ELSEVIER

Ecological Engineering 13 (1999) 15–29

ECOLOGICAL ENGINEERING

Overview and Design

Biospherics and Biosphere 2, mission one (1991–1993)

John Allen [a,*], Mark Nelson [b]

[a] *Global Ecotechnics Corporation, 7 Silver Hills Rd., Santa Fe, NM 87505, USA*
[b] *Institute of Ecotechnics, 24 Old Gloucester St., London WC1 3AL, UK*

Received 12 November 1996; received in revised form 5 November 1997; accepted 30 November 1997

Abstract

This paper outlines concepts, construction and operation of Biosphere 2, the large glass closed life facility in the mountains of southern Arizona, USA. Plans used concepts of systems ecology and biospherics from the early writings of V.I. Vernadsky, work of the Russian space program on closed ecological life support systems and other leading proponents of a total systems approach to ecology. Mission one was the first experimental closure of Biosphere 2 with eight crew members for 2 years, 1991–1993. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Biosphere 2; Biospherics; Systems ecology; Space program; Closed ecological systems; Life support

---

1. Biospheric theory background

Biospherics can be defined as the science of energetically open, relatively materially closed life systems that increase their free energy over time (Morowitz, 1979, 1988). In biospherics, one studies the total structure, dynamics and morphology of each life system, including its evolutionary history, together with all its interactions with other forces and entities such as gravity and the sun (Allen and Nelson, 1989).

In 1989 at the Second International Workshop on Closed Ecological Systems at the Institute of Biophysics, Krasnoyarsk, Russia, meeting participants passed a resolution outlining the scope of biospherics as the study of partially closed

---

[*] Corresponding author.

PII S0925-8574(98)00089-5

ecological mesocosms and closed systems, such as Biosphere 2 and facilities which have been generally associated with the development of bioregenerative life support systems for space application. The resolution listed the following challenges:

- 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.
- To create biospheres for human life support beyond the limits of Earth's biosphere which are essential for permanent human presence in space.
- To create ground-based life support systems that provide a high quality of life in extreme conditions of the Earth's biosphere, as at polar latitudes, deserts, mountains, under the ocean, etc.
- To develop technologies for the solution of pollution problems in our urban areas and for developing high yield sustainable agriculture (IBP/IE, 1989).

Vladimir Vernadsky elucidated many core concepts of modern biospheric theory in his 1926 book on the biosphere (Vernadsky, 1986) as well as in his other writings on global biogeochemistry. He proposed two laws to describe and predict biospheric activities:

1. The biogenic migration of chemical elements in the biosphere tends toward the maximum of manifestation. He identified two kinds of migration of elements by the movements of the mass of living material and by anthropogenic material movements, especially ever-increasing human technical systems.
2. Vernadsky's second law is "the evolution of species, in tending towards the creation of new forms of life, must always move in the direction of increasing biogenic migration of the atoms in the biosphere" (Vernadsky, 1986).

Efforts of US scientists, including NASA (National Aeronautical and Space Administration), to develop closed ecological systems with and without people were reviewed by Beyers and Odum (1993).

Vernadsky had summed up his theories in the striking phrase that "a biosphere is a cosmic phenomenon and a geological force" (Vernadsky, 1986). His theory, united with Tsiolkovsky's vision of space greenhouses to regenerate oxygen and produce food (Tsiolkovsky, 1979), inspired closed life system research in Russia under the direction of Drs. Oleg Gazenko and Yevgeny Shepelev at the Institute of Biomedical Problems in Moscow and Josef Gitelson at the Institute of Biophysics in Krasnoyarsk, Siberia (Shepelev, 1972; Terskov et al., 1979). In 1961, Dr Shepelev was the first man in a closed life system when he lived for 24 h with a *Chlorella* algal reactor; later Terskov for 1 month (Terskov, 1975). Josef Gitelson directed the closed life system Bios-3, whose experiments during the period 1972–1984 included 3–6-month closures with up to a three person crew living with grain, root and vegetable crops and *Chlorella* (Gitelson et al., 1973). In 1986, the authors along with other colleagues of the Biosphere 2 project made contact with these pioneers of the field in Moscow. Because exchange of biological data in closed systems was permitted under the US/USSR Space Treaty and because of the generosity of the Russians with their extensive medical data and experience in the field, the Biosphere 2 project was able to identify more rapidly the problems of human physiologic and atmospheric gas dynamics in closed life systems.

2. Design principles and objectives

The Mission One closure experiment at Biosphere 2, Oracle, AZ, USA, was designed to operate for 2 years with a crew of eight healthy ‘Biospherians’ (Walford et al., 1992), with the aim of supplying the entire food needed for the crew (Silverstone and Nelson, 1996), maintaining a 200 m^3 atmosphere with safe levels of trace gases (Nelson et al., 1994), complete recycle of human and animal wastes and recycle of water and a minimum leakage of air—less than 10% per year (Dempster, 1993, 1994) and if it failed any of these aims, to analyze the causes to improve the apparatus.

