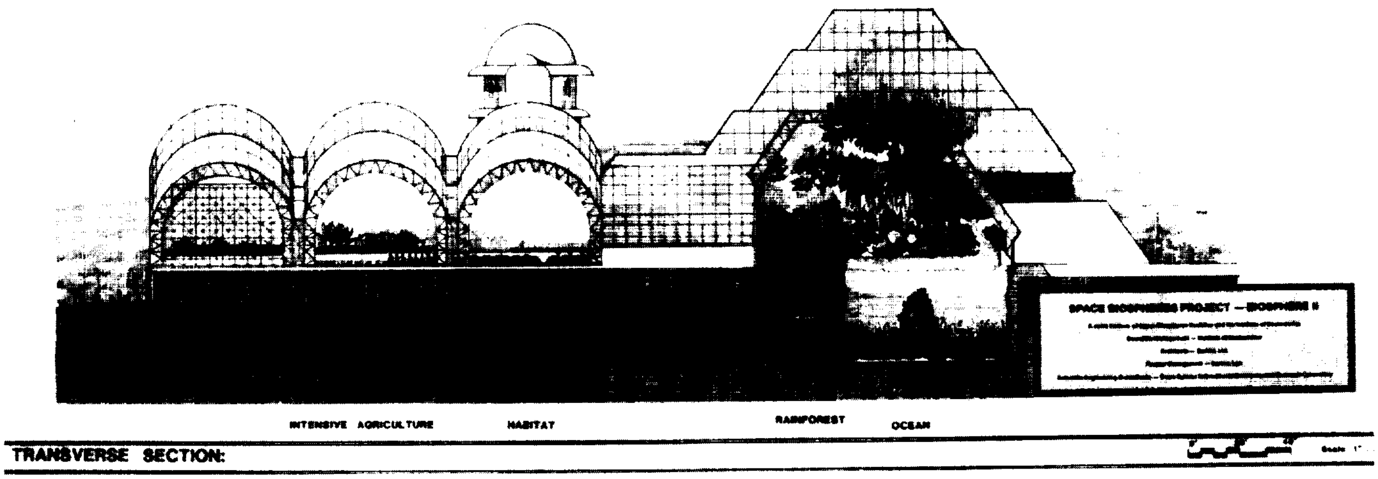

Fig. 1. Design drawing of Biosphere II showing intensive agriculture area (with rounded barrel vault roof), habitat, rainforest, and ocean.

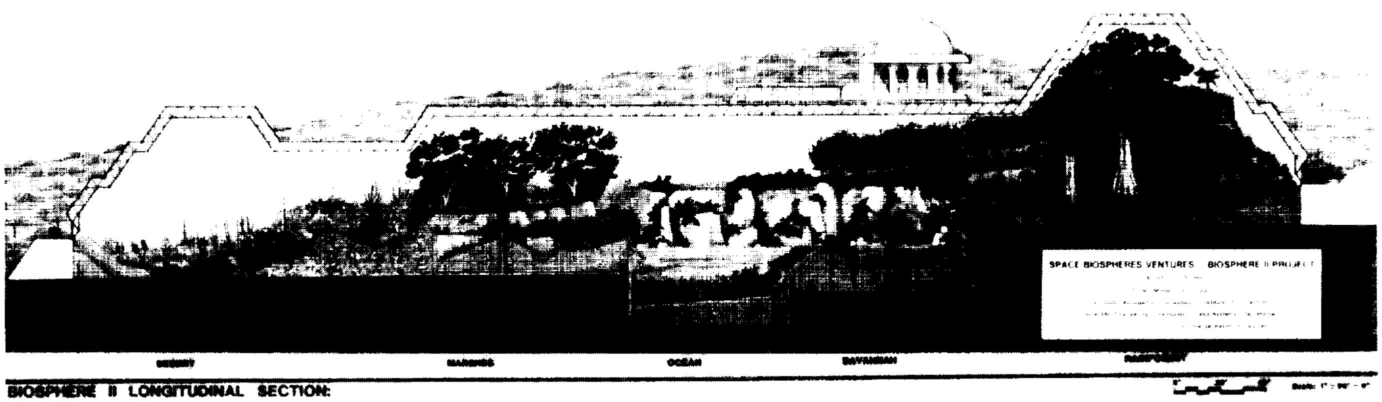

Fig. 2. Cross-sectional view of Biosphere II rainforest, savannah, desert, marsh, and ocean areas. Dome of habitat protrudes to the west of these "wilderness biomes."

