ELSEVIER

Ecological Engineering 13 (1999) 31–42

ECOLOGICAL ENGINEERING

Biosphere 2 engineering design

William F. Dempster *,[1]

Biospheric Design, Inc., 26 Synergia Rd., Santa Fe, NM 87505, USA

Received 18 November 1996; received in revised form 20 October 1997; accepted 29 November 1997

Abstract

The creation of large materially closed ecological systems for research and experimentation presents a series of engineering challenges to achieve an adequate degree of closure, to transfer energy to and from the system and to maintain an approximation to natural conditions within the system. Biosphere 2 incorporates two large expansion chambers ('lungs') as the key system that enabled the low leakage rate of about 10% year^{-1} and facilitated leakage measurement and detection. This high degree of closure achieved in Biosphere 2 made it possible to observe and account for the exchange of gases between the ecosystems and atmosphere, notably oxygen and carbon dioxide. Energy is transferred from an external energy center as electric power and using hot and cold water as a transfer medium through sealed piping systems. The energy system successfully maintained temperature and humidity conditions while at the same time serving as the primary means of condensing tens of thousands of liters per day of water vapor from the atmosphere for potable, agricultural and ecological uses. The certainty of water availability is a direct result of the fact that the system is materially closed. Subsystems of the facility include recycling of human and animal wastes, a system for generating waves in the artificial ocean, separation of fresh water from sea water and computerized sensing and control. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Biosphere 2; Closed ecological system; Leakage; Recycling; Heat transfer; Condensate; Desalination

* Tel.: +1-505-438-9873; fax: +1-505-474-5269.

[1] Director of Systems Engineering for the Biosphere 2 project from inception until 1994, and President of Biospheric Design, Inc.

PII: S0925-8574(98)00090-1

1. Introduction

It has been recognized for a century that the planet earth is essentially a materially closed self-sustaining ecological system traveling in a void of space hostile to life. Beginning in 1968 Clair Folsome at the University of Hawaii took the simple but enormously significant step of repeatedly scooping up a diversity of microbial life from a beach of the Pacific Ocean and sealing it into many flasks—permanently. Many of those sealed flasks of microbes are still living today with their microbes reproducing, growing, dying, eating and being eaten (Folsome and Hanson, 1986). Thus it is demonstrated that a self-sustaining closed ecological system can be artificially created on a scale vastly different than planet earth.

Man's ambitions to explore and colonize space have included the idea that a closed ecological system is a necessity for long term life support at great distances from earth. Both the Russian and US space programs have included experimentation with chambers and capsules of various sizes. Importantly, the Russian Bios-3 experiment supported three men in a 315 m^3 enclosure for 6 months in which crop growth under artificial light regenerated the atmosphere and provided a major portion of the food (Terskov et al., 1979; Nelson and Dempster, 1996).

Biosphere 2 near Tucson, Arizona is a far larger and more complex facility of some 180 000 m^3 and an airtight footprint of 1.27 ha. It is effectively sealed and encloses five distinct natural biomes, rainforest, savannah, ocean, marsh and desert plus an agricultural area and human habitat within one airtight envelope (Fig. 1). Its initial closure experiment included a crew of eight humans for 2 years from September 1991 to September 1993. Sunlight through the glazed enclosure provides the energy for plant growth. The crew planted, raised, harvested and cooked their own food, recycled their own wastes, maintained their infrastructure, tended and studied the natural biomes and participated in scientific conferences and meetings via video during those 2 years.

2. Sealing of Biosphere 2

The degree of closure of a closed ecological system is an important parameter and atmospheric leakage will ordinarily be both the most critical aspect and the most readily measured. If the rate of leakage is small compared to the rates of gas exchange involved in the ecological processes, then the closed system will be a powerful instrument to study those processes. We must also be clear about what we mean by leakage. In this discussion, leakage means the combined inward and outward leakage, i.e. the exchange between inside and outside.

In Biosphere 2, the exchange during the 2-year mission was about 10% $year^{-1}$ (Dempster, 1994) as estimated by two independent methods. The first method involved initially operating Biosphere 2 at a positive pressure of about 150 Pa (0.02 psi) which forced outward leakage through any existing holes in the envelope. The rate of such forced leakage was directly measured by the rate of deflation of the expansion chambers ('lungs') and found to be 65% $year^{-1}$. Knowing the leak rate at this one pressure determines what the leakage will be at other pressures within narrow margins of error. Subsequent operation in a measured pressure range within ± 8 Pa of zero (both positive and negative) resulted in both inward and outward leakage which is far less and computed to be less than 10% year^{-1}.

