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Closed Ecological Systems, Space Life Support and Biospherics

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Abstract This chapter explores the development of a new type of scientific tool – man-made closed ecological systems. These systems have had a number of applications within the past 50 years. They are unique tools for investigating fundamental processes and interactions of ecosystems. They also hold the potentiality for creating life support systems for space exploration and habitation outside of Earth's biosphere. Finally, they are an experimental method of working with small "biospheric systems" to gain insight into the functioning of Earth's biosphere. The chapter reviews the terminology of the field, the history and current work on closed ecological systems, bioregenerative space life support and biospherics in Japan, Europe, Russia, and the United States where they have been most developed. These projects include the Bios experiments in Russia, the Closed Ecological Experiment Facility in Japan, the Biosphere 2 project in Arizona, the MELiSSA program of the European Space Agency as well as fundamental work in the field by NASA and other space agencies. The challenges of achieving full closure, and of recycling air and water and producing high-production crops for such systems are discussed, with examples of different approaches being used to solve these problems. The implications for creating sustainable technologies for our Earth's environment are also illustrated.

Key Words Life support • biospherics • bioregenerative • food • air • water recycling • microcosm • closed ecological systems • Bios • NASA • CEEF • Biosphere 2 • BIO-Plex.

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1. INTRODUCTION

In the past few decades, it has become clear that our increasingly technological civilization is coming into greater conflict with the world of life, the biosphere of planet Earth. The modern technosphere is impacting adversely both vast areas of regional ecosystems and the reservoirs of the global environment, which we now appreciate are the life support systems for humans and all living creatures. The necessity to apprehend the laws of development of the biosphere (as a single whole) and for the human civilization to join it harmoniously is becoming more and more obvious and pressing.

It should also be clear that while we must study the biosphere, we have no right to conduct experiments that will endanger it. However, these researches can be done with small models, i.e., with artificial ecological systems. A new type of scientific object of study: Materially-closed ecological systems (CES) with different degrees of complexity and closure have emerged in the past half century coinciding with the advent of spaceflight. On such model ecosystems we can (and must) study both the particular laws of development of individual elements and components of the ecosystems, and the general regularities in the development of the entire biotic turnover. A new scientific discipline, Biospherics (biospherology), is being formed (1, 2). It is an integrative discipline, drawing on a number of fields of study, from biology, physiology, ecology, microbiology to engineering and social sciences. It is allied with ecological engineering in that engineering and ecology are brought together with the intent of maximizing natural ecological functions for achieving goals and solving environmental problems. Biospherics has the potential to develop the scientific basis for harmonizing the relationship of humanity, technology, and nature, and to open the path to the noosphere (the sphere of intelligence). Artificial ecological systems, from simple laboratory microsystems to more sophisticated human life-support systems (LSS) under extreme conditions on Earth and in Space, are one of its principal objectives. Biospherics is international in its scope and must be multi-disciplinary, using the achievements of many individual sciences. To design, construct, and study artificial "biospheres," it is necessary to intelligently design and manage the biogeochemical flows of matter and energy, to use sophisticated technologies and computer/information systems, to incorporate the achievements of genetics, biotechnology, and bioengineering and to make use of time-tested and reliable natural ecological mechanisms.

The needs of the current stage of development of civilization in the field of biospherics:

1. To create working models of the Earth's biosphere and its ecosystems and thus to better understand the regularities and laws that control its life. This is especially important because the Earth's biosphere is presently under ecological stress on a global scale.
2. To create artificial biospheres for human life support beyond the limits of the Earth's biosphere. These are essential for permanent human presence in space.
3. To create ground-based life-support systems that provide high quality of life in extreme conditions of the Earth's biosphere, such as polar latitudes, deserts, mountains, underwater, etc.
4. The use of artificial ecological systems offers the prospect of developing technologies for the solution of pollution problem in our urban areas and for developing high yield sustainable agriculture.

One of the principal motivations behind the creation of systems which are isolated from the general environment of Earth is to learn how to make life support systems and artificial biospheres that can regenerate, reuse, and recycle the air, water, and food normally provided by the Earth's biosphere. This is essential if we are to live outside the support of Earth's biosphere, rather than just travel in space.

Research and technological developments of these biological life support systems have enormous interest and relevance to sustainability in the environment on Earth. The conversion of natural ecosystems to agricultural areas, the loss of biodiversity, and the depletion of resources worldwide have raised questions concerning the increasing loss of life support capability for the biosphere as a whole and the impacts of the loss of ecosystems and species. The increased awareness of the ecological challenges facing humanity has led to a dramatically changed perspective of how we should regard our global biosphere. These perspectives and the focus on sustainable ways of living on the Earth have direct parallels with the challenges of developing closed ecological systems and bioregenerative life support technologies for space applications. In closed ecological systems, the emphasis is on recycle and reuse and not on the supply of new life support essentials. Research with materially closed ecosystems can thus help with the paradigm change from the destructive behaviors associated with the mindset of "unlimited resources" to that of conserving, recycling, and sustainably operating (1).

Calculation of the amount of material (air, water, food) needed for human life support is essential for cost benefit analysis, trade-off studies and the determination of when bioregenerative systems for spacecraft and space stations are advantageous compared with the approach used to date in space: Physiochemical technical systems and water, air, and food from stored supplies and resupply from Earth.

Such calculations are difficult and have yielded quite differing results. Requirements for food will vary depending on the weight and metabolism of different individuals; and water usage also depends on many factors. Furthermore, calculations based on terrestrial experience may differ from those encountered in the reduced gravity of space. Such studies have concluded that "in the course of a year, the average person is calculated to consume food three times his body weight oxygen, four times his weight, and drinking water eight times his weight. Over the course of lifetime, these materials would amount to exceed 1,000 times an adult's weight" (3).

The implications of these calculations are clear: Extended, and certainly, permanent human presence in space makes necessary "closing the loop" in the regeneration of air, food, and water involved in human life support (Table 11.1).

2. TERMINOLOGY OF CLOSED ECOLOGICAL SYSTEMS: FROM LABORATORY ECOSPHERES TO MANMADE BIOSPHERES

The emerging science of biospherics deals with the functioning of a variety of ecological systems which vary in size, degree of material closure and complexity as measured by size and complexity of their internal ecosystems. The following review of terminology for constructed (synthetic) ecosystems was reached among some of the leading researchers in the field at the

Table 11.1
Inputs required to support a person in space (1)

Inputs	1 day (kg/person)	1 year (kg/person)	Lifetime (kg/person)
Food (dry)	0.6	219	15,300
Oxygen	0.9	329	23,000
Drinking water	1.8	657	46,000
Sanitary water	2.3	840	58,800
Subtotal	5.6	2,045	143,100
Domestic water	16.8		
Total	22.4		

Second International Workshop on Closed Ecological Systems held at Krasnoyarsk, Siberia, in September 1989 (4, 5).

2.1. Materially-Closed Ecospheres

Folsome and colleagues pioneered small laboratory-sized systems (generally 100 ml to 5 l flasks), which differ from ecological microcosms and mesocosms is that they are essentially materially-closed (less the leak rate) (6–8). By contrast, ecological microcosms/mesocosms (the miniaturized ecosystems that ecologists use) are not completely isolated and were developed to permit study in the laboratory of small ecosystems taken from or imitating natural ecosystems (9). These ecological micro- and mesocosms are open to interchange with the surrounding air, and generally require inputs of nutrients and water to replace those lost by evaporation. Folsome, therefore, saw his laboratory flasks as heralding a new type of object – the materially-closed ecosystem. To differentiate these laboratory-sized systems from systems large enough to provide human life support, we can call them “materially-closed ecospheres.” They are open to energetic input (indirect sunlight or artificial lighting) and information exchange (monitoring, sensors, and observation).

2.2. Bioregenerative Technology

Technology capable of providing life support resources (food, air, water) that use biological mechanisms, even if enhanced and supported by other technology, may be termed “bioregenerative technology.” Examples are plant growth chambers in which a particular crop is grown that regenerates part of its atmosphere, purifies some quantity of water through transpiration, and produces food; or a wastewater processing unit in which aquatic plants and microbes digest sewage or graywater, producing biomass/edible crops as well as air and water regeneration. Bioregenerative technologies are crucial components of both CELSS and closed ecological life support systems.

2.3. Controlled Environmental Life Support Systems

All systems designed for space life support will rely on technology as well as biology – for controlling temperature, pumping air and water, processing food, etc. Such life support systems, only partially bioregenerative, use physiochemical means of handling wastes and producing required food, air, and water. Hence, for short-duration missions and early phases of developing space life support systems when CELSS-type systems are used, some food, air, and water will be carried from Earth or stored as a backup for emergencies or failure of other regenerative systems. CELSS provide the desired range of temperatures, humidity, carbon dioxide, pH, nutrient solution (most CELSS systems have used hydroponics as the plant-growing technology), and a high intensity of artificial lights for maximal crop performance. However, a portion of the necessary life support materials may be provided by stored supplies and/or physiochemical methods of recycling or cleanup (e.g., lithium hydroxide canisters for CO_2 removal, catalytic oxidizers for trace gas metabolism, or vapor compression distillers and membrane technology for water revitalization) rather than using only biological methods for their uptake and regeneration.

2.4. Closed Ecological Systems for Life Support

A life support system that approaches complete internal sustainability and which is biologically-based is termed a closed ecological system, meaning that it is essentially materially closed, energetically and informationally open, and recycling its major elements and nutrients. Both the CELSS and Closed Ecological Systems have generally included just a few species of plants and/or algae as their biological component, in addition to the crew compartments and associated mechanical/computer operational technologies. Energetically, such a system must be open or it would decline due to increasing entropy. The light needed for photosynthesis is supplied by artificial lights or by sunlight, direct or delivered through light pipes. A heat sink on the outside receives surplus heat from the system. Usually, it is safer to house the energy-generating unit outside the sealed life support zone. This will also lessen the amount of air-scrubbing that is required if the energy production method produces pollutants. But, while the definition of a closed ecological life support system does not require energy production within its sealed boundary, it is certainly true that lessening energetic requirements and the accomplishment of energy generation in space via solar arrays, nuclear energy, use of extra-terrestrial energy resources, etc.) are important considerations in reducing logistical dependence on resupply from Earth.

2.5. Biospheric Systems

Since both CELSS and closed ecological systems contain essentially only one type of ecosystem – an agricultural one – for human life support, they differ from "biospheric systems," such as the Biosphere 2 project in Arizona, and the Japanese CEEF (Closed Ecology Experimental Facilities) which include a number of internal ecosystems. Biospheric systems are essentially materially closed, energetically and informationally open like a closed ecological life support system, and their internal complexity provides additional buffering capacity for air and water regeneration, and increases the long-term prospects of a system resistant to catastrophic decline, and to enhance the "live-ability" for its human inhabitants. These systems also offer new opportunities for research into the complexity of ecological mechanisms operating in our Earth's biosphere.

Currently, there are some nine experimental ecosystems that can be used to conduct investigations with material cycling closed to a greater or lesser extent. They are: The Ground

Experimental Complex at the Institute of Biomedical Problems in Moscow, Russia; Bios-3 in Krasnoyarsk, Siberia at the Institute of Biophysics; BIO-Plex (Advanced Life support System Test Bed) at the NASA Johnson Space Research Center in Houston, Texas; the NASA Kennedy Space Center “Breadboard” Plant Growth Facility in Florida, Biosphere 2 in Oracle, Arizona; the “Laboratory Biosphere” in Santa Fe, New Mexico; the C.E.B.A.S. aquatic ecosystem at the Ruhr University of Bochum in Germany; the CEEF complex at the Institute of Environmental Sciences in Japan; and the Pilot Plant that is being constructed in the framework of the European program MELiSSA at Universidad Autonoma de Barcelona, Spain.

In this chapter, we will discuss some problems of bioengineering and biotechnology of these closed ecological systems which are of importance for an understanding of their operation and use.

3. DIFFERENT TYPES OF CLOSED ECOLOGICAL SYSTEMS

3.1. Research Programs in the United States

3.1.1. CELSS Program of NASA

The Controlled Environmental Life Support System (CELSS) program was initiated in 1978 by NASA. Three NASA centers were primarily involved: The Kennedy Space Center where the “Breadboard” provided a test bed for plant cultivation experiments in a closed ecological system; the Johnson Space Center focused on food processing and human diets in space, and the Ames Research Center connected with basic research in system controls. Earlier, laboratory experiments with biological regenerative systems were based on monocultures of unicellular organisms, either photosynthetic (*Chlorella*) or chemosynthetic ones (*Hydrogenomonas*). They were not successful in that the systems used did not attain a stable, steady state and could not provide a significant portion of human nutritional needs. That is why NASA and its associated university researchers decided to include traditional agricultural crops, higher plants, as the core element in their bioregenerative life support systems.

The motivations for the use of higher plants include:

1. Crop plants have the capability of fulfilling the basic autotrophic (primary producer of complex organic molecules) link in a closed system, and thereby closing the regenerative loops for CO_2, O_2, and water. This basic equation **Eq. (1)**:

$$6CO_2 + 12H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light(672 Kcal)}} 6(CH_2O) + 6O_2 + 6H_2O \qquad (1)$$

   is complemented by the action of heterotrophs such as humans reversing the equation in their oxidation of complex hydrocarbons (food) and in respiration, producing carbon dioxide, water, and minerals).
2. Unlike unicellular organisms (algae or bacteria), higher plants are easily digested and are customary sources of human food. Extensive literature on terrestrial (i.e., not in a closed environment or in microgravity) human nutritional needs and higher plant composition exists and forms a starting point for designing such systems.
3. Higher plants can purify water through the process of transpiration. Transpiration is the method whereby plants utilize the passage of water to achieve evaporative cooling. This has been

estimated at about 300 g of water evaporated for every gram of CO_2 fixed in photosynthesis. Such water can be condensed from the atmosphere of a closed system.

4. Higher plants also have the capability of processing waste materials from the crew members and other heterotrophs in the system.

The major CELSS plant crop studies included soybeans (by Raper at the North Carolina State University), sweet potatoes by a group (Hill, Mortley et al.) at Tuskegee Institute, white potatoes (by Tibbitts at the University of Wisconsin) and semi-dwarf wheat (by Salisbury and Bugbee at Utah State University). Later, the cultivar called Super-Dwarf wheat was grown under the conditions of space flight aboard the Mir space station and the NASA Space Shuttle in 1995 and 1996/97 (10).

It was shown (Utah State University experiments) that a plant growth area of 13 m^2 of high productivity dwarf wheat can provide the entire caloric requirements (but not all of the nutritional essentials) for one human, can absorb the metabolic carbon dioxide produced by this human and produce enough oxygen to allow the human to oxidize the calories contained in the wheat biomass. The excess oxygen would be equivalent to the amount of photosynthesis required to produce the non-edible biomass of the wheat plants (stems, roots, leaves). Further, production of the non-edible biomass would require more carbon dioxide than is generated by a human in the same period. This discrepancy could be resolved by oxidation of the non-edible biomass, either by a physical chemical process, or by a biological waste digestion system (11).