In Biosphere 2 each biome was made with a species list that defined the range of its environmental parameters. Our control policies were set for each biome in terms of soil/sediment type, water quality, rainfall, current flow, wind flow, light, temperature, humidity and pH by specialists in each particular biome. We specified that all of the biomass would be subtropical or tropical (which simplifies the problem of water control to two state changes rather than three) and we specified a high temperature limit of 110°F for physiological reasons. Within those control specs, roughly 35–110°F for temperature, Biosphere 2 was to model Earth’s biosphere (Biosphere 1) as closely as possible (Dempster, 1989; Nelson et al., 1993) to best fulfill its purpose as a laboratory for the intensive study of global ecological processes, including the impacts of people and their technologies.

Scale numbers for construction were calculated based on study of Space Biospheres Ventures Test Module results (Nelson et al., 1991; Alling et al., 1993b), the work on the analog systems in the Biospheric Research and Development Center, the Bios-3 work at Krasnoyarsk (Gitelson et al., 1973), the Moscow work of Shepelev and Maleshka (Shepelev, 1972), Claire Folsome’s analyses of his 1-l ecospheres (Folsome and Hanson, 1986) and by estimates of experts on the various ecosystems, the atmosphere and the soil microbes in Biosphere 1.

In addition, design thinking utilized the work of the Institute of Ecotechnics’ 16-year research into the interplay of global ecology and global technics, emphasizing the key role of biomes both material and anthropogenic (agriculture and urban) (Allen et al., 1985, Nelson, 1985). The use of a multiplicity of diverse ecosystems modeled on biomes made Biosphere 2 different from all previous closed life systems. Part of the rationale for this was the role biomes play in the global biosphere where their interplay drives natural adaptation to changing environmental conditions (Kamshilov, 1976). Also, the inclusion of synthetic ecosystems based on natural biomes was intended to produce free energy to balance the inputs that the anthropogenic biomes would require. The inclusion of a multiplicity of biomes might make the system less vulnerable to a catastrophic collapse of any single biomic system. This approach of ‘top-down’ design from the biomic level coupled with detailed consideration of the individual components (e.g. specific habitats, soils, populations) is akin to the systems ecology approach of the Odums. In a word increasingly focused on only the details, Biosphere 2’s designers in their biospheric and biomic approach were in accord with the perspective that “understanding ecosystems and their management requires recognition of the control by higher levels of the components of a smaller level” (Odum, 1989).

The Institute of Ecotechnics started up a joint-venture company, Space Biospheres Ventures, charged with the task to research, design, engineer, build and operate Biosphere 2 (Allen, 1991). Space Biospheres soon contracted with Margret Augustine, head of Biospheric Design Corporation to be the Project Director and for Biospheric Design to be the Prime Contractor.

To test the hypothesis of adaptive self-organization, we decided to expose this biospheric system composed of present day tropical and subtropical biomes to the rhythm of a temperate zone light regime that would drop to an average of less than 12 moles m^{-2} day^{-1} for the time around the winter solstice. The received light would be low, equal to about 50°N latitude, because the spaceframes cut out over 50% of the incident light. On cloudy winter days the received light fell below 5 moles m^{-2} day^{-1}.

The following concerns were among the many decided by Allen et al. to be closely monitored during the initial closure experiments in the new facility:

- The distinct biomes would not be maintained but would amalgamate into one dominated by ‘weed’ species.
- Catastrophic environmental failure could result in loss of higher plants and dominance by algae and bacteria.
- The atmosphere could be rendered insupportable for most life forms by the rise of biogenic gases such as CH_4, CO, or N_2O.
- Oxygen could go too high or too low.
- Carbon dioxide would go too high or too low. CO_2 might drop so low as to produce a desert, or severely limit crop production and plant growth. Conversely, if CO_2 rose too high, it might induce a runaway increase by reaching levels toxic to plants.
- An uncontrollable buildup of technogenic trace gases from building materials and machinery inside the facility (the ultimate sick building syndrome).
- The waste products of people could prove unrecyclable and build up to toxicity.
- The water could become undrinkable.
- The food crops could be destroyed by pathogens in the soil, or by pests.
- The system would be rendered uninhabitable through failure of technical support systems. For example, a failure of the cooling system could lead to temperatures in excess of 60°C. in several hours during a summer day.
- The people could not stand closed system conditions, or would barely survive and lose all or part of their capacity to work creatively.

Numerous auxiliary studies made with the help of outside researchers included:

- Carbon dioxide modeling (Hamilton and Botkin, 1992).
- Biodiversity and coral reef studies (Dustan and Alling, 1996).
- Oxygen cycling (Severinghaus et al., 1994).
- Genetics of the fresh water fish, *Gambusia* spp. (Scribner and Avise, 1994).
- Biomass studies (Peterson et al., 1992).
- Agricultural soil fertility and nutrient recycling (Franco-Vizcaino and Harwood, 1993).