The second method was to spike the atmosphere of Biosphere 2 with inert trace gases and to measure their progressive dilution over more than a year (Fig. 2). Sulfur hexafluoride, helium and krypton were all used and they confirmed the 10% or less estimate. The large sulfur hexafluoride molecule and the small helium molecule are diagnostic of the distribution of hole sizes contributing to the total leakage cross section. If a large part of the total leakage is due to many holes of very small size or due to permeation through elastomeric seals, then helium dilution would be much larger than sulfur hexafluoride dilution, but it was not. A more complete presentation of these methods and the data are in Dempster (1994).

There were several problems addressed in engineering a sealed envelope: (a) admittance of sunlight for plant growth, (b) control of the pressures of expansion/contraction, (c) a bottom liner to prevent leakage through the ground below, and (d) airtight penetrations for required utilities.

The glazing system is some 16 000 m^2 of laminated glass mounted on a space frame structure (see also Zabel et al. (1999) for further detail). Loss of light occurs due to reflection and absorption of the glass and also due to shading by struts of

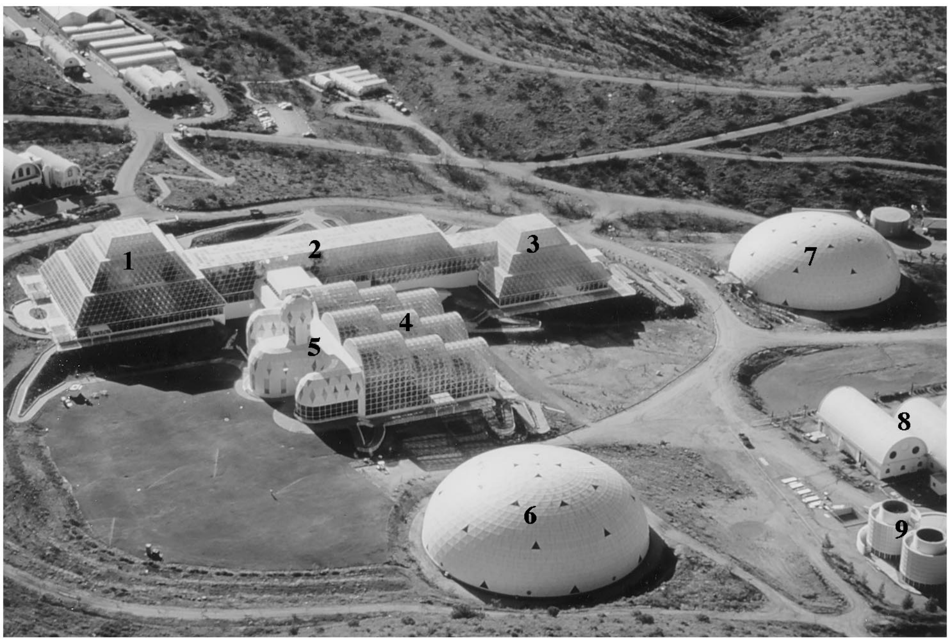

Fig. 1. Aerial view of Biosphere 2 facing southeast showing locations of: 1, rainforest; 2, savannah/ocean/marsh; 3, desert; 4, intensive agriculture; 5, habitat; 6, west lung; 7, south lung; 8, energy center; and 9, cooling towers.

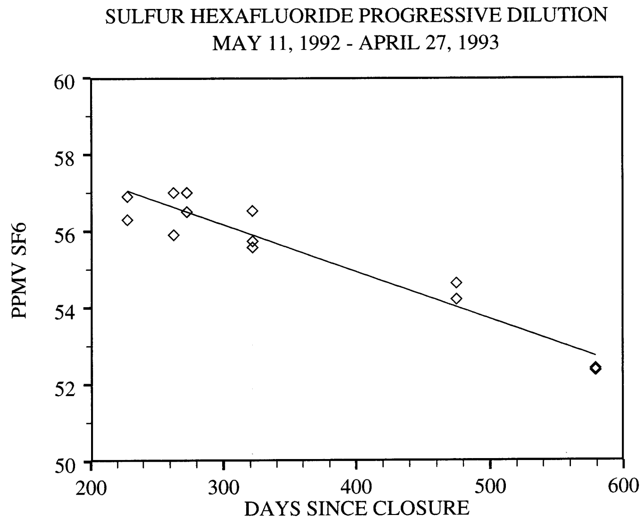

Fig. 2. Progressive dilution of SF_6 in Biosphere 2 during mission one. The regression line is -8% year^{-1} with $R^2=0.911$. Reprinted with permission from technical paper 932290 © 1993 Society of Automotive Engineers, Inc.