In 1986, the Breadboard Project (Fig. 11.1) was begun at Kennedy Space Center and active experimentation continued for over a decade. The Breadboard Project had as its goal the demonstration of the scaling-up from previous laboratory-sized research study into the production of food for human life support, water recycling, and atmospheric gas control in its biomass production chamber. Support laboratories investigated associated questions of waste recycling, food preparation, and overall data management. The Biomass Production Chamber (BPC) used is a renovated cylindrical steel hyperbaric facility approximately 3.5 m diameter by 7.5 m high. Originally used in the Mercury program, it has been modified for plant growth by the creation of two floors with eight plant racks and the installation of high pressure sodium lamps. Ventilation of the chamber is accomplished by ducts, which lead into an external air-handling system including filters. Temperature and humidity are controlled by a chilled water system and through atomized water injection. A compressed gas delivery system is used in the manipulation of atmospheric carbon dioxide and oxygen. The best leak rate achieved in the Breadboard BPC was loss of 5% of its volume per day. The configuration of growing areas inside yields a total plant area of 20 m^2. Air turnover in the BPC is about three times a minute, with ventilation air being ducted at the rate of 0.5 m^3/s into the chamber between lights and growing trays. Many years of experimentation involved many of the prime candidate food crops for space life support, along with analysis of atmospheric dynamics inside the closed system (12–15). Table 11.2 presents summary data on some of the candidate space crops grown and the amounts of life support materials produced.

The current NASA CELSS program covers different areas of tasks and purposes: from “Salad Machine” and CELSS Test Facility for using on Space Station to large-scale plant growth chambers, human habitats, and recycling equipment. Recently, a series of experiments

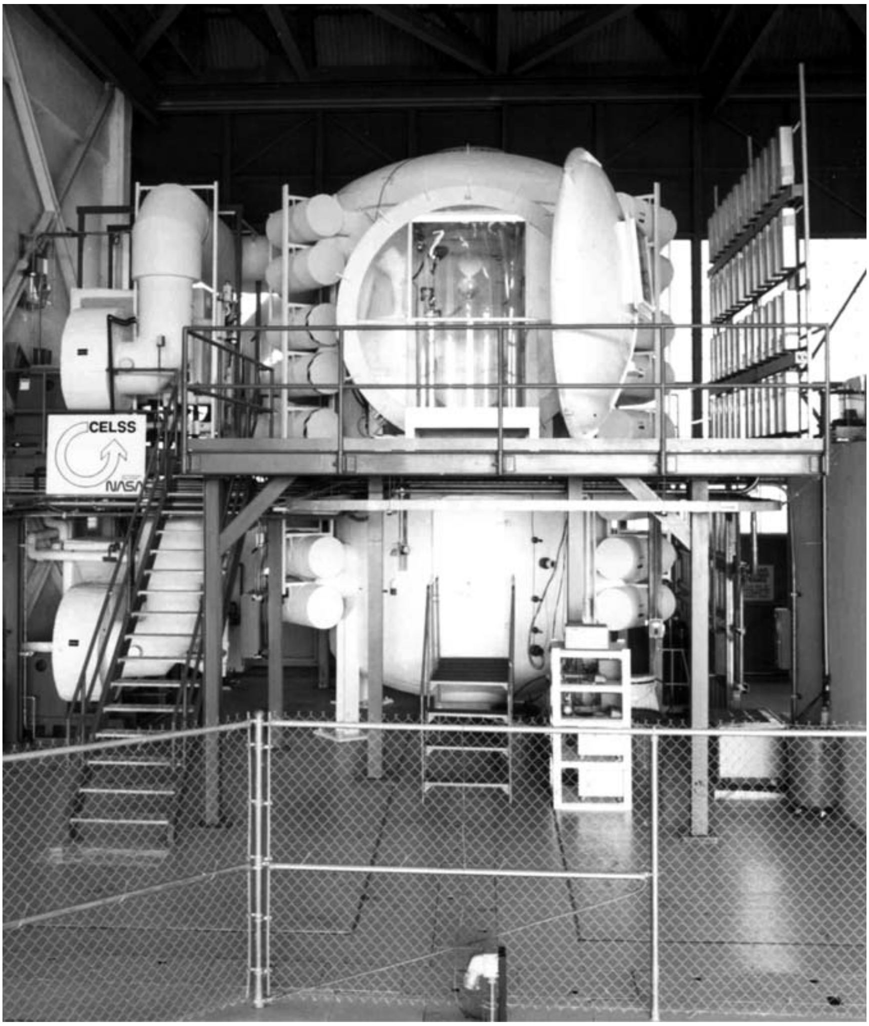

Fig. 11.1. Breadboard Plant Chamber at Hangar L at KSC, FL (front view, 1986). The chamber provided a closed atmospheric volume of about 113 m^3 (including air ducting) with 20 m^2 of crop growing area. External nutrient solution tanks were not in place at the time of this photo (12).

were conducted with the Advanced Life Support System Test Bed (ALSSTB) at the Johnson Space Center. The system is the largest of the NASA life support test systems, and the first in the US to involve humans in a system based on technology using both bioregenerative and physicochemical methods. The system can be considered as an integrative test bed developed from the experience of past NASA life support system development approaches. The three phases of the experiment with a crew were conducted (The principal references to this work: Lunar–Mars Life Support Test Project, Phase II Final Report, 1997; Lunar–Mars Life Support Test Project Phase III Final Report, 1998 (16)).

Table 11.2
Life support outputs of crops grown in the Kennedy Space Center Biomass Production Chamber (BPC) (12)

Crop/date	Days of operation (d)	Total biomass (kg)	Edible biomass (kg)	CO_2^a fixed (kg)	O_2^a produced (kg)	Water collected (kg)
Wheat 881[b]	77	23.06	9.24	35.5	25.8	3,615
Wheat 882[c]	64	26.14	Early harvest	40.3	29.3	5,700[d]
Wheat 891	86	37.76	11.01	58.2	42.3	6,903
Wheat 892	85	44.24	13.12	68.1	50.7	7,809
Wheat 931	85	64.11	18.25	98.7	71.8	7,500[d]
Wheat 941[e,f]	84	66.68	19.07	102.7	74.7	7,600
Soybean 891	90	26.62	8.58	45.0	32.7	7,758
Soybean 901	97	18.94	6.34	32.0	23.3	8,211
Soybean 902	97	20.80	7.79	32.5	25.6	8,450
Soybean 951[f,g]	90	13.51	5.18	22.8	16.6	2,594
Lettuce 901	28	–	Sequential	Harvest	Study	–
Lettuce 902	28	2.84	2.60	4.2	3.1	976
Lettuce 911	28	3.54	3.24	5.2	3.8	998
Lettuce 921	28	3.57	3.36	5.2	3.8	1,000[d]
Lettuce 931[f]	30	3.99	3.71	5.9	4.3	1,074
Potato 911	105	45.58	14.89	68.4	49.7	8,778
Potato 912	90	50.67	22.03	76.2	55.4	9,361
Potato 921	105	55.42	37.64	83.1	60.5	7,954
Potato 931	105	55.88	34.12	83.8	61.0	8,546
Potato 941[f]	418	272	167	409	296	28,446
Tomato 951[f,g]	84	11.03	5.15	16.6	12.1	3,426
Tomato 961	87[h]	33.87	17.06	50.9	37.0	12,700
Total	1991	880	409	1,344	980	149,390

[a] Estimated from total biomass and the percentage of carbon in tissue.
[b] Only the upper half of the chamber used.
[c] 3/4 of available growing area used; plant harvest prior to maturity.
[d] Some missing data; totals estimated by interpolation of water use trend.
[e] Data collected from level four only; water estimated until final data compiled.
[f] Studies where half the plants were grown on recycled nutrients from an aerobic bioreactor.
[g] Simultaneous test with tomato ($10\,m^2$) in half of the chamber and soybean ($10\,m^2$) in the other half.
[h] Upper chamber harvested at 84 days; lower chamber harvested at 91 days.

One purpose of the ALSTB Program is to validate regenerative life support technologies (e.g., air revitalization, liquid and solid waste recycling, active thermal control) through long term testing of integrated biological and physicochemical life support systems with human test subjects. The Lunar–Mars Life Support Test Project (LMLSTP) Phase I Test was performed in August of 1995. The purpose was to obtain engineering and scientific data to demonstrate the ability of a crop of wheat to provide air revitalization for a human test subject for a 15-day period. The test chamber was divided into two sections, the plant growth chamber, and the airlock that was used as the human habitation chamber. It was successfully demonstrated that an 11.2 m^2 crop of wheat could continuously provide the CO_2 removal and O_2 production functions for the air revitalization needs of a single human test subject for 15 days. But over the short duration of this test, the populations of microorganisms in the internal atmosphere of the chamber increased (This was consistent with experience in Shuttle flights and previous closed chamber tests). No microorganism that would be of concern to human or plant health at the levels measured was identified. Next two (Phase II and Phase II A) experiments with four crew members were aimed to test physicochemical systems of water and air recycling. Both were successful.

A feature of the Phase III 90-days experiment (Fig. 11.2) was integration of biological and physicochemical regenerative processes. The physicochemical systems provided approximately 75% of the air revitalization. The remainder of the air revitalization was provided by a crop of wheat. The test results demonstrated that physicochemical and biological systems can be integrated to provide air revitalization. An integrated water recovery system was operated for 91 days in support of the Lunar–Mars Life Support Test Project Phase III test. The system combined both biological and physicochemical processes to treat a combined wastewater stream consisting of waste hygiene water, urine, and humidity condensate. Biological processes were used for primary degradation of organic materials as well as for nitrification of ammonium in the wastewater. Physicochemical systems removed inorganic salts from the

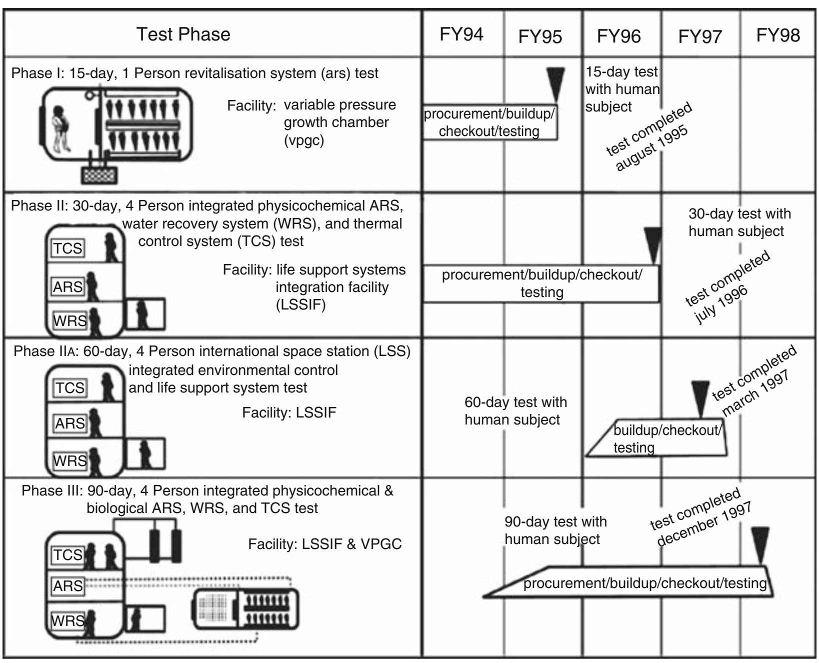

Fig. 11.2. NASA Johnson Space Center, Houston, Texas. LMLSTP 90-day three phase progression of steps for development of life support systems (17).

water and provided post-treatment. The integrated system provided potable water to the crew throughout the test. Overall positive results were obtained during Phase III test, and some difficulties were thoroughly analyzed (17).

Phase III test was the final test in a series of tests conducted to evaluate regenerative life support systems performance over increasingly longer durations. The Phase III test broke new ground for the U.S. Space Program by being the first test to look at the integration of biological and physicochemical systems for air, water, and solid waste recovery for a crew of four for 91 days. Microbial bioreactors were used as the first step in the water recovery system. This biologically based system continuously recovered 100% of the water used by the crew consistent with NASA's strict potable standards. The air revitalization system was a combination of physicochemical hardware and wheat plants which worked together to remove and reduce the crew's metabolically produced carbon dioxide and provide oxygen. In addition, for the first time, the crew's fecal matter was used as a source of carbon to produce carbon dioxide in an incineration system. The carbon dioxide was then used to support the plants for a portion of the test. After harvesting, the wheat was provided to the crew in the form of flour to use in baking bread. Overall, the test successfully demonstrated that biological systems can be integrated as part of a regenerative life support system. The use of plants to provide air revitalization while providing food for the crew and use of microbes to purify the wastewater were successfully demonstrated.

Some difficulties that emerged included better management of nutrient management of staged crops to prevent plant stress. Control systems must be developed to respond to events when the plants are maturing faster or slower than expected and harvests need to occur at different times than predicted. Controls need to be improved to prevent operation in uncontrolled conditions. The Water Recovery System suffers from two major technical problems. Conversion of raw food products to edible material was shown to be critical for using plants for human consumption. While the lettuce was eaten as is, the problems with processing wheat indicate that this is perhaps the tip of the iceberg in the development of food processing systems. Finally, integrated control systems that take into account the overall operation of the whole life support system and make adjustments as necessary without human intervention would have a huge payoff in crew and ground personnel time (17).

A future test complex at NASA Johnson Space Center referred to as ALSSIT (Advanced Life Support Systems Integration Test Bed (formerly known as BIO-Plex) will be the basis for future long-duration human missions on lunar and planetary surfaces. The overall objective of the ALSSIT Project is to support large-scale, long-duration testing of integrated, high fidelity, and biological and physicochemical regenerative life support systems with human test subjects under closed, controlled conditions. Human accommodations will be provided in the habitat to provide for the needs of four crew members and up to eight crew members during 48 h crew changeovers. ALSSIT will be comprised of a series of interconnected chambers with a sealed internal environment outfitted with a system of internally distributed utilities capable of supporting a test crew of four for periods exceeding 1 year. The full configuration calls for a habitat chamber, a life support systems chamber, two biomass production chambers, and a laboratory chamber, all of which will be linked by an interconnecting tunnel with access through an airlock. The multichamber test complex will be monitored and controlled from a nearby control center. The life support system will perform air revitalization, waste recovery, solid waste processing, thermal management, food production, and integrated command and control functions. ALSSIT will serve as the focal point for other disciplines to conduct research and to develop supporting technologies, techniques, and procedures pertinent to future planetary missions via cooperative and collaborative experimentation and testing. Different human tests are planned for the future.