The main objective of the experiment was to determine if an artificial biosphere could operate, increasing storages of energy and biomass, preserving a high level of biodiversity and biomes, stabilizing its waters, soils and atmosphere, increasing information and providing a healthy and creative life for humans working as naturalists, ecosystem scientists and technicians.

3. Biosphere 2 Test Module

Before building Biosphere 2, Augustine, Dempster and Allen made a 480 m^3 closed facility, which we called the Test Module to test the basic design concepts and building materials under these light conditions (Alling et al., 1990). The aim for this prototype, less than 1% the volume of Biosphere 2 but more than 50% bigger than Bios-3 which had been the largest closed life system facility operating, was experimentation with one person living inside with recycle of wastewater and of air except for leakage on the order of 10–50% per year, of biomass other than agriculture and for food production for up to 1 month. Extensive tests were done with and without human participants and carbon dioxide and other trace gases were tracked and modeled (Nelson et al., 1991; Alling et al., 1993b).

4. Biospheric operations during the 2-year closure

Upon completing 3 months checkout of Biosphere 2 and reaching an ‘All Systems on Go’ status, Augustine and Allen started off Mission One on September 26, 1991 which continued through its targeted 2 years to 26 September 1993 with the initial crew of eight biospherians under the research direction of Abigail Alling.

Some changes in the facility were carried out based on results on Mission One during a $5\frac{1}{2}$ month transition, which also made detailed measurements throughout Biosphere 2. Augustine, Allen and Alling started off Mission Two targeted for $10\frac{1}{2}$ months with seven biospherians, again under the research direction of Alling.

On 1 June 1994 a change of majority ownership was negotiated in Biosphere 2 and under new management, all human missions were terminated in Biosphere 2 on 6 September 1994, after only 6 months of operation of Mission Two.

Notes on the initial 2-year closure experiment follow:

One group at NASA ran a computer study showing Biosphere 2 achieved self-organized criticality (Cronise et al., 1995). The waste recycle system showed for the first time that recycle of human and animal waste, as well as the small amount of workshop and laboratory effluent, could be achieved in a small closed system. The sustainable agriculture system, the Institute of Ecotechnics’ integration of a number of tropical agricultural systems in order to provide a diet complete in all respects, provided 81% of the diet for eight humans on 0.2 ha on an average of outside sunlight of 40 moles of photons m^{-2} day^{-1}, or about 20 inside (Silverstone, 1996). With the improvements made during transition, Mission Two accomplished food sufficiency during their 6-month closure. The diet consumed in Biosphere 2 had dramatic health impacts, as it was nutritionally dense and calorically restricted (Walford et al., 1992, 1994).

Biosphere 2 during the first 2-year closure achieved equal or more uptake than release of carbon dioxide when the outside sunlight in moles m^{-2} day^{-1} equaled 25 or higher. In order to protect the ocean pH from excessive drops, Biosphere 2 was operated at less than 5000 ppm CO_2. The daily high level reached 2800 ppm during the first year's winter and 4200 ppm during winter of the second year. A carbon dioxide recycle system was used to precipitate CO_2 during low light periods or when CO_2 levels were high and the ocean was chemically buffered periodically (Nelson et al., 1993; Dustan and Alling, 1996). Two years of abnormally high cloudiness, possibly related to El Nino Southern Oscillation events, gave substantially less light than were anticipated.

Oxygen levels in Biosphere 2's atmosphere declined during the 2-year closure. At first the decline was rapid, falling from the initial levels of 20.9 to around 18% after 5 months of closure. Thereafter, the decline was more gradual. When levels approached 14.2% in mid January 1996, 16 months after closure, oxygen was inserted into the facility to prevent possible serious human health problems. The insertion raised oxygen levels in the atmosphere to about 19.5% and oxygen more slowly declined in the remaining 8 months of closure to a value of around 18.3% at the end of the 2 years. Investigations showed that while about 1.6% of atmospheric carbon dioxide was sequestered by a chemical scrubbing system, this left unaccounted the bulk of the oxygen loss (Nelson and Dempster, 1996). The remainder of the oxygen, converted to carbon dioxide, was predominantly taken up by interior structural concrete which had been left unsealed (Severinghaus et al., 1994), the sea water and in unconsolidated calcareous soils, such as in portions of the desert.

Biosphere 2 experienced a continuous increase in nitrous oxide. In Earth's biosphere (Biosphere 1) N_2O has been measured with a slight (0.2% ppm) increase per year in recent years, thus tracking CO_2 upwards. However, the increase in Biosphere 2 is on the order of 40 ppm $year^{-1}$. It is clear that this biosphere did not regulate N_2O and so in this respect was slow to self-organize. In Biosphere 1 photolysis generated by high energy UV light eliminates the excess by reactions in the stratosphere (Levine, 1989). Biosphere 2 because of its glass roof not only contained no equivalent to the Earth's stratosphere, but eliminated more than 99% of incident UV, necessitating the crew to take supplemental vitamin D to compensate.