the space frame structure. The net result is that about 45–50% of incident sunlight is available to plants growing inside the structure. The loss of sunlight became a limiting factor for food crop growth during two exceptionally cloudy winters. Supplemental artificial lighting was added to the agricultural area which increased available light by about 5 mol/m^2 per day and noticeably improved winter crops after the initial 2-year closure.

Leakage of both atmosphere and water as well as movement of microbes and insects in and out of the system would occur if the bottom was not sealed below. The bottom and basement sidewalls of Biosphere 2 are sealed with a stainless steel liner which is sealed to the lower edge of the glazing system. Stainless steel was chosen for toughness and durability over fiberglass or elastomerics considering that the liner would be buried under tons of soil, and exposed to direct contact on basement sidewalls. Common varieties of stainless steel such as alloy 316 are known to corrode in soil and sea water, so a ‘super’ stainless alloy, Allegheny Ludlum 6XN was chosen. A system of leak detection channels was installed beneath the liner which served to locate and repair flaws in the welding before the initial closure (see also Zabel et al. (1999) for further detail).

The liner also provides the means for sealing penetrations for utilities serving the enclosure because pipe or pipe fittings could be welded airtight through the liner. Numerous airtight penetrations are required for electric power and communications. In addition, the heating and cooling system requires large penetrations for the circulation of hot and cold water in sealed piping systems (further described in Section 5).

3. Lungs

Pressure fluctuations that occur in an airtight rigid enclosure must be properly understood and dealt with. As temperature rises and falls, expansion and contraction of the contained gases tend to explode or implode the enclosure. Variations of internal humidity are actually variations of the amount of gas contained (water vapor) and likewise contribute to pressure fluctuations. Thirdly, variations in external barometric pressure create positive and negative differential pressures between the inside and outside. Allowance must be made for these three factors to combine in the most extreme ways. If Biosphere 2 were a fixed volume structure, the estimated pressure variations would be about ± 5000 Pa (± 0.7 psi). These are far greater pressures than the structure could withstand. Furthermore, even if Biosphere 2 were built strong enough not to explode or implode, the leak rate would be greatly increased as the substantial pressure variations alternately drove air in and out through any small holes.

To avoid both of these undesirable consequences, Biosphere 2 has two expansion chambers, called 'lungs'. Each lung is a cylindrical tank with a flexible membrane covering and sealing the top. As air in Biosphere 2 expands, the membranes rise, and as the air contracts the membranes fall. The membranes are weighted and their weight resting on the enclosed air provides the slight pressure of about 150 Pa previously described. The combined expansion capacity of both lungs is about 43 000 m^3 serving a fixed air volume of about 140 000 m^3, or about 30%.

The lungs themselves are enclosed by weathercover domes which we may describe as 'air resistant', or nearly airtight. By operation of a moderate sized blower, the space under each dome can be reduced in atmospheric pressure just enough to neutralize the weight of the membrane by upward suction. In this state, the pressure differential between the inside and outside of Biosphere 2 becomes zero or as small as the accuracy of the blower control system will permit. Now there is no longer a driving pressure forcing leakage in either direction. The lungs are the enabling technology that permitted achievement of the low leakage rate of about 10%/year.

4. Tracking chemical pathways

It can hardly be overemphasized how powerful is the tool of material closure. It tells you that the atoms you begin with are in there somewhere. Quantitative and qualitative investigation of chemical pathways become a matter of measurement and analysis within finite boundaries. A prime example is the search for the missing oxygen in Biosphere 2.