cooperating research centers can be networked, beginning with those currently working on the project, permitting data assessment for evaluation and management of this project, and for comparative studies of global functioning.

Adjacent to the human habitat is the intensive agriculture area. Some 50 species and 150 cultivars will be grown, with about 30 in cultivation at a time. Near the broad terraces of plant crops are animal areas for chickens, pygmy African goats, and Vietnamese pot-bellied pygmy pigs. The aquaculture system contains tilapia fish and biofilters where naturally occurring microbes convert the ammonia of fish waste into nitrates. The aquaculture water is coupled with rice production bays and supports algae and the waterfern Azolla, for fish and animal feed. The Environmental Research Laboratory of the University of Arizona, directed by Carl Hodges, serves as design consultant for the intensive agriculture as well as working on aspects of the project's scientific engineering. Since Biosphere II is materially closed, the intensive agriculture area will produce all of the food required for eight people, year round (*Hodges,* 1987).

Together, the intensive agriculture and human habitat systems could serve as a prototype for short-term space life-support systems such as on a microgravity space station or for early stages of the lunar base.

Besides domestic animals, Biosphere II will be habitat for various birds, reptiles, amphibians, small mammals, insects, and other invertebrates. Biomic design work has included mapping food webs, including provision of alternative pathways and redundancy, and study of individual behavior patterns to provide sufficient food and habitat to support the animal species without endangering other populations. This evaluation will also ensure that ecological functions such as nutrient recycling and pollination are fulfilled.

Collections are underway for the plant, fungus, and insect and other arthropod species selected for inclusion in Biosphere II at closure in 1990. Collections have or will be made in Guiana, Colombia, Baja California, the Everglades, Australia, Africa, and Puerto Rico. A diverse collection of mature rainforest species has also been donated from the Missouri Botanical Garden Climatron. Plants are transplanted or propagated from seed, cuttings or tissue culture, and cultivated in greenhouses to acclimate and reach the desired state of maturity before being transplanted to Biosphere II. An insectary is presently under construction to house and propagate many of the 250 insect species currently planned for the project. The Bishop Museum Department of Entomology, under direction of department chairman Dr. Scott Miller, has been contracted for selection of species, and design of maintenance and monitoring.

BIOSPHERIC RESEARCH AND DEVELOPMENT CENTER

In preparation for the construction of Biosphere II and to facilitate applications of ecological life-support systems for space environments, Space Biospheres Ventures (SBV) has set up the Biospheric Research and Development Center. In full operation at present, this research and development complex includes the SBV Plant Tissue Culture Laboratory, Analytical Laboratory, 17,000-sq-ft. Experimental Intensive Agriculture greenhouse for horticulture, animal husbandry, and aquaculture, the 17,000-cu-ft Biosphere Test Module, and four quarantine and accession greenhouses for the collection and propagation of plants destined for Biosphere II. This complex also serves as a training facility for "Biospherians," prospective candidates for the crew of Biosphere II.

In the Experimental Intensive Agriculture greenhouses, research on cultivar selection and production, nutrient recycling, waste treatment, composting, and harvesting methods is being conducted (Fig. 3). Several cultivation methods have been tested, including soil- and compost-based systems, as well as hydroponics and aeroponics. Biosphere II will use a soil medium for plant cultivation and air purification by pumping air through the cropping areas.