5. Biospherians and management

One of the most important objective results of the Biosphere 2 experiment of Mission One was to produce 'Noosphere 1', or at the least to specify a range of conditions in biosphere–technosphere relations that would be necessary to produce a range of noospheres. Vernadsky defined a noosphere as that point in a biosphere's history when its technical and biospheric intelligence begin working together in such a way that technics reinforces life and life reinforces technics on a permanent evolutionary-sustainable basis (Dennet, 1995).

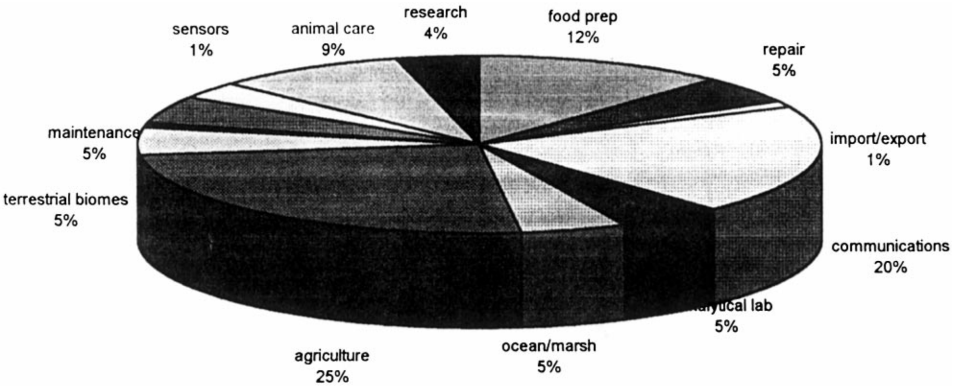

Fig. 1. Biospherian crew time tasks inside Biosphere 2. Averages are based on data from March 1992–February 1993 (Nelson and Dempster, 1996).

The eight biospherians were Abigail Alling, Linda Leigh, Taber MacCallum, Mark Nelson, Jane Poynter, Sally Silverstone, Mark Van Thillo and Roy Walford. Fig. 1 shows the time-use of the crew. Less than one person-week per week was required for maintenance and repair of all the technical systems, a surprising result showing the effectiveness of the maintenance program set up by Augustine and Van Thillo. The technology was required to supply functions excluded by closure (creation of air and water movement, waves in the ocean, heating/cooling and the extensive system of sensors for research and operation) and as a backup to the self-regulating properties of ecosystems and the biosphere (Dempster and Van Thillo, 1993; Dempster, 1996).

The emergence of eight healthy humans proves that artificial biospheres which are based on a high diversity of species and biomes in a high-tech system can work. These eight individuals had emerged from a world which they had not polluted, with clear pure water, which had grown plant biomass some 50% greater than when they entered, which was more beautiful in form, each developing with quite distinct ecosystem characteristics (Nelson and Dempster, 1996). In addition, each biospherian reported an intense heightening of awareness of their connection to their world (Alling et al., 1993a), experiencing that “in a small system, the equation, our biosphere’s health equals our health becomes dramatically evident” (Nelson and Alling, 1993). The successful 2-year closure of Biosphere 2 was an initial, but important, step in combining needs of life, imperatives of technology, information processing, diversity, microbial evolution and recycling towards realization of Vernadsky’s noosphere.

Acknowledgements

Biosphere 2 was mostly funded from 1984–1993 by Decisions Investment Corporation which was 90% owned by Edward P. Bass, 5% by SARBID (Synergetic

Architecture and Biospheric Design), CEO: Margret Augustine and 5% by Institute of Ecotechnics, Mark Nelson, Chairman. In addition, Decisions Team, Inc., the managing partner in creating Space Biospheres Ventures, the 50–50 joint venture that controlled Biosphere 2, contributed substantially to the enterprise in non-reimbursed managerial, technical and scientific expertise. William Dempster invented the variable pressure units, the 'lungs' which enabled the record closure to be maintained. Over 20 corporate sponsors donated equipment and materials. Plants from over 40 nations are represented in Biosphere 2. Mexico cooperated with permits for coral reef collections from the Yucatan and desert plants from Baja, CA; Guyana for savannah and Venezuela for rain forest collections. Missouri Botanic Gardens, under its director Peter Raven, contributed valuable rainforest specimens from its climatron. Among the outstanding scientists who generously contributed their knowledge, experience and data were Keith Runcorn, FRS (overall scientific policy), Academican Oleg Gazenko (physiology in closed systems and space applications), Josef Gitelson (physiology and nutrient cycling in closed systems), Yevgeny Shepelev (physiology and experience), Clair Folsome (microbiology of closed systems), Richard Evans Schultes (rainforests), Robert Walsh (material science), Stephen O'Brien (genetics), Thomas A. Paine (strategic planning), Jack McCauley and Carole Breed (site geology), Scott Miller (entomology), Sir Ghillean Prance (rainforest), E.P. Odum (ecological systems), Richard Harwood (sustainable agriculture systems) and H.T. Odum (systems ecology and ecological engineering). H.T. Odum also assisted in the rewrite of this paper. Hundreds of other scientists and engineers contributed to the creation and research of Biosphere 2 and we thank them all for their efforts.