From early in the 2-year closure it was evident that atmospheric oxygen was diminishing. During the first 16 months, oxygen concentration declined from normal ambient, 21%, to 14% (Dempster, 1993). The obvious explanation of loss to respiration was not evident because the implied increase of carbon dioxide did not occur, and furthermore, the atmospheric volume of Biosphere 2 was shrinking (Figs. 3 and 4). The basic respiration/photosynthetic equation,

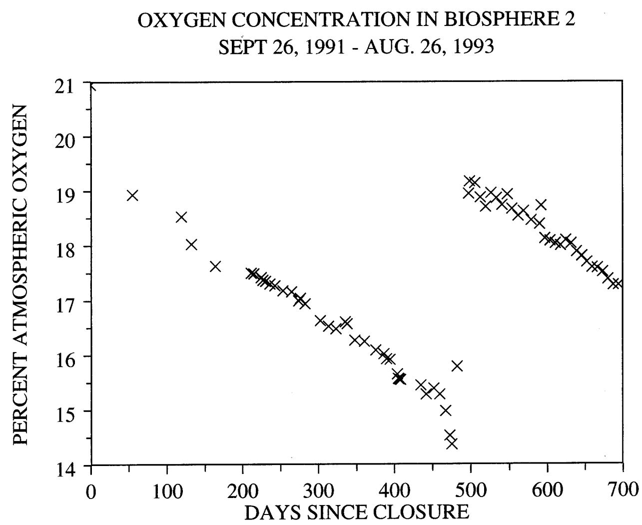

Fig. 3. Oxygen concentration in Biosphere 2 during mission one. Injection of pure oxygen occurred between days 475 and 494.

$$CH_2O + O_2 \leftrightarrow CO_2 + H_2O$$

implies that 1 mol of carbon dioxide is produced for each mole of oxygen consumed and that the gas volume is invariant (at constant pressure/temperature). An investigation (Severinghaus et al., 1994), analyzed concentrations of both carbon 12 and carbon 13 in atmosphere, biomass, scrubber product (see below) and concrete

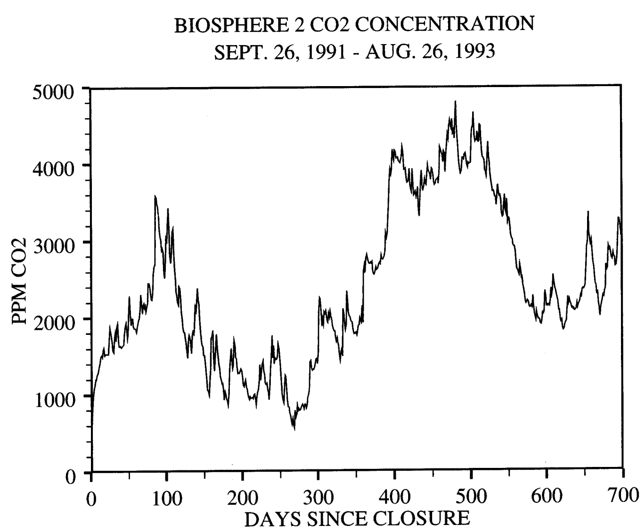

Fig. 4. Carbon dioxide concentration in Biosphere 2 during mission one.

inside Biosphere 2. It was determined that carbon dioxide from the atmosphere was being captured by carbonation of concrete as in

$$CaO + CO_2 \rightarrow CaCO_3$$

on the order of 600 kmol, or 26 t distributed over about 15 800 m^2 of exposed concrete. Thus, the explanation of oxygen loss by respiration of organic matter in the soil was reinstated. Photosynthesis was returning oxygen to the atmosphere, but the rates of the two processes were not in balance. The method of investigation rested on the accountability inherent in a closed system.

In anticipation of seasonal imbalances between the rates of oxygen/carbon dioxide production and consumption, a scrubber system was installed enabling the removal of carbon dioxide from the atmosphere. The scrubber extracts carbon dioxide by blowing air through a falling 'rain' of NaOH solution which produces the reaction

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$$

Subsequent addition of lime to the sodium carbonate solution precipitates the carbonate as solid

$$Na_2CO_3 + CaO + H_2O \rightarrow CaCO_3 + 2NaOH$$

which returns the sodium hydroxide for reuse and results in a storable solid calcium carbonate. Operation of the scrubber system captured about 98 kmol of carbon dioxide (4.3 t) total for the two fall–winter periods during the 2 years of closure from September 1991 to September 1993.