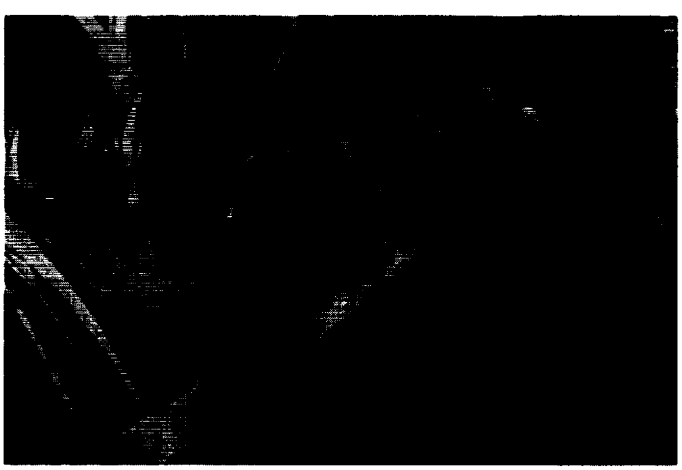

Fig. 3. View of some of the crops in the prototype intensive agriculture research area at the Biospheric Research and Design Complex at Space Biospheres Ventures.

The aquaculture system is designed to produce two meals of fish per person per week. The water from the aquaculture is applied to crops. After being filtered through the soil, the water is returned to the fish tanks. The fish eat water ferns, algae, roots of aquatic plants, and food grown in the greenhouses.

A primary function of the agriculture system is to establish a diverse soil community that will include rich microbial assemblages and invertebrate fauna, functioning to maintain the cycling of nutrients through the system. These biological systems will also be important to the purification of the atmosphere from potential toxic buildups through their use as soil bed reactors through which the entire air volume of Biosphere II can be pumped.

Screening of potential crop plants from around the world is currently underway. Production of edible and total biomass, ease of harvest and processing, toleration of environmental variance and ability to intercrop are being assessed. Some of the crops currently being grown in the Experimental Intensive Agriculture are rice, sorghum, alfalfa, soybeans, cowpea, wheat, potato, tomato, papaya, banana, and sweet potato. Small patches of each crop are used, thus rotating the harvest schedule in order to minimize the perturbation of the system at any given time.

No chemical pesticides have been used in the agricultural greenhouses and they will not be employed in the Biosphere II agricultural system. Rather, an integrated pest management system has been developed for the exclusion, resistance to, and avoidance of pests and pathogens. Biological, mechanical, and cultural controls are all employed.

SBV PLANT LABORATORY

The SBV Plant Laboratory conducts plant tissue culture work for Biosphere II, for propagation of endangered species, and for commercial agriculture and nurseries. Tissue culture allows the rapid propagation of plants from a very small piece of meristem tissue material, and enhances the ability to select for desired characteristics, such as resistance to pests or disease. This technique can provide a large genetic reservoir for Biosphere II and other closed systems in a relatively small area.

The Plant Tissue Culture Laboratory at SBV is currently concentrating on two orders of the plant kingdom: the Lilliales, and the Zingiberales. The techniques developed in micropropagation of a diversity of life forms can be used in the export of plants from Earth to minimize weight and volume requirements for the innocula of space and lunar life systems.

BIOSPHERE II TEST MODULE

The Biosphere II Test Module, approximately 27×27 ft in area and 17,000 cu ft in volume (including its lung), was constructed to test constructioon and sealing techniques, cooling and computer monitoring, and data acquisition systems. The chamber construction is spaceframe and glass, with a stainless steel liner to seal the system from the underlying soil (Fig. 4).

The Test Module is now being used for closed ecosystem experiments with plants, soils, and insect populations to test generation and maintenance of atmospheric gases, plant growth, photosynthetic efficiency in closed systems, and overall system dynamics. Observation of pollination and behavior of potential pests and pathogenic factors in closed ecological systems has also been conducted in the test module. The facility is the largest materially closed system in operation in the world.