Appendix A. Addendum

A.1. Maintenance and Monitoring

Mark Van Thillo[a], Norberto Alvarez-Romo[b], Gary M. Hudman[c], Sally Silverstone[a]
[a] *Biospheres, Inc., 32038 Caminito Quieto, Bonsall, CA 92003, USA*
[b] *19 Synergia Rd., Santa Fe, NM 87505, USA*
[c] *PO Box 5345, Oracle, AZ 85623, USA*

The technical systems of Biosphere 2 located within the sealed facility mostly underneath the life systems in a concrete basement included 120 operating pumps, 50 air handlers, several miles of electrical wire and pipes, water storage tanks, computer controllers, video systems, communications systems, filters, an algae-based nutrient removal system for the ocean and marsh, rainfall irrigation, heating and cooling exchangers, desalination systems, lights, a chemical recycler for atmospheric carbon dioxide, diving equipment, composting equipment, miscellaneous tools.

A maintenance workshop. was divided into six areas: mechanical, plumbing, electrical, woodwork, rigging, and spare parts storage. The mechanical section included a South Bend lathe, milling machine, bandsaw, grinder and buffer, welding machine, plasma cutter, taps and dies, drills, precision instruments, and stock to fabricate parts that might be needed. The space included a work bench, a sonic bath to clean parts (since it is necessary not to use solvents in the closed system), and a setup for making gaskets. The plumbing section had pipe wrenches, taps, dies, automatic and manual plumbing snakes, spare PVC parts, glues, and electrical hand tools like drill motors and grinders. The electric and electronic area had two work benches with a tool board including all major electrical tools, a soldering station, and a transformer to test voltages. An oscilloscope was shared with the analytical lab. Broadband outlets were installed throughout the shop for video cameras and/or monitors to facilitate outside assistance by video conference demonstration. Spools of wire included many sizes and types from power wire to single pair telephone wire. There was a telephone repair kit, medical equipment repair kit, and calibration kits.

The woodwork area had a tool board with woodworking tools, a small table saw, jigsaw, skill saw, hammers, nails, and screws for emergency woodwork. Two storage rooms contained spare parts, including parts for every type of operating pump and enough parts to rebuild pumps up to four times. Stores included electrical motors, light bulbs, valves, gaskets, v-belts, switches, outlets, electronic boards, and computer chips. For the kitchen there were spare hot plates, oven switches, heating elements, blender motors, fuses, breakers, starters, heaters, and fans. The rigging area included blocks and tackles, enough rope to build a rope bridge from one side of the rainforest to the other, hydraulic pallet jack, small hydraulic crane that could lift two tons, suction cups to adhere to glass, two full sets of rappelling gear for working on the cliff face, carts to move motors around, and scaffolding to set up small work platforms.

Because of the danger of any fire in a closed facility, an extensive smoke-detection and automatic sprinkler system was installed throughout, with many fire extinguishers and a high-pressure water delivery system for fire-fighting. A central control panel was located in the command room to give the location of a fire. The crew carried two-way radios for communication about fire or other emergencies and for communication with personnel on the outside.

The three types of heating/cooling water (hot, chilled, and cold water) had a flourescent dye that could be picked up by a black light to locate leaks. Routine check of the pipes and heat exchangers with the black light was made every six months.

A computer-based program was designed to assist maintenance schedules and to keep a historical record of repairs and preventive maintenance jobs. This artificial intelligence program was set up to inform the manager of daily tasks and of procedures to use. In addition, the program provided a current inventory of available spare parts, their storage location, and the last date and service person of preventive maintenance procedures. During the 2-year closure the program proved to be too complicated and slow. Overall maintenance of technical systems was about 30 man-hours per week, which was less than expected.

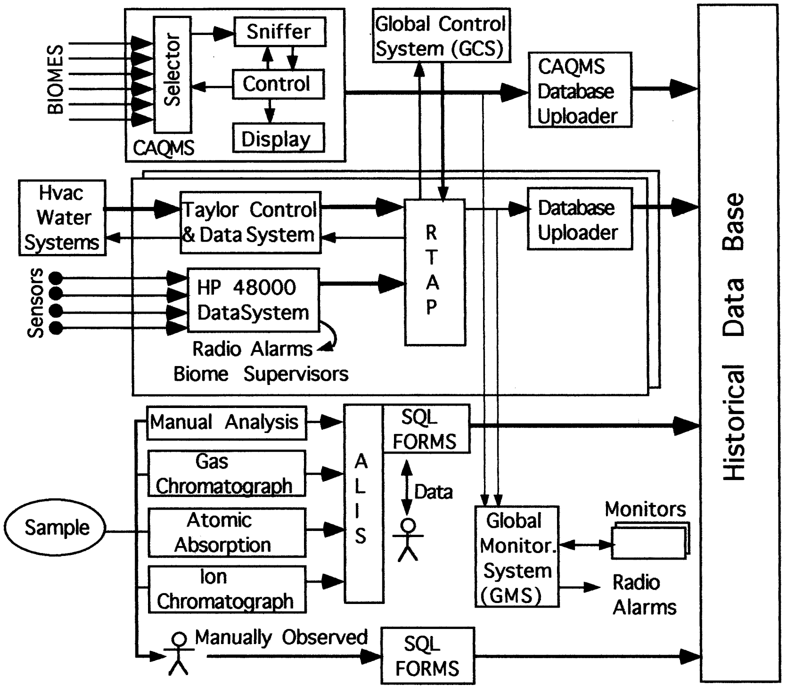

Fig. A.1. Schematic of data acquisition and monitoring systems in Biosphere 2.