An electric furnace was installed which was intended to dissociate calcium carbonate at high temperature

$$CaCO_3 \rightarrow CaO + CO_2$$

If successful, this would have fully completed the cycles and returned carbon dioxide and lime during summer months, but heating elements in the furnace failed and the completion of that cycle was unrealized during the 2-year closure.

5. Energy

The primary energy demand of Biosphere 2 is light for plant growth which, except for a relatively small supplement of artificial light added to the agriculture after the 2-year mission, is provided by sunshine. The combined effects of light absorption and reflection by the glass and shading by the structure result in about 45–50% of ambient incident light reaching the plants inside.

The largest demand for an artificial energy supply is maintenance of temperature and humidity conditions. Biosphere 2, being a large glass airtight enclosure fully exposed to Arizona solar radiation, can also be viewed as a moderately good collector of solar energy. It was estimated that equilibrium temperature inside on a bright sunny summer day would be 65°C, easily fatal to plants and animals. The summertime cooling requirement can reach about 35 000 000 kJ/h (2800 t). The wintertime heating requirement can reach about 11 000 000 kJ/h.

Both heating and cooling are provided by hot and cold water circulated from outside through heat exchangers within Biosphere 2. These circulating energy transfer waters are rigorously sealed in closed piping systems to preclude any leakage or commingling with any of the ecosystem waters. The water is marked with a dye colorant to reveal leaks that might occur. Heating or cooling energy is transferred to Biosphere 2 by fan-forced air circulation across the heat exchangers in conventional air handlers. This air circulation is entirely internal to Biosphere 2 but the air transfers energy to and from the externally supplied cold and hot water.

There are 25 air handlers placed throughout the planted biomes, each capable of moving varying airflow up to 24 m^3/s (50 000 cubic feet per minute). About half the air handlers are for cooling only, the other half are capable of cooling and reheating which controls humidity by condensing moisture out of the air and reheating to the desired temperature. For example, if humid air is cooled to 4°C it can hold only about 5 g of water vapor per kg of dry air (specific humidity = 0.005). The same airstream reheated to 18°C now has a relative humidity of about 40%. The habitat section of Biosphere 2 which is mostly opaque is fitted with smaller air handlers typical of commercial application.

Electrical power for fans, pumps, lights, tools, communications etc. is similarly supplied from outside through airtight penetrations. The peak demand is about 1500 kW, averaging 700 kW, and is distributed throughout as 480/277 V and 208/120 V 3-phase and single phase power. An external energy center houses generators for on-site power generation, hot water boilers and ammonia-based chillers. Ammonia was specifically selected to avoid the use of freons and the associated hazard for earth's ozone layer.

The transfer of heat from Biosphere 2 into cold water circulated from the energy center in turn results in a large demand to reject heat from the energy center to the local environment. Heat rejection from the energy center is by evaporating water in cooling towers. Average evaporation for the whole system was about 400 000 l/day ranging from about 100 000 l/day in winter to 750 000 l/day in summer.

Redundancy of energy systems is an important safety feature of Biosphere 2 since loss of electric power for internal air circulation or loss of cold or hot heat exchange water could result in sudden and drastic loss of temperature control (Dempster, 1991). The energy center was provided with three generators, 1500, 1500, and 2250 kW plus connection to the external electric power grid. Although normal operation combines power sources in excess of 1500 kW, any one of these four electric power sources alone could sustain the minimum necessary degree of operational control. Additionally, the power is delivered over two independent busses which in turn distribute to equipment which is interleaved in every area of Biosphere 2. Thus, failure of either power train will not result in catastrophic failure in any area inside the enclosure.

Multiple generator systems serving a common load are vulnerable to domino-effect failure if one generator fails which could leave the remaining generator(s) overloaded. To preclude this scenario, sensing equipment is in place to detect failure of one generator in the energy center and send a signal to Biosphere 2 to shed several major loads within a few tens of milliseconds. The shed loads can later be restarted in sequence once more generating capacity is brought on-line which avoids a surge the power system couldn't handle.