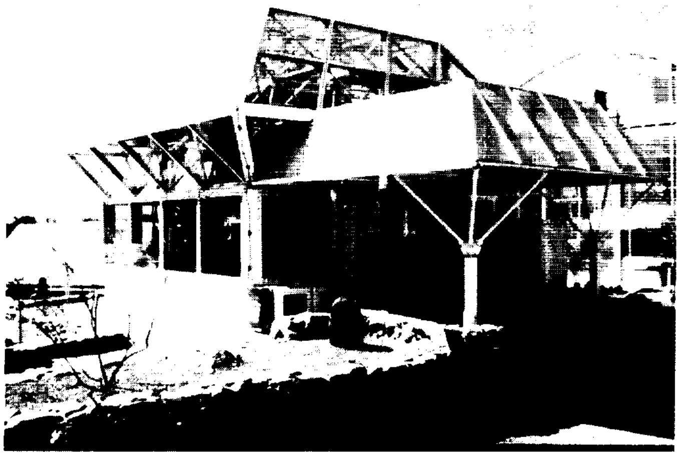

Fig. 4. The Biosphere II Test Module, which is 12,800 cu ft of volume in the biochamber. When the variable volume chamber is included, the total is about 17,000 cu ft. Experiments have been conducted in it since January 1987, and are ongoing, including human closed ecosystem work.

In operation since January 1987, current experiments include studies of plants representative of the planned ecosystems of Biosphere II, soils and soil fauna, and insect populations sealed for up to three-month periods. During these experimental closures, internal computer sensors continuously monitor O and CO_2 and regularly sample other atmospheric gases for evaluation via gas chromatography. Trace gases are being measured in parts per billion.

There are continuing studies on the biomass of primary producers and consumers, pollen dispersal, and pollination success under conditions of high humidity and low air circulation, and microbial function analysis and optimization of light availability.

Another series of experiments is exploring the maintenance of air quality through the use of microbial and biological systems. Research has demonstrated effective removal of ethylene, methyl mercaptan, methane, carbon monoxide, and other trace gases (J. Allen and coworkers, unpublished data, 1988; *American Conference of Industrial Hygienists,* 1987).

Human experiments in the Test Module have included a three-day closure in September 1988, both preceded and followed by a period of closure without the person inside, a five-day closure in March 1989, and a 21-day human closure in November 1989 (Fig. 5). These were the first closed ecological systems experiments to include complete waste recycling as well as food production and air and water regeneration using bioregenerative methods.

HISTORY OF BIOSPHERIC SYSTEMS

Biospherics, or the science of biospheres, is a young discipline. The term biosphere was first used by Eduard Suess in 1875 (*Hutchinson,* 1970), and the scientific concept developed by Vladimir Vernadsky since the mid 1920s (*Vernadsky,* 1986). The first laboratory-sized closed ecologial microbial systems date from 1967 in the work of Clair Folsome at the University of Hawaii, Basset Maguire at the University of Texas, Frieda Taub at the University of Washington, and Joe Hanson at the Jet Propulsion Laboratory (*Folsome and Hanson,* 1986; *Maguire,* 1978; *Taub,* 1974). At the Second International Workshop on Closed Ecological Systems held at Krasnoyarsk and Shushenskoye, Siberia, in September 1989, which was attended by scientists representing research in the field from the U.S., Europe, and the U.S.S.R., it was resolved that the term "biospherics" be used for the study of essentially materially closed ecological systems, which include planetary biospheres (the Earth's), man-made biospheric systems, fully or partly closed CELSS facilities, and laboratory ecospheres.

The most advanced work in the field before Biosphere II was conducted by Josef Gitelson and his team at the Bios-3 facility, Institute of Biophysics, Krasnoyarsk, Siberia. There, crews of two and three people operated a system some 300 cu m in volume for periods up to six months, recycling 100% of the air, 95% of the water, and producing about 50% of their food. This was the first time that men and higher plants were linked in an ecological system closed to this extent. Because of the low diversity of their system, organic trace gases had to be oxidized in a catalytic burner and the plants experienced problems. The solid waste materials of the people were not included in the cycling (*Gitelson et al.,* 1973).