NASA considers that for expansion of the human experience into the far reaches of space, it becomes imperative to minimize consumables and increase the autonomy of the life support system. Two basic classes of life support systems must be developed, those directed toward applications on transportation/habitation vehicles (e.g., space shuttle, international space station (ISS), next generation launch vehicles, crew-tended stations/observatories, planetary transit spacecraft, etc.) and those for lunar or planetary surfaces. The Advanced Life Support Project Plan was developed to define the Project objectives, Project-level requirements, the management organizations responsible for the Project throughout its life cycle, and Project-level resources, schedules, and controls. This Plan is the top-level document for the Project and provides guidance and direction for its implementation by the participating NASA field centers, namely Ames Research Center (ARC), Kennedy Space Center (KSC), Marshall Space Flight Center (MSFC), and the Johnson Space Center (JSC) serving as the lead center. The Project Plan will be reviewed and updated annually to ensure that the Project remains properly focused and responsive to the goals of the Agency and Biological and Physical Research Enterprise (18). The goal of the Advanced Life Support Project is to provide life support self-sufficiency for human beings to carry out research and exploration safely and productively in space for benefits on Earth and to open the door for extended on-orbit stays and planetary exploration. The five major technical objectives of the Advanced Life Support Project are as follows:

1. Provide Advanced Life Support technologies that significantly reduce life cycle costs, improve operational performance, promote self-sufficiency, and minimize expenditure of resources for long-duration missions.
2. Develop and apply methods of systems analysis and engineering to guide investments in technology, resolve and integrate competing needs, and guide evolution of technologies.
3. Resolve issues of microgravity performance through space flight research and evaluation.
4. Ensure timely transfer of new life support technologies to missions.
5. Transfer technologies to industrial and residential sectors for national benefit.

To accomplish these objectives, the Advanced Life Support Project will conduct a focused Research and Technology Development (R&TD) effort to advance technology readiness of regenerative life support and thermal control components, validate regenerative life support technologies integration through long-term testing with humans, and identify terrestrial applications for life support technologies. JSC, as designated lead center, has delegated the authority and overall Advanced Life Support Project management responsibility to the Engineering Directorate, Crew and Thermal Systems Division (CTSD). CTSD also is responsible for the development of biological and physicochemical subsystem/component (Technical Research Levels 3–6) technologies and flight experiments; the integration of physicochemical/biological systems technologies, including systems-level testing with humans; and the lead for systems modeling and analysis activities.

As summarized in the Project Technical Summary, advanced life support technologies must:

- Regenerate air, water, and food in a manner that minimizes overall logistical burdens, minimizes demands on space habitat resources, ensures habitability, and promotes self-sufficiency.
- Manage wastes to maintain a safe environment within the habitat and minimize waste storage and buildup, and process wastes to achieve optimum resource recovery, when required.
- Minimize involvement of the crew in life support system operation while assuring proper monitoring and control of essential systems.
- Provide effective environmental monitoring to preclude hazardous conditions (e.g., fire, buildup of toxic contaminants).
- Provide thermal control without the use of expendable heat sinks and without imposing a hazard to the crew.
- Assure prolonged reliability of components and systems.
- Provide for in situ maintenance.
- Minimize the impact of life support on planetary environments.

Figure 11.3 depicts the research and technology development (R&TD) phases for the Project, emphasizing that as the technology and research level (TRL) of candidate technologies increases, the number of options decrease. Thus, the Project will continue to develop only those technologies that show the most promise in terms of meeting mission requirements. Major schedule milestones for the Advanced Life Support Project are based on experiments

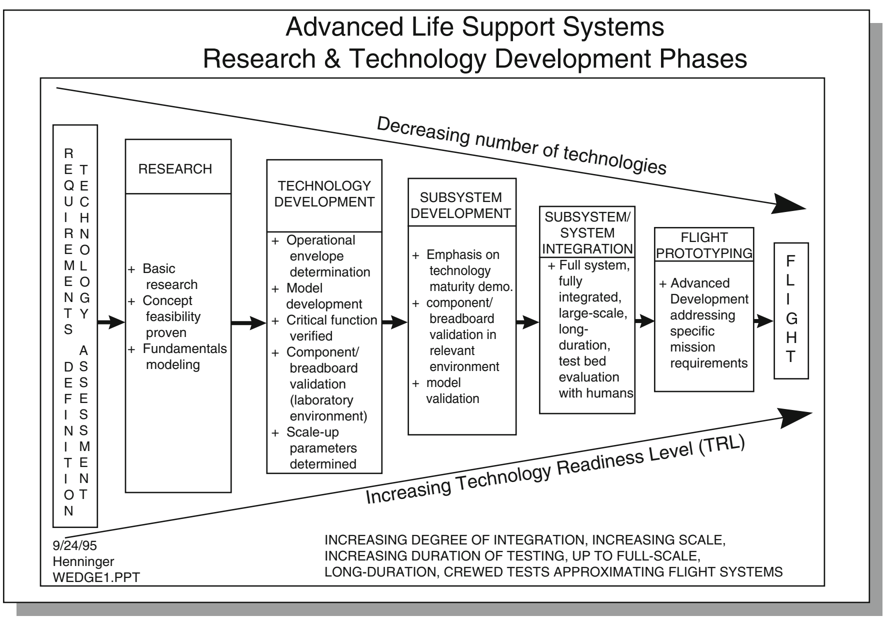

Fig. 11.3. Advanced life support research and technology development phases, NASA JSC (17).

with a modified BIO-Plex. The BIO-Plex facility, located in the Johnson Space Center Building 29 rotunda, is an atmospherically closed multi-chamber test bed large enough to house a crew of four for test durations in excess of 400 days. The multi-chamber facility shall provide sufficient volume within which all life support system test articles for air revitalization, water recovery, biomass production, food processing, solids processing, and thermal control can be located, with the exception of external thermal control system hardware. The multi-chamber facility shall also provide sufficient internal volume to accommodate power, lighting, communications, data network, thermal system, air distribution, water distribution (potable and fire protection), and drainage utility runs throughout the complex. These energy, information, and safety utilities shall be interfaced to the external facility systems via a localized penetration interface for the purposes of simplifying leak detection, increasing aesthetics and maintaining high facility fidelity.

3.1.2. Biosphere Design: Lessons from the Biosphere 2 Experiment

3.1.2.1. Overview of Biosphere 2 Facility

Biosphere 2 is a pioneering $150,000,000, research, and development laboratory designed to study global ecology and to test bioregenerative life support on a biospheric scale. The facility, built in Oracle, Arizona, was designed by Biospheric Design, Inc. to operate on a long-term basis (50–100 years) and to study viability and dynamics of life cycles within a complex seven biome system that included a coral reef, marsh, agriculture, rainforest, savannah, desert, and human habitat. From the years of 1991–1994, the Biosphere 2 facility was essentially materially closed (with an annual air leakage rate under 10%), energetically open to electricity and sunlight, and covered some 1.2 hectares (3.15 acres) in its airtight footprint, including over $200,000\,m^3$ (seven million cubic feet) of atmospheric volume (Fig. 11.4). The name Biosphere 2 was chosen to emphasize that the Earth's biosphere (Biosphere 1) was the only biosphere known to science. A detailed list of scientific papers for the first 3 years of its operation (September 21, 1991 to September 6, 1994) can be viewed at www.biospherics.org and in (19).

Biosphere 2 was materially isolated by a skin of steel spaceframe and double laminated glass panels above ground, and by a stainless steel liner underground. Energetically, it was open to sunlight, thermal and electrical energy produced for the operation of its heating, cooling, and other mechanical systems. It was also informationally open to communications media: electronic, radio and visual. The structure of Biosphere 2 included two variable volume chambers ("lungs") permitting expansion/contraction of the internal atmosphere without incurring leakage by keeping the pressure carefully adjusted to the outside pressure. The research and development for Biosphere 2 spun off a number of other technologies of potential application for environmental protection and monitoring and for potential space applications in smaller life support systems. These technologies include soil beds for air purification, aquatic plant wastewater recyclers, non-polluting analytic and monitoring labs, multi-level cybernetic systems for system operation and analysis, and high yield sustainable soil-based agricultural systems. The visible structure was underlain by the complex technosphere (4, 20–22).

Fig. 11.4. Biosphere 2, Oracle, Arizona, constructed 1985–1991, operated as a closed ecological system and biospheric laboratory, 1991–1994 in two closure experiments with crews.

Mission One, a 2 year experiment, was conducted from 1991 to 1993 with a crew of eight biospherians who operated the intensive agricultural system, managed and monitored the other biomes, and maintained the equipment and computers inside the facility. After a Transition Mission to carefully measure results of Mission One and improve some technical details, a second closure experiment ran from March 10, 1994 to September 6, 1994 with a crew of seven people. The new owner then shut down all further closed system research.

Biosphere 2 achieved a flourishing complex life-support system by the designed integration of seven biomes: rainforest, savannah, desert, marsh, ocean, intensive agriculture, and human habitat. The tallest structure of the rainforest rose 27.7 m high. The ocean contained a coral reef system, including a shallow lagoon area and sandy beach. Its waves were generated by a vacuum pump wave generator. An ecosystem modeled on the estuarine Everglades ecology adjoined the coral reef with a series of communities that graded from freshwater marsh to oligohaline Spartina grass marsh, through areas dominated by white mangrove (*Laguncolaria racemosa*) and black mangrove (*Avicenna germinans*) to the more highly saline waters that support oyster beds and red mangrove (*Rhizophera mangle*) (4, 23).

3.1.2.2. The Scale of Biospheric Design

Designing a biospheric scale materially closed, informationally and energetically open life system requires co-coordinating an unusual number of sciences and disciplines. Biospheric scale means that there will be three or more “biomes” or relatively independent ecosystems. For life support, a human habitat (living and working area), agricultural ecosystem, including means for reusing and recycling inedible crop material, and a wastewater recycling system are required. The system shares a common atmosphere, water, and waste recycling systems,

Fig. 11.5. Mark van Thillo, co-captain of the eight-person biospherian crew, in the technosphere of Biosphere 2 during the closure experiment, 1991–1993.

genetic pool, temperature/weather regimes and overall psychological and economic dimensions. To create such things during the closure experiment, a biospheric system requires three new integrative disciplines: Biospherics (how to create and study complex ecological entities) technospherics (the world of technologies, especially from the viewpoint of ecotechnics) (Fig. 11.5), and ethnospherics (designing for the human culture which will emerge with a wide range of behavior and values) (4, 24, 25). The key factor in biosphere design is deciding how many humans will be supported. Certain parameters governing minimum size can then be calculated for given human requirements for food, temperature, hygiene, safety, beauty, fulfillment, and socializing that must be met (26).

Biosphere 2 was designed to determine the technical, biological, and cultural vectors of a total biospheric system by creating a living, experimental model of the tropical zones of Earth (Fig. 11.6). Excluded were not only temperate and arctic regions, but the upper atmosphere, deep geologic strata, and deep ocean biosphere minus the freezing zones (27). Therefore, its goals included studying the technologies required which included a complete global communications center and their ecological impacts on the complex agricultural system, the five wilderness biomes, and on human and animal health.

3.1.2.3. Design Requirements for a Biosphere

An artificial biosphere, because of its size, cannot depend on nature to supply certain needs, for example, tides, winds, and rains. A "technosphere" must be designed that can supply, measure, and control these functions performed by the moon, sun, and vast weather systems in Earth's biosphere. For example, in Biosphere 2, wind generation by air handlers helped

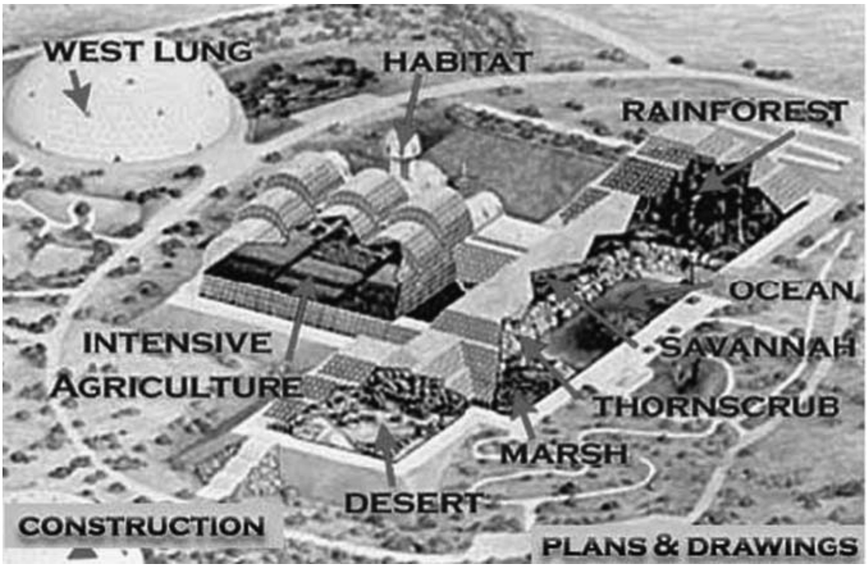

Fig. 11.6. Plan of Biosphere 2, showing the human habitat and intensive agriculture; the five wilderness biomes: rainforest, desert, ocean, and marsh; and the variable volume "lungs."

regulate temperatures in the biomes and its airflow was also necessary for wind-pollinated plants. Above all, in order for an artificial biosphere to exist, a container must be designed that will allow recycling to occur with minimal loss or input of outside material. In Biosphere 2 that meant stringent engineering which resulted in a leak rate of air of less than 10% a year. Leak rates were monitored through depletion determinations of several trace gases (SF6, He and Kr), which were spiked into the atmosphere of Biosphere 2. The degree of air-tightness was much greater than those in the previous closed systems allowing exact tracking of essential life element cycles (28, 29). Water, food, and waste had to and did recycle during the 3 years and Biosphere 2 operated as a research facility for closed ecological systems. Buildup of trace elements from technogenic, biogenic and anthropogenic sources must be monitored and not allowed to exceed the minimum exposure limits (although there is still little information about the long-term tolerable limits for many trace gases) (30, 31).

On the other hand, desired throughputs of energy and information must be engineered into the container. The energy source(s) must be distributed to the different regions of the biosphere so that the proper temperature differentials are maintained, the proper light is received, and the tides and winds perform their ecological functions. The energy sink(s) must reliably get rid of heat excesses. If the system is healthy, some of the energy input will be stored by the biosphere as increased free energy in its biomass, complex molecules, and information. In the case of Biosphere 2, which started out at its initial closure in September 1991 with about 15 tons of biomass, by the end of its first 2 year mission, plant growth had been so robust that biomass had doubled.

Biospheric design must take a two-pronged approach to its life systems: One, the selection and layout of its biomes and ecosystems; two, the selection of its species and individuals in those species. All five kingdoms must be represented with humans representing a sixth kingdom in design load if not taxonomically (32). The most important of these kingdoms in terms of the work performed in a biosphere are the bacteria, prokaryotes, and eukaryotes, which are found in great number in both aerobic and anaerobic levels of the soils and water bodies. All the functional suites of bacteria must be represented, since they are essential for the successful completion (cycling) of biogeochemical elements essential for life (6). Fortunately, once sufficient diversity of microbes is present, natural processes operate to increase microbes that use particular elements as food stuffs. For example, the methanogens increase in response to an abundance of methane and help ensure completion of cycling feedback loops (33–35).