Redundancy in cooling water is achieved by supply of both chilled water and evaporatively cooled water through independent piping systems. Although normal operation uses both cooled water and chilled water, the cooled water alone will suffice to maintain a minimal degree of temperature control. This redundancy also pays for itself because cooled water (by evaporation at the cooling towers) is far less expensive than chilled water (produced by compressive chillers). The warm air inside Biosphere 2 is cooled in two stages, first and mostly using the cooled water, then the chilled water. Thus, the inexpensive cooled water provides the larger portion of the energy transfer. If, instead, all cooling were provided by chilled water, the fuel bill would perhaps be double the $1 million annual consumption.

Two of the three generators and the hot water boilers in the energy center are fired with natural gas for economical and relatively clean operation. However, in the event of disruption of the gas supply, these machines are 'dual fuel' so they can be fired on diesel fuel alone from storage tanks on site.

Waste heat in the exhaust stream and jacket water of the generators is captured by an absorption chiller to produce chilled water for Biosphere 2. An insulated chilled water storage tank packed with eutectic salts provides 54 GJ (4300 ton-hours) of chilling reserve. The combination allows the energy of waste heat from nighttime generation to be used for cooling Biosphere 2 the following day. This was further enhanced by an electric power buy–sell agreement with the local utility company which increased the waste heat available for on-site cogeneration cooling.

6. Water system

Warm moist Biosphere 2 air in contact with a cold heat exchanger provides a steady stream of relatively high purity condensate water. Evapotranspiration from plants and soils is continually loading the Biosphere 2 atmosphere with water vapor. Because the atmosphere is closed and the air handlers have capacity to limit the atmospheric humidity, it follows that the supply of condensate water is equal to the evapotranspiration (except for brief transients), thus assuring a water supply in balance with water demand. Condensate collection in Biosphere 2 was on the order of 20 000–40 000 l/day. A storage tank with a capacity of 870 000 l allows for management of transitory mismatches between the rate of condensation and the delivery of irrigation water and also compensates for seasonal variation in the moisture content of the 30 000 t of soil. During the 2-year closure the tank ranged from full to less than a quarter full.

In wintertime, the air handlers supply heating rather than cooling and condensate may be unavailable from the heat exchange coils. In this situation the cold glass envelope serves to condense water from the warm humid air. A network of water collection troughs at the edges of the panes of glass delivers condensate water to tanks for subsequent delivery to irrigation and other uses. See also Dempster (1992) for further description and schematic diagram of the water systems.

On this scale of water production, the need for potable and hygienic water is only a relatively small sidestream demand. The water was found to be clean enough for direct human consumption although an ultraviolet sterilization system was included as a precaution.

Toilet, hygiene and kitchen wastewaters are sent first to anaerobic holding tanks and then to a marsh bed where aerobic root zone bacteria break down waste products to nutrients for supply to the agriculture system. This type of system had been extensively developed by B.C. Wolverton at NASA Stennis Space Center (Wolverton, 1988).

7. Marine waters

The ocean and salt water marsh biomes comprise over 4 million liters and are maintained separately from the fresh water systems. Continual water movement is necessary to bring food supply to filter feeders and immobile species. To this end, systems for generating waves and currents within the ocean were developed.

The wave generator works by vacuum uplift of ocean water into a chamber elevated above the ocean surface. Release of the vacuum to atmosphere (within Biosphere 2) allows the uplifted water to suddenly fall, propagating a wave across the ocean. In addition, pumps circulate about 2500 l/min throughout the ocean system.

The coral reef community is one of the most fragile ecosystems of Biosphere 2. Maintenance of low nutrient conditions is essential to prevent eutrophication and algae blooms. A system of protein skimmers operated by airlift pumps brings excess proteins to a surface froth where it is removed and this system also adds to overall ocean water circulation.

In anticipation of fresh water intrusion into the ocean waters, a special desalinization system was incorporated into Biosphere 2. Fresh water can enter the ocean by two routes; condensation dripping from the overhead glass in winter, and irrigation runoff from planting pockets on the cliff facing the ocean. Unless a matching extraction of fresh water (which would include evaporation) is taken from the ocean, the ocean basin will eventually overflow and/or fresh water will become progressively unavailable. The desalination system is a flash evaporator that boils salt water at low temperature (55°C) in a vacuum and recondenses the vapor into fresh water. The heat required to boil the salt water is exchanged from the hot water externally supplied from the energy center. In this way, up to 15 l/min of fresh water can be extracted from the ocean.