Much has also been learned from Controlled Ecological Life Support Systems (CELSS) research underway in the U.S., U.S.S.R., and Japan. Ongoing research, such as the Kennedy Space Center Breadboard project will provide data in a field of extreme importance for the development of long-term bases on the Moon and elsewhere (*Averner et al.,* 1987).

Recent experiments in the Biosphere II Test Module, including the human and closed ecosystem experiments, have successfully tested the ability of such systems to perform complete recycling, and have confirmed computer modeling and predictions of systems dynamics based on earlier experiments.

LUNAR BASE MODULES

Space Biospheres Ventures is designing lifesystem configurations for microgravity and surplanetary bases. For permanent habitation, including the psychological health of the people, these systems are designed on a biospheric basis. This will ensure ecological stability and evolutionary potential, as well as offering its human inhabitants what Earth's biosphere provides: a place of relaxation and beauty. "Humans have evolved in the context of a biosphere—surrounded by the beauty, the diversity, the vitality and the mysteries of nature. Our future in space will depend both

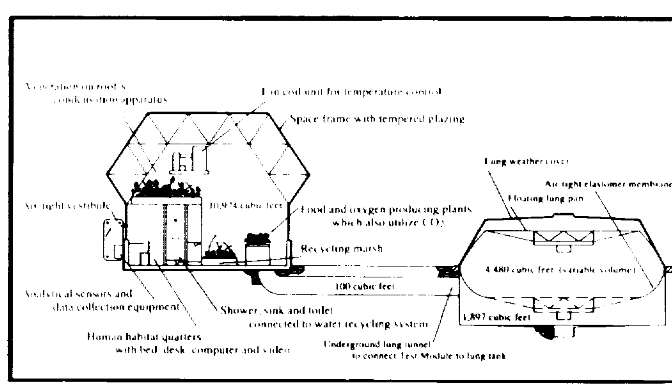

Fig. 5. Configuration of Biosphere II Test Module for Human and Closed Ecosystem experiments in September 1988, March and November 1989.

physically and psychologically on habitats that provide not only air, water and food, but also a stimulus to wonder and to learn, to participate in the sphere of life of which we are a part" (*Augustine,* 1987).

Initial steps in the creation of ecological life support capabilities for a lunar base will involve minimalist systems of the same order of magnitude as the Biosphere II test module. One scenario would see the use of the lunar landing vehicles as providing a nucleus area for the starting life support system. Subsequent landings could bring additional plants and genetic materials as well as processing tools and equipment for the utilization of lunar mineral resources, transformation of lunar regolith into soil, and liberation of useful elements such as oxygen.

These early and even temporary life support systems might not be totally materially closed. Purification and recycling of air and water and at least partial production of food requirements would be high priority tasks.

Current Soviet research on plants in lunar light cycles indicates that utilization of the natural 14-day light and dark cycle is feasible for adequate plant yields of tested crops (*Lisovsky,* 1987); however, utilization of artificial lighting will optimize use of plant-protected growing areas.

Such a lunar base will be designed as modular components, to be expanded progressively over time. The complete complex would include four units radiating outward and connected to a central "commons" area. Each of the four units would support six to ten people and could be oriented to provide various functions for the operation of the overall lunar base and its eventual expansion into additional biospheric units. These functional orientations would include transport, biological systems, mining, and processing operations. Each lunar complex might cover 12.5 acres, be 40×10^6 cu ft in volume, with an average height of 85 ft (*Allen and Nelson,* 1989).

All the biospheric units would be stocked with atmospheric gases derived as much as possible from the surrounding environment. Once operation of these lunar biospheric systems commences, further cycling of elements will be accomplished by microbe/fungus/plant/animal metabolism just as in the Earth's biosphere.

SUMMARY

Space Biospheres Ventures is developing project laboratories through its Research and Development Center and Biosphere II for the study and application of closed ecological systems. This research can play an important role in designing life support systems for initial and later configurations of lunar bases.

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