A.1.1. Electronic network and data monitoring

Fig. A.1 schematically shows the data acquisition and monitoring systems together with the principal flows. Rainforest, savannah, desert, intensive agriculture, and habitat biomes each had a Biome Supervisor, and the continuous air quality monitoring system (CAQMS) was integrated with the habitat Biome Supervisor.

Real-time monitoring of Biosphere 2 was performed on an electronic network, termed the Nerve System, made up of UNIX workstations and low-level control/data acquisition computers located on a redundant broadband network carrier. The data network was designed to allow complete access to all systems from any node on the network. This allowed the Mission Control support team to perform maintenance and control changes from outside Biosphere 2.

Within Biosphere 2, UNIX workstations were located in the basement of the major biomes. These were called Biome Supervisory Controllers (BSCs) and provided local data collection from several low-level data acquisition and control systems; local biome control of temperature, humidity and water systems; local data display; and communication to ‘global’ expert systems stems and the historical database.

The sensors for temperature, humidity, light, energy, gas concentrations, water quality, and soil conditions were industrial grade. Although there were seal-tight terminal boxes and conduits covered with silicone, the most difficult problem was corrosion of electrical and electronic equipment because of humidity or the use of dissimilar metals. Most of the maintenance hours were spent on the data acquisition system, calibrating and replacing corroded sensors or terminals.

Sensors included:

Air	Carbon dioxide, oxygen, and humidity (dry- wet-bulb temperature)
Soil	Temperature and soil moisture
Light	Light energy and photometer

Altogether there were 220 temperature sensors. Evolving response of control systems to the requirements of the biological system was part of the ongoing research.

Expert systems were located in the Biosphere 2 command room and outside the Biosphere in Mission Control to provide data display, an alarm system, and intelligent detection of sensor error. The primary system was the Global Monitor, which monitored over 500 key elements throughout the structure. The Network Monitor System verified the operation of the broadband network and all components on the network. If problems were detected in any system, visual and radio/pager alarms were activated.

A CAQMS was developed for Biosphere 2 to automatically monitor O_2, N_2, NH_3, NO, NO_x, N_2O, H_2S, SO_2, CO, CO_2, CH_4 and total non-methane hydrocarbons from six locations in Biosphere 2. An expert computer system performed all data acquisition and control of the system. An automated ion chromatograph was also developed to monitor the nitrate and nitrite concentrations of the marine system.

Analytical systems included ion chromatography for inorganic analyses, a graphite furnace atomic absorption unit for detection of metals contamination, gas chromatographs for organic analyses and a wet chemistry bench including instruments for analyses such as dissolved oxygen, pH, alkalinity, turbidity, and salinity.

A.1.2. Crew time requirement

A task of the Mission One crew was to record the time spent at each of 14 work categories to develop a record of time required to operate this large life-support system. The data presented here are from September 1992 to May 1993. (Table A.1). This period in the second year of operation is intentionally selected to avoid the start-up period before the standard routines were completely established through experience. It is recognized that a summer period is not included, which may skew the data somewhat.

Prior to initial closure it was estimated that the biospherians would work an 8-h day, 6 days per week, and about half the time would be spent on operations, the other half on various research and data collection activities and communications. In fact, the split turned out to be closer to two thirds on operations and one third on research and communications. Each crew member worked an average of 66 h per week.

By far the largest amount of operations time was spent related to agriculture and food production. Changes in time required can occur as the experiment progresses. For example, during the first year, digging and conditioning fields for replanting was slow due to heavy condition of the soil. By the second year, soil tilth improved, which translated into shorter time required to turn a field. Time needed to rough process food can also be reduced with more efficient machinery. The wide diversity of crops necessitates a corresponding diversity of processing equipment.

The domestic animal systems (initially pigs, pygmy goats, and chickens) took 9% of total crew hours, which raises questions about the efficiency of animals in the system. It is likely that time needed to collect fodder will decrease as the whole agriculture system matures and fodder is more readily available. At the same time, it is anticipated that production from animals will increase as more feed is available, thus warranting the time spent which results in meat and dairy products.

It was found that the arrangement of having each crew member prepare three meals in a row for the entire crew every 8 days was efficient. On average, each cook took 8 h every eighth day for food preparation, serving and kitchen cleanup.