The pumps and piping of both marine and fresh water inside Biosphere 2 almost entirely use fiberglass or PVC construction to prevent corrosion. Even energy center water which is corrosion inhibited is carried in fiberglass piping because the outside of the pipes are exposed to warm humid Biosphere 2 air (Dempster and Van Thillo, 1993).

8. Nerve system and communications

A multi-level computer sensing, control and data processing system is distributed among many terminals both inside Biosphere 2 and outside at facilities on the site. These are linked together by an on-site network and together comprise the 'nerve system' of Biosphere 2. Connections are networked to most of the business offices as well as to the technical staff offices.

Hundreds of sensors collect data on temperature, humidity, light intensity, atmospheric gas concentrations, the operating status of equipment and the like. All data is polled at 15 min intervals and logged to an ever increasing database.

Site-wide data communications are possible through the network, enabling simultaneous access to the data base. Telephone, walkie-talkie radios and video connections are also heavily used means of communication between the inside and outside of Biosphere 2. Meetings 'at the window' concurrent with a telephone on both sides of the window or walkie-talkie added a personal dimension to inside–outside communications during the 2-year closure.

Control of equipment, particularly the air handlers that control internal temperature and humidity is possible from either inside or outside through the nerve system. Temperature and humidity control is regarded as so important that two levels of back-up are in place below the nerve system for control of the air handlers. The first back-up level is programmable controllers which normally receive their control parameters from the higher level nerve system but which can be set to operate in isolation with manual parameter entry. The second back-up level is the on-off-air volume control and water circulation valving on each individual air handler which can be manually overridden from the programmable controllers. Manual intervention at the appropriate level can override a nerve system failure at any level. Each biome of Biosphere 2 is equipped with from three to nine air handlers. Similarly, all the mechanical systems in Biosphere 2 and the energy center can be operated manually to guard against catastrophic consequences of computer failure.

9. Conclusions

As the discipline of biospherics emerges as a new field of scientific and technical undertaking, a variety of closed systems will be necessary for many applications and experimental programs. The payload of these systems will be ecosystems of varying degrees of complexity and sophistication, some of which will be irreplaceable and invaluable for their contribution to understanding in the field. The engineered enclosure and support systems will be challenged to meet requirements of closure and reliability in addition to services otherwise provided by nature. Biosphere 2 has attempted to meet these challenges and hopefully the lessons learned will be applied to future systems.

References

Dempster, W.F., 1991. Biosphere 2: design approaches to redundancy and back-up. In: 21st International Conference on Environmental Systems. San Francisco, CA, July 1991, SAE Technical Paper Series 911328.

Dempster, W., 1992. Water systems of Biosphere 2. Presented at the International Conference on Life Support and Biospherics, University of Alabama, Huntsville, February 20, 1992, Space Biospheres Ventures, Oracle, AZ.

Dempster, W.F., 1993. Biosphere 2: System dynamics and observations during the initial two-year closure trial. In: 23rd International Conference on Environmental Systems, Colorado Springs, CO, July 12–15, 1993, SAE Technical Paper Series 932290.

Dempster, W.F., 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.F., Van Thillo, M., 1993. Maintenance and operational support characteristics of Biosphere 2. AIAA 93-4181. Presented to AIAA Space Programs and Technologies Conference and Exhibit, September 21–23, 1993, Huntsville, AL.

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

Nelson, M., Dempster, W.F., 1996. Living in space: results from Biosphere 2's initial closure, an early testbed for closed ecological systems on Mars, AAS 95-488. In: Stoker, C.R., Emmart, C. (Eds.), Strategies for Mars: A Guide to Human Exploration, vol. 86, Science and Technology Series, American Astronautical Society, Univelt, San Diego, CA, pp. 373–390.

Severinghaus, J.P., Broecker, W.S., Dempster, W.F., MacCallum, T., Wahlen, M., 1994. Oxygen loss in Biosphere 2, EOS. Trans. Am. Geophys. Union 75 (3) 33, 35–37.

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

Wolverton, B.C., 1989. Aquatic plant/microbial filters for treating septic tank effluent. In: Hammer, D.A., Constructed Wetlands for Wastewater Treatment, Lewis Publishers, Boca Raton, FL.

Zabel, B., Hawes, P., Stuart, H., Marino, B., 1998. Construction and engineering of a created environment: Overview of the Biosphere 2 closed system. Ecol. Eng. 13, 43–63.