The initial set chosen of each species from the prokaryotes, eukaryotes, plants, animals, and fungi must contain enough members to ensure reproduction under the given conditions of the new biosphere. The determination of this number needed to ensure viable survival is a major part of biospheric research and design. Biosphere 2 was designed with nearly 4,000 species (not including microbial diversity) allowing for a loss of 20–30% of original biodiversity as ecological communities adapted (21). This species surplus was built into the initial state conditions in order to allow real competition to occur, and thus allow the system to self-organize (4).

Biomes are the key design levels in making biospheres sustainable and thriving. In our planetary biosphere, they constitute the most sustainable large functional units. The Russian biologist Kamshilov noted, "The stability of the biosphere as a whole, and its ability to evolve, depend… on the fact that it is a system of relatively independent biogeocoenoses (biomes) … which compete for habitat, substance, and energy and so provides for the evolution of the biosphere as a whole (36)." Biomes provide integrative matrices for maximizing numbers of econiches, stable and complex food chains, and varied biochemical cycling routes. Continuous monitoring assessed the health of humans, the other species, the different biomes' integrity, and changes in the cycles and compositions of air and water and how that affected humans or biomes. To assist the health of biomes, the crew ("biospherians") must function as an analogue to "keystone predators" responsible for maintaining balances in each biome by assisting threatened important species and controlling invasive species (37, 38).

Once the number of humans, biomes and their species, and the support technospheric systems are determined, then the needed volume of the container can be calculated in order to provide carbon dioxide and oxygen ratios desired during the different seasonal cycles. Biosphere 2 was modeled on subtropical seasonal cycles. Carbon dioxide minimums and maximums cycled from 300 to 4,200 ppm annually, and CO_2 flux between day and night could reach over 500 ppm (Figs. 11.7 and 11.8) (20, 39). Except for the coral reef, which is affected by the pH, which rises with elevated atmospheric carbon dioxide levels, the carbon dioxide could have been designed to reach levels as high as 10,000 ppm without human health problems.

The cycle of overriding interest and concern in biospheric operation is that of carbon dioxide. The ratio of living biomass (to reach 60–70 tons in Biosphere 2 after 10 years) and soil material (some 30,000 tons, from 1 m deep in the agricultural biome to up to 5 m in the rainforest) to atmospheric mass was far greater than those in the planetary biosphere. This

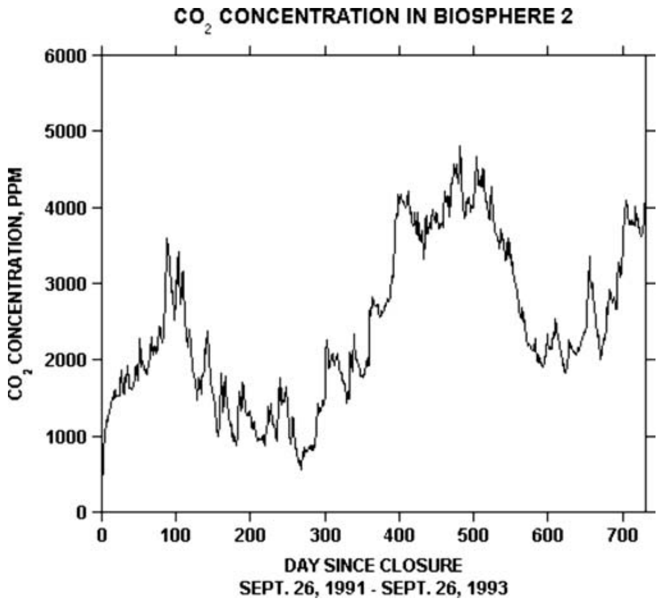

Fig. 11.7. Carbon dioxide average daily concentration in the Biosphere 2 atmosphere during the Mission 1 two-year closure experiment, 1991–1993.

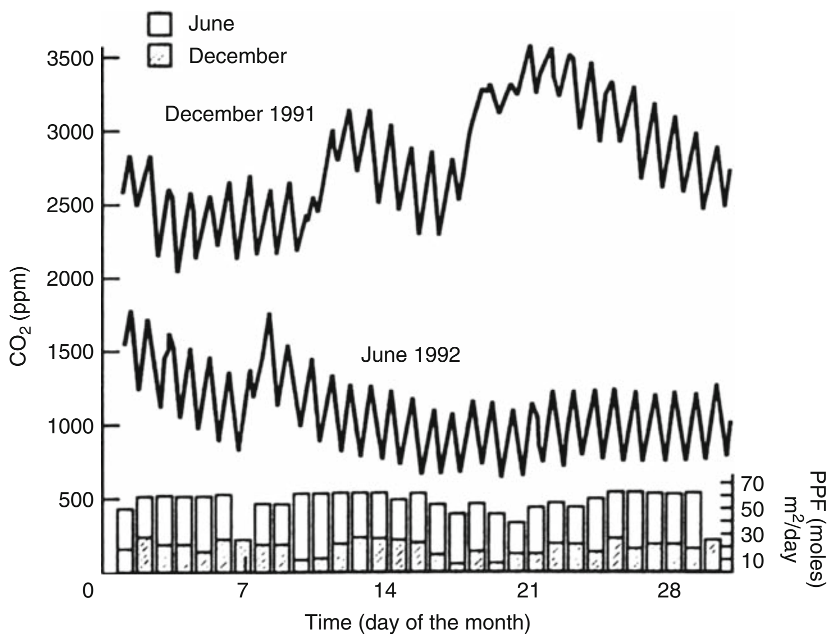

Fig. 11.8. Day-night oscillation of CO_2, about 500 ppm, is shown in this graph of a winter and a summer month. The histogram at the *bottom* also shows total daily light for the winter month (*shaded bar*) and for the summer month (*clear bar*).

higher ratio, even at the beginning 15 tons of biomass, results in a far shorter residence time for CO_2 in artificial biospheres than in Earth's biosphere, an estimated 4 days as contrasted to 3–10 years (21). Therefore, to operate small artificial systems the CO_2 sources (people, animals, soil microbes, compost, liquid waste recycle wetlands) must match uptake (plants and algae) rather closely (1, 4, 40).

After making the first approximations to human number, biomass, biodiversity, biomes, atmospheric volume, and technosphere (including sealing), the kinds and volumes of dryland and wetland soils and rock substrate (e.g., limestone for coral reef, "parent rock" underlying topsoil), design must provide and recycle the nutrients for the life forms and to balance the atmospheric cycle. For example, deserts require a somewhat basic soil, rainforests, a somewhat acidic soil. Wetland (paddy) rice varieties need anaerobic soils, while root crops prefer light, sandy soils. The challenge of creating biospheric systems on the Moon and Mars will be to learn to amend local regolith and soil to make them suitable for agriculture and support of a range of organisms and ecosystems (19, 23, 25, 41). Worms as well as bacteria and fungi play a key role in making productive soils. In addition, fungi imperfecta, mycorrhizae, play an enormous role in soil health and nutrient recycling through composting of inedible crop residues and litter decomposition by natural detritivores is a crucial requirement for a sustainable system (23, 42, 43). Biosphere 2 was designed as a soil-based system because soils play a major role in purifying and recycling the atmosphere as well as in controlling the rate of water use and providing support and nutrients to the plants. They enable the use of time-tested and low-energy methods of recycling of inedible crop matter; wastewater treatment through wetland plants; and increase the diversity of microbes able to be supported (44). Soils also give a rich and satisfying aroma to humans and provide essential aesthetic and even spiritual experiences.

Creating a sustainable high yield agricultural system with low time requirement (less than 1/3 of biospherian time) to plant, harvest, measure, process, and cook is one of the most difficult design tasks in making a habitable biosphere. The chief technical requirement is that the agriculture must supply a complete nutritional diet. This agriculture must be sustainable without gradual loss of vital nutrients if the human health is to be maintained properly. The design of the Biosphere 2 agricultural system, the Polynesian sweet potato and pig, the East Asian rice and fish, the Indian wheat and chicken, and tree fruits, such as banana and papaya, seen in Mayan and Ugandan farms were integrated in a 0.2 hectare system that used over 80 crop varieties. Biosphere 2 was the first instance of a closed ecological life support system in which a complete nutritional diet was the goal and in which domestic animals were successfully included. The diet for the eight crew members of Biosphere 2 included milk (from African pygmy goats), eggs (from the system's domestic chickens), meat (from the goats, chickens, and Ossabaw feral pygmy pigs), and fish (from Tilapia grown as in the rice/azolla water fern paddies). In addition, a wide range of vegetables, grains, starches, and fruit are grown. This agriculture kept eight biospherians leading a strenuous life in top health and work morale for 2 years (40, 45, 46). The reliance on ambient sunlight reduced by 50–55% in passing through the glazed envelope also limits area productivity and might differ in space applications where advantage may be taken of enhanced artificial light techniques to boost yields (19, 21, 47).

In small closed systems like man-made biospheres, the agricultural system cannot use toxic chemicals such as biocides or pesticides, but must develop non-polluting methods of controlling crop diseases and harmful insects, and nutrients from the food produced must be returned to keep the soil fertile (23, 48). Processing, storage, and culinary systems that do not waste vital nutrients and that present the dishes at table in an appetizing form must be developed. No artificial biosphere could survive paying the energetic and pollution costs of modern agriculture and, indeed, one of the main applications of biospheres can be in the development of a comprehensive sustainable agriculture.

After the first approximations of atmosphere, soils, life forms, human needs, agricultural system, and technospheric scale and content, biospheric design work must begin to calculate water needs and how to control its flows and arrange the size and location of its reservoirs. The four subsystems are potable water, wastewater recycling from the human habitat and farm animals, irrigation water for the crops, and rain and stream/pond/marine water for the wilderness biomes. In Biosphere 2, sunlight drove evapotranspiration and technical systems were installed to condense atmospheric humidity to produce high-quality, low-salt water for drinking and for agriculture and wilderness biomes. The technosphere must take the place of many ecological functions in man-made biospheric systems through storage and pumping of water to where it is needed.

Finally, to complete the basic design program, a hierarchy of computerbased monitoring and control must be developed to track the performance of the entire system and its key components. This system must operate by “mission rules,” which specify the tolerable range of environmental parameters. The five minimum functional levels are: (a) Point sensing and activation, (b) local data acquisition and control, (c) system supervisory monitoring and controls (though much of a biosphere’s operations are self-organizing), (d) global monitoring and historical archives, (e) telecommunications between crew and monitor stations inside and those on the outside. An alarm system which will activate either manual or AI intervention as necessary must be included. Final biospheric design results from a number of iterations of integrations of the above vectors until it satisfies the critical economic, ecological, and human criteria.

3.1.2.4. The Use of Test Modules in Design

A note of caution: In engineering a biospheric scale apparatus with its attendant cost requirements, it is advisable to make a test module to develop skills in making and living in closed ecological life systems and to test probable sub-contractors. The Biosphere 2 Test Module (Fig. 11.9) was the first closed life system that had complete wastewater and water recycle with very low leak rate, but its size prevented total supply of food support for longer than a month’s occupation by a single experimenter (33, 34). There was a scale jump of 500:1 to go from the Biosphere 2 Test Module to Biosphere 2.

Important findings were made during experimentation from 1987 to 1989 with the Biosphere 2 Test Module. The total system remained quite productive and the many microbial and fungal vectors were held in balance by competition despite concerns that a soil-based system might fuel fungal growth or microbial pathogens and was able to recycle its carbon dioxide at atmospheric levels far below hazardous levels. Experimenters in the closure experiments

Fig. 11.9. Biosphere 2 Test Module.

reported that living inside a closed ecological system was more than survivable: It was very enjoyable, Engineering challenges included achieving the desired leak rate and use of the variable volume chamber (lung), and working out the practicality of demanding specifications far beyond normal engineering requirements with newly invented technologies (19, 33, 34).

3.1.2.5. Biospheric Laboratories and Experimental Ecology

Biomass in the analogue wilderness biomes continued to increase during the period when Biosphere 2 was operated as a closed ecological system (1991–1994), with woodland canopies rapidly developing in rainforest, savannah, and marsh. The Biosphere 2 desert biome self-organized in an unexpected way and resulted in a community dominance shift from cacti/succulents to shrubs/annuals. Ocean water clarity was greatly improved with the installation of protein skimmers constructed from materials available inside Biosphere 2 and post-closure studies showed the maintenance of most coral species and the start of many new coral colonies. Overall, fewer species appear to have been lost than anticipated, though what level of biodiversity will be maintained in the various biomes was a question designed to be studied over the long-term operation of Biosphere 2 (4, 20).

Biospheric laboratories can provide data and model experiments for the field of restoration ecology, since the issues of small numbers of organisms and small areas and the sustainability of critical biodiversity are shared with many natural areas (49). In Biosphere 2, this was especially illustrated by the creation of a very flourishing mangrove marsh system, a system that had been thought quite difficult to restore. More fundamentally, biospheric laboratories can contribute to the transformation of ecology from a descriptive to an experimental science because all the variables can be measured starting from known initial state conditions and integrating ongoing energy and information inputs. Experimental biospheres can be to the life sciences what cyclotrons are to physics.

3.1.2.6. Variety of Purposes for Biospheric Experiments

Biospheric experiments can yield valuable insights on the interactions between natural ecosystems and global technical systems (27). They can also operate as unique test facilities for long-term space stations, travel, and space settlements where inhabitants must operate bioregenerative and technical systems as a synergy. Learning to integrate advanced technical systems with complex life systems can be of immense educational value, both in hands-on training of a managerial corps for complex projects, a corps able to handle the difficulties of contemporary life and in providing general principles for the general public by outreach education. Another use is to take advantage of the isolation of biospheric systems for conducting potentially dangerous experiments on new chemicals, pollutants or genetically modified life forms to see their impact on complex ecosystems. Smaller scale closed life systems cannot provide this scale and quality of results. Deciding which of the possible results are aimed for is a fundamental design control (Allen et al, 2003). Spin-off benefits from biospheric experiments include valuable insights as to human behavior, cultural formation, and ways for humans to integrate their sciences, arts, and enterprises into a harmonious dynamic. This potentially integrated world has been called by Vernadsky and others as a noosphere, or a world of intelligence (25, 40).

3.1.3. Mars on Earth® Closed Ecological System Project

The Mars on Earth® (MOE) Project is a simulation of a four-person life support system for a Mars Base that is located on Earth. Phase 1 of the project includes the design, construction, and operation of a prototype life support base – the Mars Base Modular Biosphere – that will support a crew of four people. This closed life support system will provide a test bed for developing space-based life support systems, such as water and wastewater recycling, food production, air purification, etc. that will be needed to undertake a manned mission to Mars (50). Project location is still to be determined.

The Mars on Earth research and development agriculture system consists of six modular units each with a footprint of 110 sq m (total 660 m^2). Approximately 478 m^2 will be used for growing crops leaving approximately 182 m^2 for access, equipment, and processing. The units will be soil-based using soils produced by amending simulants of Mars surface soil, since the goal is to use in situ planetary resources. The goal of the Mars on Earth facility is to produce a complete diet and to recycle all waste products, including human waste from the crew while maintaining an atmospheric balance suitable for plant growth and human habitation. Six modular units provide both variety in temperature regime and safety in redundancy. The units will share air and water circulation system, but be linked in such a way that they could operate independently or in case of damage be isolated from the rest of the system.