Maintenance of wilderness areas including marine systems took 11% of crew hours. How this will develop in the future is uncertain. The terrestrial biomes may take more time for pruning and maintenance as plants mature, while more mature ecosystems may reduce time needed for weed control as, for example, tree canopies shade out potential invaders. The marine systems may take less maintenance time as more efficient systems for ensuring low nutrients in the ocean are introduced (e.g. protein skimmers to replace the original algae scrubber system).

In communications, there was some expenditure not originally anticipated. It was found that media events involving crew took up 2% of the total time and

Table A.1
Breakdown of biospherian activity from September 1992–May 1993

Percent of time*	Activity
9	Domestic animals
10	Food preparation, serving, kitchen cleanup
25	All other agriculture and food related
4	Sample and data collection
2	Research communications
2	Media and educational communications
16	All other communications
3	Medical
5	Analytical
5	Marine systems maintenance
6	Terrestrial biomes maintenance
5	Infrastructure maintenance
5	Repairs
1	Import/Export, airlock operations
2	Nerve system, technical

* Average work week of 66 h per person per week.

occasionally (e.g. the 1-year anniversary, the re-entry) rose to far higher proportions of time. This also included the participation of crew members in educational activities such as phone calls to classrooms, which will likely continue into future missions.

Although actual time recorded for research was 4%, that figure reflected only time spent directly on collection of samples or data. Research collaboration, which included communication between crew and scientific consultants on the outside, demanded a further 2%. Neither of these categories included analysis of data, report and grant writing, or presentation by satellite, video, and telephone.

It seems likely that as operations become more efficient and technical systems are improved, more time will be available for research and communications.

References

Allen, J., 1991. Biosphere 2: The Human Experiment. Viking/Penguin, New York, 156 pp.

Allen, J., Nelson, M., 1989. Space Biospheres, 2. Synergetic Press, Oracle, AZ.

Allen, J.P., Nelson, M., Snyder, T.P., 1985. Institute of Ecotechnics. Environmentalist 4, 205–218.

Alling, A., Leigh, L., McCallum, T., Alvarez-Romo, N., 1990. Biosphere 2 test module experimentation program. Biological life support systems, In: Nelson, M., Soffen, G. (Eds.), Proceedings of the Workshop on Biological Life Support Technologies: Commercial Opportunities. Synergetic Press, Oracle, AZ.

Alling, A., Nelson, M., Silverstone, S., 1993a. Life Under Glass: The Inside Story of Biosphere 2. The Biosphere Press, Oracle, AZ, 254 pp.

Alling, A., Nelson, M., Leigh, L., Frye, R., Alvarez-Romo, N., MacCallum, T., Allen, J., 1993b. Experiments on the Closed Ecological System in the Biosphere 2 Test Module. Appendix chapter in Beyers, R., Odum H.T., Ecological Microcosms. Springer-Verlag, New York.

Beyers, R.J., Odum, H.T., 1993. Ecological Microcosms. Springer, New York, 557 pp.

Cronise, R., Noever, D., Brittain, A., 1995. Self-organized criticality in closed ecosystems; carbon dioxide fluctuations in Biosphere 2. Int. J. Climatol. 16, 1–6.

Dempster, W., 1989. Biosphere 2: Technical overview of a manned closed ecological system. Nineteenth Intersociety Conference on Environmental Systems, San Diego, CA. SAE Technical Paper Series 891599.

Dempster, W., 1993. Biosphere 2: System dynamics and observations during the initial two-year closure trial. In: 23rd International Conference on Environmental System, Colorado Springs, CO. SAE Technical Paper Series 932290.

Dempster, W., 1994. Methods for measurement and control of leakage in CELSS and their application and performance in the Biosphere 2 facility, Adv. Space Res. 14 (11) 331–335.

Dempster, W., 1996. Biosphere 2 engineering and design performance. Paper presented at Linnean Society, Fourth International Conference on Closed Systems, 10–11 April 1996, London.

Dempster, W., Van Thillo, M., 1993. Maintenance and operational support characteristics of Biosphere 2. Paper presented to the Space Programs and Technologies Conference, AAIA, Washington, DC.

Dennet, D., 1995. Darwin's Dangerous Idea. Simon and Schuster, New York.

Dustan, P., Alling, A., 1996. Coral Reef Ecosystem of Biosphere 2. Paper presented at Linnean Society, Fourth International Conference on Closed Systems, 10–11 April 1996, London.

Folsome, D., Hanson, J., 1986. The emergence of materially closed system ecology. In: Polunin, N. (Ed.), Ecosystem Theory and Application. Wiley, New York, pp. 269–288.

Franco-Vizcaino, E., Harwood, R.R., 1993. Chemical and Biological Properties of Soils and Plant Tissues from the Intensive Agriculture Biome, Biosphere 2. Project report from Department of Crop and Soil Sciences, Michigan State University, East Lansing, MI.

Gitelson, I.I., Terskov, I.A., Kovrov, B.G., et al., 1973. Life support system with internal control based on photosynthesis of high and unicellular plants. L.V. Kirensky Institute of Physics, SD Academy of Sciences, USSR.