Crop composition is outlined below (Table 11.3). Ten basic crops can provide 3,000 Kcal, 79 g of protein, and 35 g of fat per person per day. These crops would be supplemented with vegetables, herbs, and spices, from a 32.5 m^2 area. Table 11.4 shows some estimated yield

Table 11.3
Projected diet based on ten major crops, Mars on Earth® Prototype Space Life Support System (43)

Crop	% of diet	Kcal/ person/ day	Crop wt/calorie content (Kcal/g)	Gams of crop per day	Protein content grams	Protein from crop/day	Fat con- tent/ gram	Fat from crop/day
Rice	15%	450	3.5	128.57	0.13	16.71	0.01	1.29
Wheat	10%	300	3.3	90.91	0.13	11.82	0.02	1.82
Sweet potato	25%	750	1.06	707.55	0.01	7.08	0.0028	1.98
Peanut	5%	150	5.84	25.68	0.26	6.68	0.48	12.33
Soybean	5%	150	4.02	37.31	0.08	2.99	0.18	6.72
Pinto bean	10%	300	3.42	87.72	0.24	21.05	0.0086	0.75
Winter squash	7.50%	225	0.634	354.89	0.01	3.55	0.001	0.35
Beet root	7.50%	225	0.445	505.62	0.01	5.06	0.0002	0.1
Banana	10%	300	0.6	500.00	0.006	3.00	0.02	10
Papaya	5%	150	0.26	576.92	0.003	1.73	0.0007	0.4
Total		3,000		3,015.18		79.66		35.74

Table 11.4
Projected light levels, yield and estimated cropping area for Mars on Earth® Biological Life Support System (43)

Crop	Kcal required for 4 crew daily	Best yield Bio (kg m^{-2} d^{-1})	Light level (mol^{-1} m^{-2} d^{-1})	Correction factor for 50 mol^{-1} m^{-2} d^{-1}	Extrapolated Yield in 50 mol^{-1} m^{-2} d^{-1} kg m^{-2} d^{-1}	Extrapolated yield in Kcal/m^{-2} d^{-1}	Area 4 required for feeding crew
Wheat	1,200	0.0024	16	3	0.0073	24.38	49.22
Rice	1,800	0.0057	25	2	0.0114	40.55	44.39
Sweet potato	3,000	0.0160	25	2	0.0320	33.89	88.51
Peanut	600	0.0014	25	2	0.0028	16.32	36.77
Soybean	600	0.0013	25	2	0.0026	10.64	56.41
Pinto Bean	1,200	0.0037	25	2	0.0074	25.36	47.32
Beet (root)	900	0.0232	25	2	0.0464	20.45	44.01
Winter squash	900	0.0425	25	2	0.0850	54.32	16.57
Banana	1,200	0.0498	25	1	0.0498	29.64	40.48
Papaya	600	0.1084	25	1	0.1084	28.68	20.92
	12,000						445

Add 33 sq m of salad greens and other leafy vegetables, = 478 m^2.

Fig. 11.10. The Laboratory Biosphere facility, Santa, Fe, New Mexico (52).

figures and necessary crop growing area with a light input of 50 mol m^{-2} d^{-1}. After further research, design scenarios may call for less growing area to supply a Mars exploration crew of 4–5 (43). The diet utilizes the ten crops chosen; wheat, rice, sweet potato, peanut, soybean, pinto, beetroot, winter squash, banana, and papaya because of their success and suitability in the Biosphere 2 experiments. They are hardy, dependable, and relatively easy to harvest and process with a minimum of equipment. Supplemented with fruits and vegetables from the vegetable area and horticulture understory, they can form the basis of a healthy vegetarian diet (45, 51).

3.1.3.1. Experimentation in the "Laboratory Biosphere," Santa Fe, New Mexico

In preparation for the Mars on Earth Project, the "Laboratory Biosphere" (Fig. 11.10), a new closed ecological system test bed was designed, constructed, and put into operation by the initial consortium of Global Ecotechnics Corporation, the Institute of Ecotechnics and the Biosphere Foundation. Currently the facility is owned and operated by the Global Ecotechnics Corporation in Santa Fe, New Mexico (52). The facility was initially sealed in April 2002; and three experiments using soybeans, wheat and sweet potato as the chamber's crops were conducted between May 2002 and January 2004 (53). The Laboratory Biosphere was created as a test bed to continue experiments with a sustainable soilbased agriculture system unlike most bioregenerative systems, which use hydroponic systems dependent on the supply of nutrient solution. Because of the small volume of the system (34–43 m^3), (Table 11.5), developing mechanisms to keep parameters like carbon dioxide within acceptable limits is critical. Recycling of nutrients within the system to maintain soil fertility and the ability of

Table 11.5
Component volume and mass of Laboratory Biosphere Closed Ecological Facility, Santa Fe, New Mexico (52)

Component	Volume, m^3	Mass, kg
Fixed air	33.6	32
Variable air (lung)	0–9	0–8
Soil (dry)	1.46	1,650
Water	0.3–0.5	300–500
Plants (variable)	0–0.02	0–20 (estimate)

the inherent complex ecology of soils to handle trace gas buildups are primary research goals. Other objectives include studies of short and long-term exchanges of carbon dioxide, oxygen, nitrogen, NO_x, and methane between soil, plants and atmosphere, the impact of cultivation (tillage) on soil/atmospheric exchanges, investigation and development of strategies to return nutrients to the soil to maintain fertility, (e.g., shredding biomass vs. composting) and the impact on soil chemistry of returning leachate water to the soil as irrigation water. Integration of automated sensors and controls in the system with real-time modeling has importance for operation, research, and educational outreach programs. The Laboratory Biosphere is also intended to test and develop a "cybersphere" (network of shared intelligence) that may be scaled up for the Mars on Earth project as well as having potential applications for natural ecosystems and global biosphere research.

3.2. Russian Research in Closed Ecosystems

The history and methodology of experimental work on creating closed ecological systems in Russia owes its inspiration to the concepts of "Russian Cosmism," an important philosophical system in Russia during the nineteenth century. In the beginning of the twentieth century, K.E. Tsiolkovsky, a forerunner of Russian cosmonautics, wrote that planet Earth was like a "cradle" for human civilization and commented that it was impossible for humanity, to, stay in the cradle forever. Tsiolkovsky's concept of a "greenhouse" for space flights is amazingly close to modern experimental findings on creating closed ecological systems (54). V.I. Vernadsky, elaborating the concept of the biosphere as a planetary-scaled essentially closed material cycle, was convinced that it would be possible to sustain life indefinitely in a system with a closed material cycle.

Experimental work on creating biological life support systems on the basis of closed loop, internal material cycling, started in the Soviet Union in the 1960s.

3.2.1. Experimental Facilities of IBMP (Moscow)

The Institute of Biomedical Problems (IBMP), founded in Moscow, organized a specialized department to work out the biotechnological foundations for biological life support systems. General biological concepts of closed ecological ecosystems and their space applications were developed (55, 56).

Microalgae were chosen for the first experiments as the main metabolic balancing link (to coordinate with the human metabolism). It was assumed that the CO_2 produced by humans would be removed by the algae, which would incorporate its carbon into their structure. The O_2 produced by algae would be released for human use. Also, it was assumed that humans could directly utilize algae as a food.

The first experimental installation was constructed in the IBMP. It allowed direct gas exchange, and later water exchange, between a human and microalgal culture. Five experiments were conducted, in which three cultivators (15 l in volume each), containing a culture of 10–12 g/l density of dry matter, continuously provided requirements of the human, placed in the sealed cabin 5 m^3 in volume, for atmosphere and water regeneration during 29–32 days. During the experiments, a CO_2 imbalance, amounting to 5–17% per day, was recorded, as a result of the difference between the human respiratory quotient and the assimilatory quotient of microalgae. The gas closure of the "human–microalgae" system reached 90%. Carbon monoxide and methane concentrations, and quantity of microorganisms in the atmosphere also were stabilized (56).

Next steps to close the system further were to be connected by closing the trophic cycle. Unfortunately, microalgae could not be extensively used as food (The biochemical composition of algal biomass, containing over 60% of proteins and nucleic acids, does not conform to human nutritional requirements, not less than 60% of which must be supplied by carbohydrates).

This was the main reason, which motivated early Russian researchers to include higher plants as a traditional source of food for humans. A greenhouse was part of the Ground Experimental Complex (GEC). Environment in the GEC was regenerated principally by physicochemical processes; the greenhouse was a source of fresh food (The greenhouse, 15 m^2 in area, daily produced 482 g of dry biomass, including 86 g of edible biomass: 54 g of wheat and 32 g of vegetables). Only 18% of the produced biomass was used for food. It was obvious that transformation of unused plant biomass to food was necessary in order to increase material closure of the system (57).

The principles of intensive cultivation of autotrophic and heterotrophic organisms as BLSS (biological life support systems) components were established and laboratory prototypes of BLSS incorporating humans were designed and tested. Six ground-based experiments were performed in which atmosphere and water were regenerated in closed ecosystems, including unicellular algae, higher plants, and one to two human subjects. These systems were designed to fully regenerate atmosphere, water and grow some of the crews' food (58). Creation of closed ecosystems for a space crew requires test verification of various components of these systems during orbital flights. To this end, an effort was made to devise associated experimental equipment and start investigations on growth, development, and cultivation of biological species (animals, lower and higher plants) as BLSS components in microgravity.

Some animals were choen to be included in the human life support as producers of animal protein: Possible candidates were quail and fish (59). For the first time, animals were tested in real space flights, using short bio-satellite flights and onboard Mir Space Station (60).

Since 1990, the orbital complex MIR has witnessed several incubator experiments for the determination of spaceflight effects on embryogenesis of Japanese quail. First, viable chicks that had completed the whole embryological cycle in MIR microgravity hatched out in 1990; it became clear that newborns would not be able to adapt to microgravity unaided. There were eight successful incubations of chicks in the period from 1990 to 1999.

The experiments were marked by high mortality rate at various phases of embryonic development and a number of developmental abnormalities. The number of embryos with these abnormalities varied from 12 to 26% in different experiments and did not correlate with the total number of dead embryos; however, the types of abnormalities were the same as may happen during incubation of eggs on Earth (microphthalmia, ectopia, abnormal development of limbs). At present, there is no clarity about causes of the developmental abnormalities in space embryos. The experiments on bird embryogenesis in microgravity showed that embryonic development of birds does not depend on the gravity factor. It is necessary to study the whole cycle of development of embryo from the moment of egg insemination and early stages of zygote division. This is the only way to fully evaluate the significance of the gravity factor for avian embryogenesis, and the role of shifts in the egg macrostructure occurring in microgravity as one of possible causes of developmental abnormalities (61).

The initial attempt to grow leaf cabbage and radishes in a mini "greenhouse Svet" (a small plant growth unit developed for spaceflight experimentation) onboard space station Mir was made in 1990. The experiment showed normal morphogenesis of plants in microgravity. However, space plants were conspicuously behind ground controls in their growth and development rate, and so they were significantly smaller. This was attributed, among other reasons, to peculiarities of moisture transfer in capillary/porous media (artificial soils) in the zero-g environment. In preparation for the fundamental biological research on the MIR/NASA program, Russian and the U.S. investigators joined their efforts to develop the Greenhouse Environmental Monitoring System (GEMS) enabling monitoring and control of environmental parameters of plants. Outfitting of greenhouse Svet with GEMS allowed investigators to keep track of all plant growth parameters and to adjust water supply to the crop in Mir experiments (61).

The main purposes of the experiments with Greenhouse-4 and -5 were to investigate the reproductive function of wheat in microgravity, and to grow crops of several generations of wheat. The goal was achieved with the use of the well-designed cultivation technology and ethylene-resistant wheat species USU-Apogee. The experiments were further proof that in microgravity wheat growth and development proceeds on the same pattern as on Earth. The period of crop development to harvest as a whole was not extended. Neither were the individual phases of wheat development. Experiment Greenhouse-4 yielded almost 500 seeds from 12 plants.

A second generation of space seeds was obtained in experiment Greenhouse-5. The series of Greenhouse experiments on space station Mir showed the importance of compensating for the altered physical conditions in microgravity and providing the plants needs. Plant organisms can make up for the lack of the gravity vector by other trophic reactions and ensure productivity comparable with ground controls.

Space investigations of organisms – candidate components of closed ecosystems of life support – give grounds to assert the feasibility of development of LSS based on the biological turnover of substances for manned spacecraft. Autotrophs are able to sustain normal functioning within LSS in the zero-gravity environment, given appropriate equipment is designed to offset the microgravity-induced changes in ambient conditions and provide for plant organisms. Introduction of heterotrophs in space LSS is a more formidable problem since gravity is a very unusual condition for congenital reflexes and instincts of newborns, the absence of which creates grave difficulties for living in microgravity.

Missions to Mars will be the longest duration human space flight that we can anticipate in the next decades. The Martian LSS may include a greater scope of biological processes to regenerate environment than merely one greenhouse. Ground-based BLSS tests gave proof of the high efficiency of unicellular algae in oxygen and water regeneration (58). Five ground-based experiments were conducted at IBMP to study closely the human–algae-mineralization life support model. The system for one person was $15\,m^3$ in volume and contained 45 l of algal suspension (dry algae density = 10–12 g/l of water), water volume, including the algal suspension was equal to 59 l. More sophisticated models in which unicellular algae were replaced partially by higher plants (crop area = $15\,m^2$) were tested in three experiments with a duration of 1.5 to 2 months. Algae, as a primary BLSS component in the, ground-based experiments, were able to fully regenerate atmosphere and water, and to provide the following: Partial closure of the nitrogen cycle due to complete consumption of the human urinal nitrogen by unicellular algae; purification of the pressurized chamber atmosphere from various water-soluble gaseous admixtures through adsorption and utilization in a photoreactor filled with algae and associated microorganisms (a photoreactor is a hydrobiological filter); optimization of the airborne ions and aerosol balance in the atmosphere (negatively charged ions normally dominate in pressurized chamber atmosphere); stabilization of water-insoluble gaseous admixtures in atmosphere (methane, carbon monoxide, and others) as a result of their adsorption on the surface of algal and microbial cells, and subsequent withdrawal together with the biomass yield, ousting from the microbial populations, by competition with foreign microflora to the algobacterial ecosystem in the photoreactor microflora, including human pathogens. In other words, though simple by structure, BLSS based on unicellular algae carries out a multitude of functions, including regeneration of atmosphere and water, as well as some other specific functions through which the human environment becomes healthier (58). Polyfunctionality of the biological regeneration of the human environment is another argument for its integration into space life support systems.

Life support systems with the use of a biological material cycle for humans outside the realm of Earth's biosphere can be divided into two classes: (a) For interplanetary vehicles (IPV) and (b) for planetary outposts (PO). IPV LSS may represent one or another embodiment of the system in which unicellular algae will constitute the autotrophic element and participate in regeneration of the environment alone with a cluster of biological and physical–chemical systems. Microgravity is the factor that will, in many respects, define the look of future IPV LSS as it will require the development of innovative technologies and techniques to ensure normal system operation, particularly of the biological component. The reason why unicellular algae are given preference as the basic IPV LSS autotrophic element is that their population, in contrast to higher plants, possess a number of very important features, which are the presence of much greater numbers of organisms, short life cycle (hours), tolerance to stress factors, autoselection, a huge diversity of metabolic functions and, as mentioned above, polyfunctionality as a environment-forming element (62).

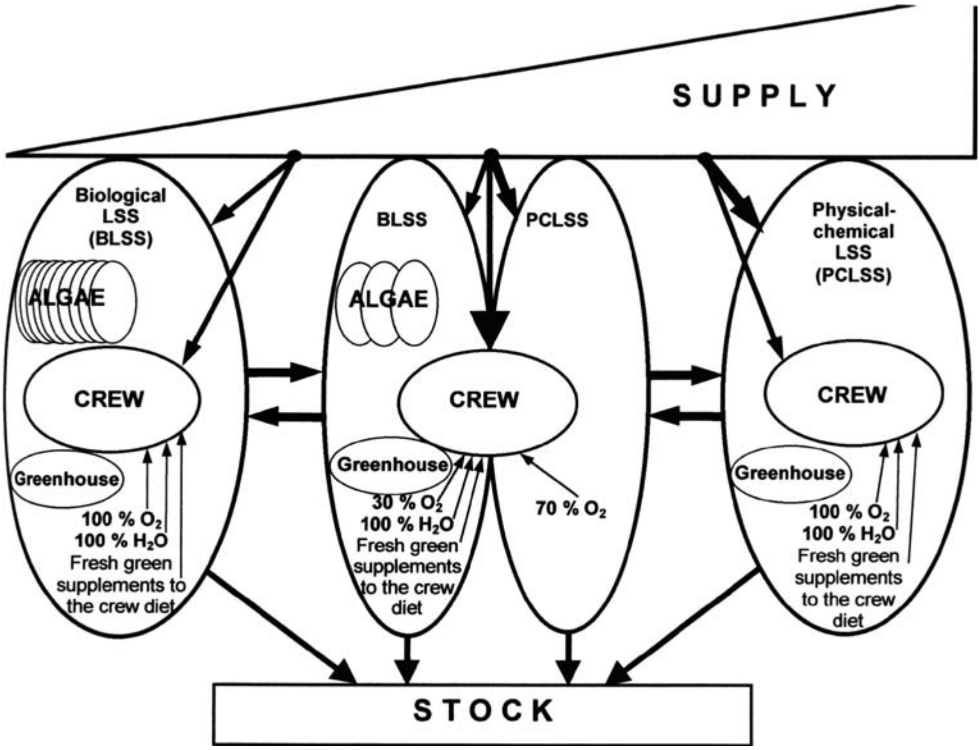

Fig. 11.11. Functional diagram of LSS of a space vehicle outbound to Mars (IBMP) (61).

For a long period of time, any future Martian crew will be separated from the biosphere of Earth, and therefore, LSS should be highly robust and reliable, and fully redundant. Redundancy can be achieved by installation on the Martian vehicle of two systems with different regeneration machinery, i.e., based on both physical–chemical and biological processes, each one will have the property of serving all the physical needs of the Martian crew. The best plan is to make the two systems function concurrently, each one fulfilling a specified portion of the regenerative functions.

The functional diagram of LSS is shown in Fig. 11.11. It is based on the assumption that urine processing by unicellular algae will result in a 30% supply of the autotrophic element from the total crew demand in oxygen. The urine will be fully consumed by growing and developing algae. That is why it is believed that nominally the LSS biological component will regenerate 100% of water, 30% of oxygen and consume 30% of CO_2. In case of physical–chemical underproduction of oxygen, within 24 h oxygen production by unicellular algae can be doubled. The size of stored reserves will be largely determined by the requirements of physical–chemical LSS, for in view of the technologies used on the present-day orbital stations, water electrolysis will remain the main source of oxygen for the crew. The diagram (Fig. 11.11) is considered to be very preliminary and will require more careful development work and more integrated studies, particularly at transition periods when one of the LSS components starts increasing its rate of production. However, this composition of LSS for an expedition to Mars will enable the resolution of many issues, including robustness and reliability of the LSS functioning during long periods of absence of any connection with Earth's biosphere, and adequate sustenance of the human environment (62).

The construction of the real full BLSS for space crews cannot be done without international cooperation in the theoretical and experimental groundwork for using these systems in space.

3.2.2. Experiments with Bios-3 (Institute of Biophysics, Krasnoyarsk)

In all experimental ecosystems implemented before Bios-3, the human test subject participated in the system only as a metabolic link. Transferring control to within the system required the development of new technological variants and bioregenerative techniques: It was necessary to reduce the hours spent on technological operations, to minimize the types of analyses essential to system governance, and to prepare the system inhabitants to work independently in maintaining the life support system. Bios-3 was constructed to implement and to research experimental ecosystems with internal control.

The experimental complex Bios-3 is illustrated in Figs. 11.12 and 11.13. Bios-3 is enclosed in a stainless steel, hermetically-sealed, rectangular, welded housing of dimensions $14.9 \times 9 \times 2.5$ m. It is partitioned into four equal and airtight compartments. The higher plants (grown in phytotrons) are accommodated in two of these compartments, one is occupied by the unicellular algae growing in cultivators, and the last is inhabited by a crew of three people. In the crew's compartment, there are three individual cabins, a kitchen–dining room, and a room equipped with a shower and a toilet. One of the cabins can be materially sealed to study the metabolism of the person located within it. The toilet serves as the entrance to the whole complex through an entryway compression airlock. The crew's compartment also includes a common area that functions as a laboratory, studio, and recreational room (16).

The overall dimensions of the complex are 315 m^3. The volume of each compartment is about 79 m^3. All the compartments of the complex are joined by airtight doors, and there are airtight doors that open to the outside of the complex from each compartment. Each door is designed to be opened by one person from the inside and the outside, when necessary, in no more than 20 s. This was extremely important for maintaining the safety of the test subjects: They were able to leave Bios-3 without delay and without external help in cases of danger from fire, etc. (Figs. 11.12–11.14).

Experiments testing prolonged human life in the Bios-3 Life Support System were conducted from 1970 to 1980. What follows are some results of the Bios-3 experiment that began on December 24, 1972 and which ended according to schedule on the 180th day on June 22, 1973. It consisted of three phases, each 2 months long, which differed in their mass transfer characteristics.

During the first phase of the experiment, the system consisted of two phytotrons containing both a wheat culture and a selection of vegetables and a living compartment for the crew. All crew requirements for gas and water were satisfied by the higher plants. Graywater (sinks, showers, laundry) from the living compartment was pumped into the wheat's nutrient medium. Solid and liquid wastes from the crew were removed from the Bios-3 complex. Crew food

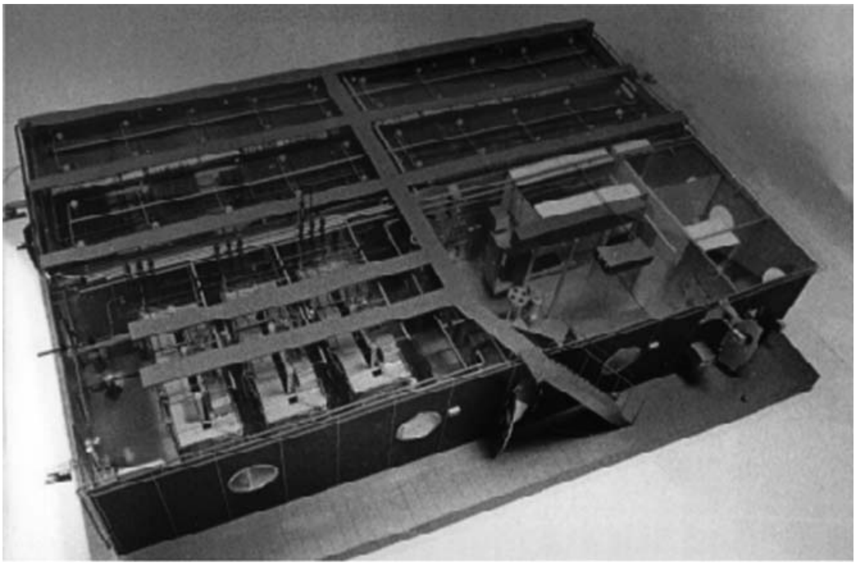

Fig. 11.12. General view of the Bios-3 (model with transparent roof). Front left – algal compartment; right – crew compartment; back – two higher-plant compartments. Light sources are on the roof of installation. Ladders and gangways on the roof are for servicing light sources. On the front wall, to the right – entrance of one of crew's cabins. To the right and left of it – airlocks for passing tools, chemical reagents, and other things in and out (16).

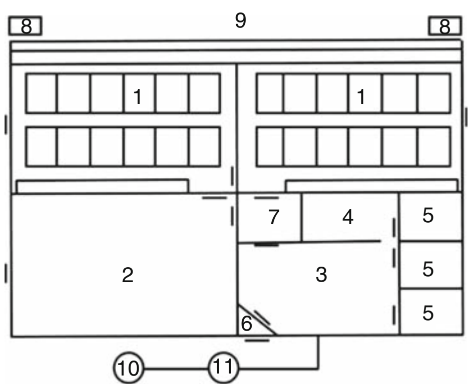

Fig. 11.13. BIOS – 3. Design of the Bios-3 experimental system. 1 – phytotrons; 2 – algal cultivator compartment; 3 – living quarters; 4 – kitchen–dining-room; 5 – cabins; 6 – toilet lock; 7 – vestibule; 8 – pumps of the cooling system for light sources; 9 – watering collector of the heat exchange wall of phytotrons; 10 – pressurization compressor; 11 – bacterial filter (16).

requirements were satisfied in two ways. The grain (bread) and vegetables produced by the higher plants provided fresh food, and the freeze-dried (lyophilized) food stores stocked in the Bios-3 complex at the beginning of the experiment were sources of animal protein and other processed food (16).

Fig. 11.14. Harvesting in the Bios-3 phytotron crop section (16).

During Phase II of the experiment, one phytotron was removed from the system, and a compartment containing *Chlorella* cultivators was introduced in its place. The cultivator photoreactor enabled the system to attain a higher degree of closure with respect to gas and water exchange. Human gas and water exchange requirements were satisfied by the combined photosynthetic activity of the photoreactors and the phytotron. Crew liquid wastes were consumed by the photoreactors; the solid wastes were dried so that water could be returned to the system. The nutrition system supplying the plants remained as it was in Phase I.

In Phase III, the phytotron containing wheat and vegetables was replaced with a phytotron containing only a selection of vegetable crops.

System mass transfer with the surrounding environment and between links was studied and described as the daily movement of mass throughout the system. The human role in the mass transfer of an autonomous system did not differ from the same human role in a nonautonomous ecological system. The crew fit into the closed ecosystem like a single ecosystem link with characteristic rates of consumption of resources (air, food, water) and the production of metabolic byproducts, gaseous, liquid, and solid. A link composed of three people rather than one person is advantageous since temporary fluctuations in an individual's metabolism are smoothed over by the total metabolism of the three people taken together.

Trace element dynamics in the system was a special research topic (The trace elements were: iron, lead, nickel, chromium, aluminum, titanium, molybdenum, boron, copper, zinc, and manganese). It was found that macroelement dynamics – for instance, the dynamics of nitrogen and phosphorous – are controllable and balanced, as opposed to trace element dynamics that cannot be easily governed. Trace elements were emitted from certain components in the system, mainly from building materials, after which they accumulate elsewhere in the system. For instance, trace elements were accumulated in the edible parts of plants. During the length of the experiment, no toxic effects were discovered due to uncontrolled trace element dynamics, but the concentration of some of them in the solutions circulated within the system rose or fell two- to tenfold. Any imbalance in the movement of these trace elements poses a potential threat to the continued health and survival of the system. For future longterm missions, it will be necessary to pay special attention to the trace element dynamics of a closed system and to the ways to control them.

The closure of the material exchange cycle in the system is evaluated by the cumulative index $R = (1 - \mathrm{m/M}) \times 100\%$ (Where M = daily crew requirements, m = daily ecosystem requirements). System closure during Phase I for the "humans-higher plants" experiment was evaluated at 82% ($m = 6128.2$ g/day, $M = 34395.8$ g/day). When a third link, *Chlorella*, that consumes human liquid excretions, was introduced into the system, then closure grew to 91% (16).

The composition of the atmosphere regenerated by the system was characterized by the presence of a series of organic volatiles and heightened carbon dioxide content – from 0.4 to 1% for short-lived spikes to 2.3% at various phases of the experiment. Volatile concentrations quickly reached equilibrium values and fluctuated around these values during the course of the remainder of the experiment.

An exception to this were the short-lived spikes in carbon monoxide concentrations or other carbon compounds, which occur during emergency situations and which are subsequently corrected by the crew. After the system returned to its normal state, CO concentration was maintained at a low equilibrium level by internal system procedures. These observations demonstrated that there were not only producers, but also consumers of CO in the system. Levels of CO could be maintained at steady-state by processes internal to the system only if this were the case. This conclusion is applicable to other toxic gases measured in Bios-3's atmosphere (16).

At various stages of the experiment, the condensate water collected from the green plants in the phytotrons and algal cultivators served as a source of drinking and sanitary/cleaning water. Water was procured from these sources and then purified over ion-exchanging resins and charcoal. After this final purification, this water satisfied health standards for drinking water.

The food consumed (rations and vitamins included) in a system containing two phytotrons provided three people with 26% of their carbohydrates, 14% of their proteins, and 2.3% of their fats. The foods yielded from plants grown in the phytotrons – the bread baked by the test subjects and the vegetables – did not differ in their biochemical composition and taste characteristics from high quality food produced by ordinary agricultural methods. Inclusion of these products in the diet boosts crew morale. During all phases of experiments, it was found that it was possible to maintain a balanced atmospheric composition by manipulating the biochemical composition of the crew diet within physiologically acceptable norms. Some results on the microflora dynamics, including microflora exchange are presented in the chapter in this book devoted to Microbial Ecology of CES (Somova et al. this volume).