Hamilton, J., Botkin, D., 1992. Progress towards a carbon cycle model of Biosphere 2. Presented at the Third International Workshop on Closed Ecological Systems, Oracle, AZ.

IBP/IE (Institute of Biophysics, Krasnoyarsk, Russia and Institute of Ecotechnics, London), 1989. Second International Workshop on Closed Ecological Systems, September 1989, Krasnoyarsk, Russia.

Kamshilov, M.M., 1976. The Evolution of the Biosphere. Mir, Moscow.

Levine, J.S., 1989. Global Ecology. Academic Press, New York.

Morowitz, H., 1979. Energy Flow in Biology. OxBow Press, Woodbridge, CT.

Morowitz, H., 1988. Energy Flow in Biology. Academic Press, New York.

Nelson, M., 1985. Synergetic management of the savannahs. In: Mott, J., Tothill, J. (Eds.), The World's Savannah: Ecology and Management, Australian Academy of Science. University of Queensland Press, Brisbane, Australia.

Nelson, M., Alling, A., 1993. Biosphere 2 and its lessons for long-duration space habitats, In: Faughnan (Ed.), Space Manufacturing 9. The High Frontier: Accession, Development and Utilization. AIAA, Washington, DC, pp. 280–287.

Nelson, M., Dempster, W., 1996. Living in space: results from Biosphere 2's initial closure, an early testbed for closed ecological systems on Mars, In: Stoker, C.R., Emmart, C. (Eds.), Strategies for Mars: A Guide to Human Exploration, vol. 86. Science and Technology Series, AAS, Univelt, San Diego, CA, pp. 373–390.

Nelson, M., Leigh, L., Alling, A., MacCallum, T., Allen, J., Alvarez-Romo, N., 1991. Biosphere 2 Test Module: a ground-based sunlight-driven prototype of a closed ecological system. Adv. Space Res. 12 (5), 151–158.

Nelson, M., Burgess, T., Alling, A., Alvarez-Romo, N., Dempster, W., Walford, R., Allen, J., 1993. Using a closed ecological system to study earth's biosphere: initial results from Biosphere 2. BioScience 43, 225–236.

Nelson, M., Dempster, W., Alvarez-Romo, N., MacCallum, T., 1994. Atmospheric dynamics and bioregenerative technologies in a soil-based ecological life support system: initial results from Biosphere 2. Adv. Space Res. 14 (11), 417–426.

Odum, H.T., 1989. Ecological engineering and self-organization. In: Mitsch, W.J., Jorgensen, S.E. (Eds.), Ecological Engineering: An Introduction to Ecotechnology. Wiley, New York, pp. 79–101.

Peterson, J., Haberstock, A., Siccama, T., Vogt, K., Vogt, D., Tusting, B., 1992. The making of Biosphere 2. Rest. Manage. Notes 10 (2), 158–168.

Scribner, K., Avise, J., 1994. Cytonuclear genetics of experimental fish hybrid zones inside Biosphere 2. Proc. Natl. Acad. Sci. USA 91 (May), 5066–5069.

Severinghaus, J.P., Broecker, W., Dempster, W., MacCallum, T., Wahlen, M., 1994. Oxygen loss in Biosphere 2. Trans. Am. Geophys. Union 75 (3), 33–37.

Shepelev, Y., 1972. Biological life support systems, In: Calvin, M., Gazenko, O. (Eds.), Foundations of Space Biology and Medicine. vol. 3 Academy of Sciences USSR and NASA, Washington, DC, pp. 274–308.

Silverstone, S., 1996. Food production and nutrition for the crew during the first two-year mission (1991–1993). Paper presented at the Linnean Society Fourth International Conference on Closed Ecological Systems. 10–11 April 1996, London.

Silverstone, S., Nelson, M., 1996. Food production and nutrition in Biosphere 2: Results from the first mission September 1991–1993. Adv. Space Res. 18 (4/5), 49–61.

Terskov, I.A., 1975. A Month Alone with Chlorella. NASA-TT-F-16463.

Terskov, I.A., Gitelson, J.I., Kovrov, B.G., 1979. Closed System: Man-Higher Plants (Four Month Experiment) Translation of Nauka Press, Siberian Branch, Novocibirsk, NASA-TM-76452, Washington DC.

Tsiolkovsky, K.S., 1979. Selected Writings. Mir, Moscow.

Vernadsky, V.I., 1986. The Biosphere. Synergetic Press, Oracle, AZ.

Walford, R.L., Harris, S.B., Gunion, M.W., 1992. The calorically restricted low-fat nutrient-dense diet in Biosphere 2 significantly lowers blood glucose, total leukocyte count, cholesterol and blood pressure in humans. Proc. Natl. Acad. Sci. USA 89 (23), 11533–11537.

Walford, R.L., Weber, L., Panov, S., 1994. Caloric restriction and aging as viewed from Biosphere 2. Receptor 5, 29–33.