Table 11.6
Calculation of daily gas exchange of the crew in one of the Bios-3 experiments (63)

	I stage			II–III Stages		
Indicator	Proteins	Fats	Carbohydrates	Proteins	Fats	Carbohydrates
Composition of ration (g)	230	230	1150	165	165	825
Assimilability of foodstuffs (%)	86.9	96.9	99.4	86.0	86.9	99.4
Assimilated quantity of foodstuffs (g)	200	223	1143	143	160	820
Quantity of O_2 necessary to oxidize 1 g of substance (l)	0.966	2.019	0.829	0.966	2.019	0.966
Quantity of CO_2 formed during oxidation of 1 g of substance (l)	0.774	1.427	0.829	0.774	1.427	0.829
Quantity of O_2 necessary to oxidize assimilated substances (l)	193	450	948	138	323	680
Quantity of CO_2 formed during oxidation of assimilated substances (l)	155	318	948	111	228	680
Total quantity of consumed O_2 (l)		1,591			1,141	
Total quantity of released CO_2 (l)		1,421			1,019	
Respiratory coefficient		0.893			0.893	

Comprehensive medical examinations of test subjects during the half-year experiment and for an extended period after the closure experiment revealed neither any worsening of their health nor any deviations of their physiological parameters from the original state. So, it was concluded "that the habitat generated in Bios-3 is adequate for human physiological and ecological requirements, and a healthy human can stay in this biological life support system for quite a long time" (16).

Table 11.6 gives the results of the gas exchange during the 1977 four-month closure in Bios-3 (63).

3.3. European Research on Closed Ecological Systems

European efforts have included much work on microgravity issues of biological development, essential to the successful translation of ground-based CELSS to space, and work on basic physiological responses of plants to environmental factors (such as that of André and associates at CNRS, Cadarache, France (64). Binot and colleagues at the European Space Technology Center at Noordwijk, the Netherlands are studying various microbial systems as elements in spacecraft life support systems. Closed ecological system research by the European Space Agency under the "MELiSSA" program is being conducted at the University of Barcelona, Spain and is summarized in the chapter on the microbial aspects of CES by Somova et al (this volume) and below.

3.3.1. The Closed Equilibrated Biological Aquatic System

The Closed Equilibrated Biological Aquatic System (C.E.B.A.S.) was developed by V. Blüm and co-workers at the Ruhr-University of Bochum (RUB). It was originally designed as an aquarium for long-term zoological space research. Research on the idea of a balance, sustainable system utilizing aquaculture of plants and fish began in 1985 in ground-based, open experimental format. As it eventually developed, C.E.B.A.S. can be described as a closed ecological system based on an engineered aquatic ecosystem, which contains fish and/or water snails, bacteria which are capable of oxidizing ammonia and water plants, which add oxygen and are a food source for the other tropic levels. It serves as a model for aquatic food production modules, which are not seriously affected by microgravity and other space conditions. Its space flight version, the so-called C.E.B.A.S. MINI-MODULE was successfully tested in spaceflight on the STS-89 and STS-90 (NEUROLAB) Space Shuttle missions.

The balance of the ecosystem relies on the management of the green plants, which as the autotrophic producers through photosynthesis produce organic compounds by the conversion of light energy into chemical energy. This process also produces oxygen, which is essential for the metabolic respiration of the animals (the fish and snails) and the bacterial microbes, all of whom function as the consumers in the closed ecosystem. The consumers in turn produce carbon dioxide, which is required by the plants for their photosynthesis. The nitrogen cycle is kept cycling since the consumers excrete ammonia, which is then converted by bacterial action into nitrate, which can be used by the plants (Fig. 11.15).

The live-bearing fish *Xiphophorus helleri*, the swordtail used in the vertebrate models of the experimental apparatus and the water snail *Biomphalaria glabrata*, used in the invertebrate version, were chosen after evaluation of their adaptive and physiological features, which make them extremely suitable to address the scientific goals. The plant bioreactor is designed for rootless, buoyant higher water plants with a high capacity for nitrate and phosphate ion uptake. *Ceratophyllum demersum* (horn-weed) was chosen as the most suitable species.

After initial development of C.E.B.A.S., it has been further developed as a test bed for animal/plant biomass production systems for Earth application (Fig. 11.16), as well as a very promising approach for bioregenerative life support systems for human food production and water and oxygen regeneration in space. The scientific program was then extended and currently four German and three U.S. American universities are involved in the research project. The scientific areas cover biomineralization (snails: W. Becker, U. Marxen) University of Hamburg; fishes: S. Doty, Hospital of Special Surgery, New York); CES-analysis (V. Blüm, M. Andriske, RUB); embryology (snails: W. Becker, fishes: V. Blüm, F. Paris, RUB); immunology (fishes: R. Goerlich, University of Düsseldorf); microbiology (W. Rueger, RUB);

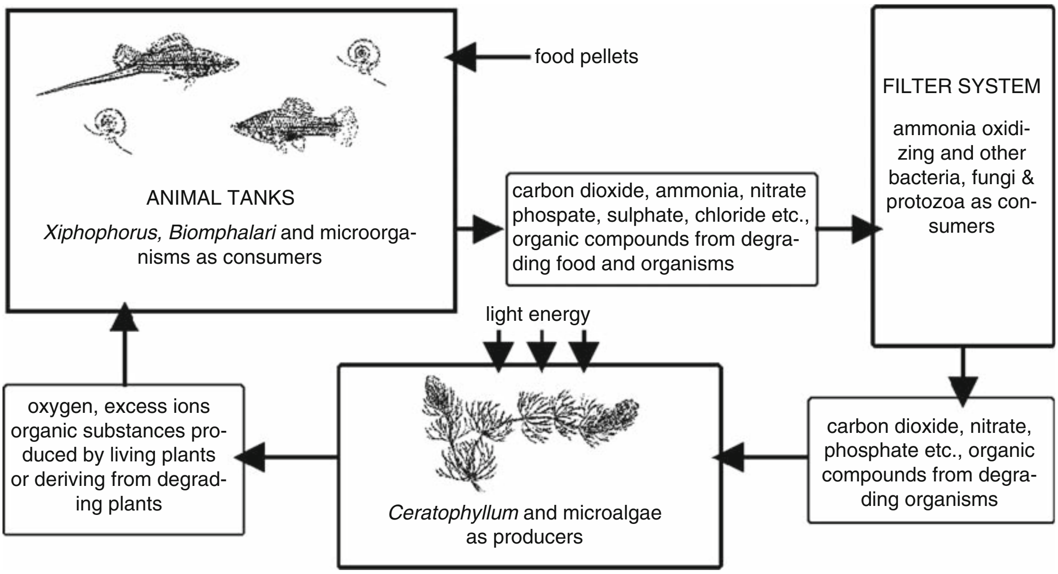

Fig. 11.15. Functional relationships of the basic components of the C.E.B.A.S. The animal tank is combined with an aquatic plant bioreactor and with a bacteria filter, which contains ammonia oxidizing bacteria (65).

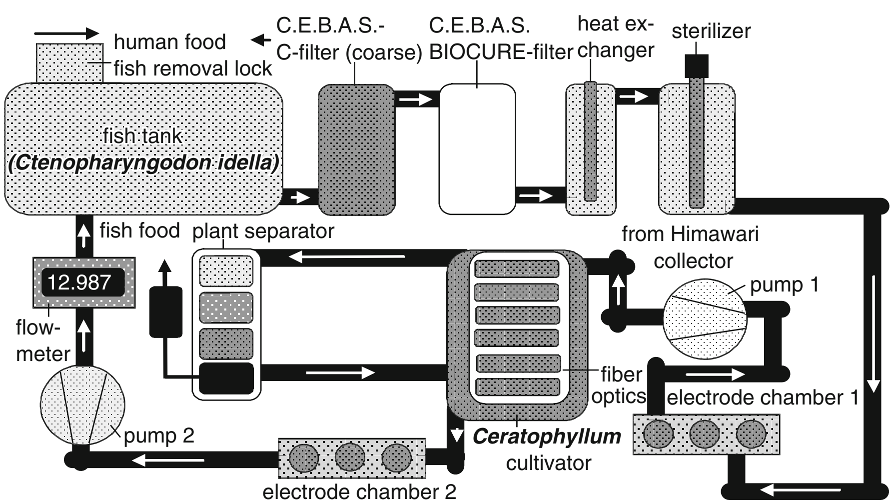

Fig. 11.16. Schematic of a variant of C.E.B.A.S. for high intensity production of fish and plants in terrestrial applications (65).

neurobiology (fishes: H. Rahmann, R. Anken, University Stuttgart-Hohenheim); plant morphology/physiology (H. Hollaender-Czytko, D. Voeste, RUB); statocyst/vestibular research (snails and fishes: M. Wiederhold, University of Texas, San Antonio); and reproductive endocrinology/physiology (fishes: V. Blüm, F. Paris, RUB, M.P. Schreibman, Brooklyn College, New York). They are closely linked to applied projects in the field of innovative combined animal–plant aquaculture (V. Blüm and co-workers) (65).

The C.E.B.A.S. exists in two different versions: The original C.E.B.A.S. with a total volume of about 150 l and the C.E.B.A.S. MINI-MODULE, which is operative in several types with volumes between 7.7 and 10 l. The first completed mid-term tests were over 9 and 12 months. The latter passed numerous tests up to 3 months duration. The C.E.B.A.S. MINI-MODULE was developed to fit into a space shuttle middeck locker tray as a spaceflight version. After numerous successful tests of the laboratory models, the spaceflight hardware was constructed by OHB Systems in Bremen.

The results of the space experiments with the C.E.B.A.S. MINIMODULE confirmed the initial hypothesis that aquatic organisms will not be seriously impacted by microgravity and other space environmental factors. A brief summary of major findings included (66–70):

- The fish behaved normally, orienting themselves with respect to the light source and tank walls, and exhibited normal patterns of feeding and domination/hierarchical fighting. Their overall bodily coordination was unimpaired. Loop swimming was only observed for a brief period during a docking maneuver. Reproductive system was functional as evidenced by birth of new fish in space and embryonic and early development of juvenile fish was normal. There were no peritoneal fat deposits which indicates insufficient nutrition.
- The snails adhered to the substrate, and when they floated free in the water stream, they stretched their bodies out of their shells, made contact with other floating snails and adhered to each other. Embryonic development and biomineralization of the shell were also unimpaired.
- Ground control plants and the spaceflight water plants behaved similarly. Photosynthesis was excellent and there was high biomass production. In the STS-90 mission, reductions in productivity were attributed to self-shading. Both spaceflight and ground-control plants flowered. "The only morphological change observed was a irregular arrangement of starch grains in the cells of the xylem–phloem sheath of spaceflown plants, which is radial in ground plants" (65).
- The bacteria in the microbial filter also performed well. In the STS-89 mission, bacterial density was comparable to those in natural ponds. In the STS-90 missions, a much higher bacterial density was attributed to higher mortality of juvenile fishes, thus reducing the major predator.

3.3.2. The MELiSSA (Micro-Ecological Life Support System Alternative) Project

A major effort in bioregenerative closed ecological systems for life support is the Micro-Ecological Life Support System Alternative (MELiSSA) of the European Space Agency with numerous European, Canadian, and other international cooperation. The basic concept behind MELiSSA is to conjoin the metabolic abilities of both microorganisms and higher plants in a series of steps to create a closed loop, producing air, water, and food for astronauts in space. It should, when complete, be another powerful tool for research in the behavior of artificial ecosystems and for developing the capacity for life support on long-duration space missions. Key processes being developed are the recycling of waste (inedible biomass, feces, and urine), carbon dioxide and minerals and the production of food, fresh water, and air revitalization.

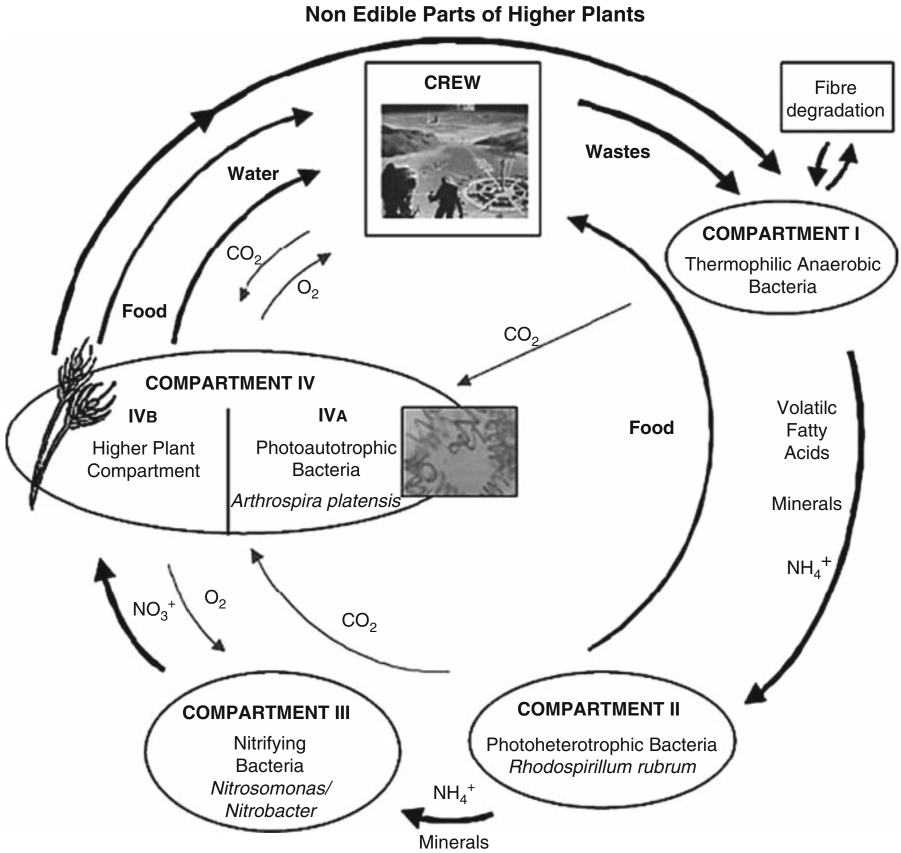

Fig. 11.17. Diagram layout of MELiSSA Loop (Microecological Life Support System Alternative) European Space Agency (http://www.estec.esa.nl/ecls/melissa/newmelissaloop.html).

Project design calls for the integration of various sub compartments of MELiSSA at a facility at the university of Barcelona, Spain. MELiSSA is being researched and built in various research and industrial labs in Europe and Canada. Construction of the project began in 1995, and now early versions of two of the three fermentation chambers are operational at the integrated facility in Barcelona. The complete pilot plant is expected to be fully operational by 2005 (http://extids.estec.esa.nl/melissa) (Fig. 11.17).

The closing of the loop in MELiSSA is conceived of as being effected through the interconnections of five internal compartments. Compartment 1 is the Liquefying Compartment where the wastes produced by the consumers (the crew) such as feces, urea, non-edible crop residues and non-edible microbial byproducts are collected and then anaerobically transformed into more usable forms, such as ammonia, hydrogen gas, CO_2, and minerals. The likelihood is that Compartment 1 will operate at high temperatures (55° C), using thermophilic fermentative bacteria to perform the microbial degradation of the waste materials. Research on the optimal mix of thermophilic bacteria has increased the rates of proteolysis from 15 to 70% using a consortium of bacteria. To improve this degradation level, several technologies are currently studied (subcritical oxidation, fungi, rumen bacteria, hyperthermophilic bacteria). Compartment 2 is the Photoheterotrophic compartment. Here, 2 subcomponents, photoautotrophs and photoheterotrophs, will eliminate the liquid waste products of Compartment 1. Recent research has led to the expectation that the very successful substrate degradation obtained with *R. rubrum* may lead to the necessity of a single second compartment, the photoheterotrophic one. Next step is the nitrifying step, accomplished in Compartment 3. Here, ammonia from wastes is converted to nitrates, which are more easily utilized by higher plants and autotrophic algae/bacteria. It is expected that a mix of *Nitrosomas* and *Nitrobacter* will be used in Compartment 3. Since this is essentially a fixed bed reactor, the importance of the hydrodynamic factors, loading/rate reactions and overall stochiometry of the process must be well understood and managed. The fourth compartment has two sections, an algae compartment with the cyanobacteria: *Arthrospira platensis* and the Higher Plant (HP) compartment. These compartments are essential for the regeneration of oxygen and the production of food. Eight candidate food crops are being studied: Wheat, tomato, potato, soybean, rice, spinach, onion, and lettuce. Research at the University of Guelph in Canada is examining biomass production rates, as well as mineral and nutritive content. Research into optimizing environmental considerations (light, nutrients, humidity), development of supportive technology for higher plant production and sensor development are also being undertaken (71) http://extids.estec.esa.nl/melissa.

3.4. *Japanese Research in Closed Ecological Systems*

Japanese research started under the leadership of Nitta and Oguchi of the National Aerospace Laboratory in Tokyo, initially concentrated on gas recycling systems, involving oxygen and carbon dioxide separation and concentration, water recycling systems, plant and algae physiology and cultivation techniques, as well as animal and fish physiology and breeding (72).

In the 1990s, a large and ambitious project “Closed Ecological Experimental Facility” (CEEF) was supported by the Japanese state, and the Institute of Environmental Sciences facility was founded on the Island of Honshu in Rokkasho, a small township in the prefecture Aomori.

Since, the, 1990s, great strides toward creating artificial closed ecological systems have been made by Japanese researchers, supported by generous financial aid from industry and government. It is evident that Japanese society, with a very high population density and insular psychology, is able to comprehend the crucial importance of biospheric problems for civilization. In a period of a few years, the project CEEF – Closed Ecology Experiment Facilities – has been designed and basically implemented (Fig. 11.18).

CEEF consists of a connected series of different subsystems: (a) For the cultivation of plants, Closed Plantation Experiment Facility, (b) for domestic animals, the Closed Animal Breeding (c) for the crew of two, the Habitat Experiment Facility, and (d) a Closed Geo-Hydrosphere Experiment Facility, which are schematically shown in Figs. 11.18 and 11.19. The material circulated in CEEF is controlled strictly in the materially-sealed closed system by air-conditioners and material processing subsystems. Only energy and information are exchanged with the outside. Each facility can be operated independently or linked with

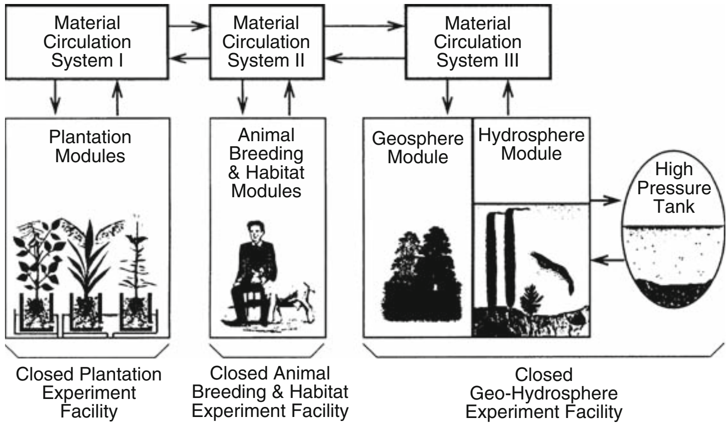

Fig. 11.18. Closed ecology experimental facility (CEEF) (From Closed Ecology Experiment Facilities (CEEF) (73).

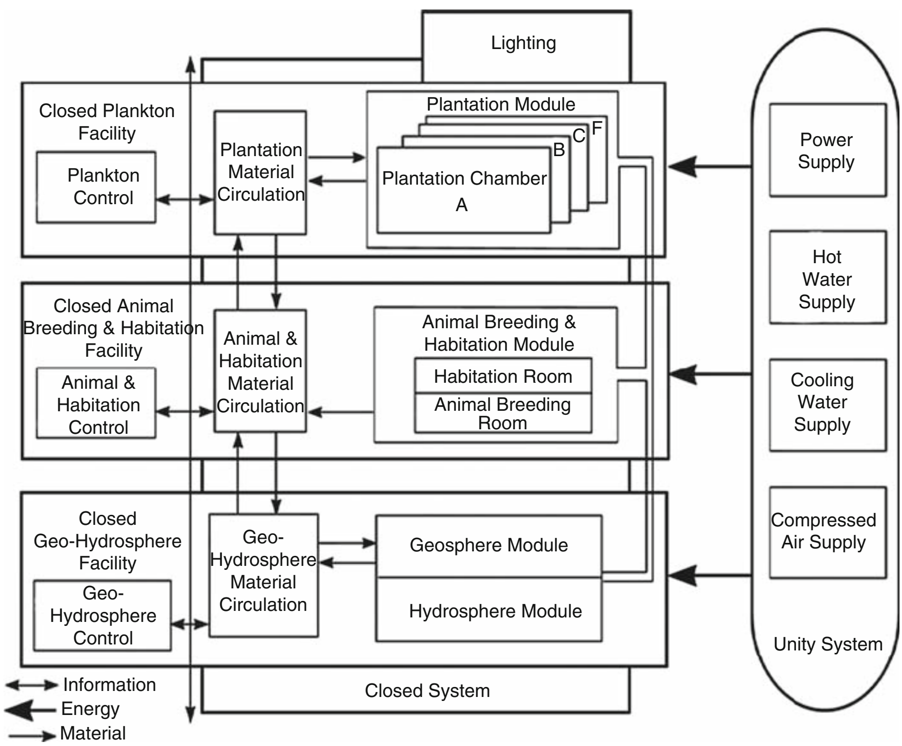

Fig. 11.19. System Configuration of Closed Ecology Experiment Facilities (CEEF) (73).

another facility. The subsystems of CEEF are a unique tool for the environmental sciences and other fields of research such as test beds for life support systems for human and Mars base application, the global change problem and furthering the solutions for a pollution-free or “zero-emission society” (73).

There are two basic important objectives for the CEEF facility. One is the topical problem of thorough investigation of the migration of radioactive elements by the metabolic pathways in ecosystems. Another objective is to model global change, specifically the ecological consequences of global warming. Thus, the closed ecological system is increasingly perceived not only as a means to support human life in a hostile environment – in space – but primarily as a tool for the experimental investigation of the problems of the Earth’s biosphere.

Special emphasis was placed on designing a physicochemical subsystem to form a closed loop of the material circulation of biological processes via the mineralization of wastes and end products to return the elements to the biological cycling. These technologies are called the Artificial Material Processing Equipment.

The largest industrial companies of Japan took part in manufacturing equipment and elaborating technology for the facility. CEEF and its subsystems are described in detail in publications of the Institute for Environmental Sciences (74).

Comparison of the complex Bios-3, operating in Siberia, and the system CEEF allows the conclusion that they complement each other. CEEF can separate the closed material cycle to quantify the flow rates and dynamics, of, numerous individual components, which can then be analyzed individually. Bios-3 (as well as successor biospheric systems like Biosphere 2) has made it possible to investigate the properties of ecosystems that emerge when they get closed, and that are not peculiar to any of its elements taken separately (16).

An integrated system is far simpler to operate owing to the multitude of natural, ecological cyclic processes occurring in it and auto regulatory feedbacks. This process is often called the “self-organizing principle” of natural ecosystems (e.g., (75)). As an example of a complication caused by the separation of functions in CEEF, we can mention that to avoid disruption of metabolic closure, the personnel servicing the system inside is provided with specially designed suits, similar to spacesuits, so that their respiration does not mix with the system gas exchange. In Bios-3, however, the crew services and controls the system entirely, their respiration being part of the system metabolism. However, to study particular processes, it is inconvenient, and sometimes absolutely impossible, to use the integral system. For this purpose, it would be expedient to turn to the Japanese “analytical” system separated into subsystems. Thus, the results, which will be obtained by the experiments on the closure in CEEF will add to the knowledge gained in other closed ecological systems and biospheric systems as well as the ongoing studies of natural ecosystems and the Earth’s biosphere.

The CEEF facility is still under development, although plant cultivation experiments with a 120 m^2 planting bed have been conducted. In addition to specific research, the facility is designed as a “mini-Earth” to allow investigation of processes analogous to those in the Earth’s biosphere, such as the dynamics of radioactive isotopes in agricultural, terrestrial, and marine environments (74).

In the past few years, the team working on CEEF also presented their first experimental data which includes understanding how higher crop plants and domestic animals might respond to environmental changes. The research leaders at CEEF think the facility could help in predicting the effect of small temperature rises, perhaps due to global warming, on rice growth. Nitta has also investigated the potential impact on the carbon cycle of small amounts of radioactive carbon dioxide that will likely be released into the air by the Rokkasho-Mura nuclear fuel reprocessing plant, which is currently under construction and could still be modified. This use of closed ecological systems for conducting experiments in controlled conditions shows the potential of the new discipline of biospherics as an appropriate predictive and experimental tool before such experiments are released unwittingly and tried on the global biosphere.

All of these unique facilities have a common fundamental goal – to model the biosphere – and a common practical objective – to create closed human life support systems. It is very complicated and costly both to construct these facilities and to use them for experiments. Since this work is important for humanity as a whole, it is necessary to coordinate the experiments at the preparatory stages and while analyzing the results, following the example of atomic physicists cooperating in using the few nuclear-particle accelerators existing in the world. The importance of the work on creation of artificial closed ecosystems for humanity as a whole and the complexity and high cost of experiments – all make further international cooperation in this field of knowledge imperative (4, 16, 19, 25, 37).

4. CONCLUSION

Tsiolkovsky, the Russian space visionary who laid the basis for modern rocketry and astronautics, also foresaw the need for regenerative life support systems in the spacecraft: "The supply of oxygen for breathing and food would soon run out, the byproducts of breathing and cooking contaminate the air. The specifics of living are necessary – safety, light, the desired temperature, renewable oxygen, a constant flow of food" (54).

The expansion of human presence into space, both in the microgravity conditions of orbital space and on lunar or planetary surfaces, will in one sense be but the latest in the series of expansionary advances of life. With man's growing technical ability to create living spaces out of contact with the Earth's biotic regeneration (as in submarines, high altitude aircraft, and spacecraft), and to voyage to extraplanetary ones, a new chapter in this biospheric expansion stands ready to be opened. The creation, initially ground-based and later off the Earth, of simple closed ecological life support systems, and eventually of stable and evolving biospheric systems, will mark the transition of life from one-planet phenomena to the one capable of permanent expansion into the Solar System and beyond.

Permanent human presence in space and a number of ambitious long-duration missions are beginning to emerge as significant goals in the evolving international space agenda. This changing framework of space development has had a number of important inputs, including the U.S. National Commission on Space, (41) which looked at the next 50 years in space and outlined a coherent set of objectives, which could build an effective space infrastructure. These studies emphasized the importance of bioregenerative life support as a key enabling technology. In 1988, the U.S. Congress amended NASA's charter to include permanent human presence as a legitimate part of its activity. This emerging American space agenda is similar to what many saw as the central focus of the Russian (then Soviet) space program whose accomplishments include the series of Salyut then Mir space stations, which operated for decades. Soviet plans, now derailed by lack of financial resources, included plans for lunar bases early in the twenty-first century, to be followed by manned exploration, and finally, Mars bases. For many years, the motto of the Soviet space life scientists had been: "On Mars we must grow our own apples!" Economic pressures make cooperative international ventures increasingly attractive. International cooperation in space is also valuable as a way of aligning all people of the Earth and inspiring them with our shared, grander historic and evolutionary challenges. The strategy of "evolutionary expansion" into space as opposed to space spectaculars with no infrastructural increase (known as "footprints and flags") is beginning to dominate space exploration planning.

This far-reaching space agenda requires, and is producing, a shift in life support away from the type of technologies that were developed for the sprint missions to the Moon or for short duration spaceflights. It is now becoming clear that bioregenerative life support is one of the chief technologies that can make possible our long-term future in space. It will be a huge undertaking to translate ground-based test bed work into plausible space-based systems. Living in space will also require better understanding of radiation hazards and defenses, measures to deal with microgravity and reduced gravitational effects on living systems, and the ability to utilize extraterrestrial materials. But, what is becoming clear to space planners and the public alike is that bioregenerative life support systems are the key to be able to *live* in space.

The Russian pioneer of the science of the biosphere, V.I. Vernadsky, saw that the challenge of our time was the harmonization of what he termed the "technosphere" with the biosphere. He foresaw the emergence of the "noosphere," a sphere of intelligence, which humanity must develop since our impacts on the global biosphere are so powerful.

H.T. Odum is considered the father of "Ecological Engineering," a new discipline, which seeks a symbiotic mix of man-made and ecological self-design that maximizes productive work of the entire system (including the human economy and the large-scale environmental system) (75). By minimizing human manipulation and the use of machinery, ecological engineering solutions aim to increase material recycling, enhance efficiency, reduce costs, and maximize the contributions of ecological processes in the total system. An important application of ecological engineering is the design of interface ecosystems, such as constructed wetland sewage treatment systems (as were developed by Wolverton (76) for NASA's life support systems, and further developed for Biosphere 2 (48)), to handle byproducts of the human economy and to maximize the performance of both the human economy and natural ecosystems (77).

H.T. Odum and E.P. Odum, the founders of Systems Ecology, tried in vain during the early days of space life support development in the 1960s to get a model of complex, high diversity species systems able to self-organize, accepted as a viable path of development. Instead the prevailing mode that has been extremely highly engineered systems minimizes such ecological diversity and robustness (78). It is perhaps time to heal this historical division within the field of space life support systems, recognizing the strengths that both approaches represent.

The opportunity and challenge for those working on bioregenerative technologies, CELSS and closed ecological systems for space life support is starkly underscored by their necessity to achieve successful recycling and stability of their systems in volumes far smaller than those of Earth's natural ecosystems, and with vastly accelerated cycling times. This means that there is enormous necessity for intelligent design to make small closed ecological systems function properly. In the coming decades, the opportunity exists for this work to become ever more relevant to the parallel efforts to understand the Earth's biosphere and to transform the human endeavor to a sustainable basis. We live in a virtually materially closed ecological system on Earth – and to live long-term in space, we will need to create new closed ecological systems. Learning to sustain, recycle and harmoniously live within our world(s) is the overriding challenge we face both on Earth, and if we are to live in space, whether in space stations or on lunar and planetary surfaces. The stakes are huge: We must learn from both efforts to prosper and evolve (79–82).

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