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Lessons Learned From Biosphere 2: When Viewed as a Ground Simulation/Analog for Long Duration Human Space Exploration and Settlement

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ABSTRACT

President Bush's recent announcement of the Exploration Initiative dictates manned bases on the Moon and eventually Mars. A ground swell of credible privately funded space projects is also reaffirming the notion that was for a time taken for granted but in recent years has seemed further and further from being realized – that humans will live permanently in space.

A human mission to Mars, or a base on the Moon or Mars is a lengthier more complex mission than any space endeavor undertaken to date. Simulation Based Acquisition is a fundamental part of preparing for such a mission. Ground simulations provide a relevant, analogous environment for testing technologies and learning how to manage complex, long duration missions, while addressing inherent mission risks.

Multiphase human missions and settlements with limited opportunities for immediate return to Earth should a problem occur, require high fidelity, end-to-end, full mission duration tests in order to evaluate a system's ability to sustain the crew for the entire mission and return them safely to Earth. Moreover, abort scenarios are essentially precluded in many mission scenarios, though certain risks may only become evident late in the mission. Aging and compounding effects cannot be simulated through accelerated tests for all aspects of the mission.

Until such high fidelity long duration simulations are available, and in order to help prepare those simulations and mission designs, it is important to extract as many lessons as possible from analogous environments. Biosphere 2 is a three-acre materially closed ecological system that supported eight crewmembers with food, air and water in a sunlight driven bioregenerative system for two years. It was designed for research applicable to environmental management on Earth and the development of human life support for space. Although the two-year mission of Biosphere 2 was completed ten years ago, it is quite possibly the best analog for a long duration space mission that has been conducted and warrants reexamination in light of NASA's new direction.

A brief overview of the two-year Biosphere 2 mission is presented, followed by select data and lessons learned that are applicable to the design and operation of a long duration human space mission, settlement or test bed. These lessons include technical, programmatic, and psychological issues.

INTRODUCTION

A human planetary mission is longer and more complex than any space endeavor undertaken to date. Biosphere 2 provides an opportunity to learn in a relevant, analogous environment to manage such complex, long duration missions, while addressing the fundamental risks inherent to the mission.

Time is a recurring theme through many risk categories of a long duration space mission. While some systems lend themselves to accelerated tests (e.g., thermal cycling of electronics or batteries), biological systems testing typically cannot be accelerated. Complex, multiphase human missions that preclude a rapid return to Earth, require high fidelity, end-to-end, full mission duration tests in order to evaluate the system's ability to sustain the crew for the entire mission and return the crew safely to Earth. This risk is amplified by the fact that in most cases abort scenarios are precluded. Certain risks may only become evident late in the mission. Aging and compounding effects cannot be simulated through accelerated tests for all aspects of the mission.

Apollo 13 is a prime example of a crew being saved by a risk mitigation strategy that was heavily based on simulation, before and during the mission. In this case, they had to keep the crew alive long enough to get them back from the Moon.

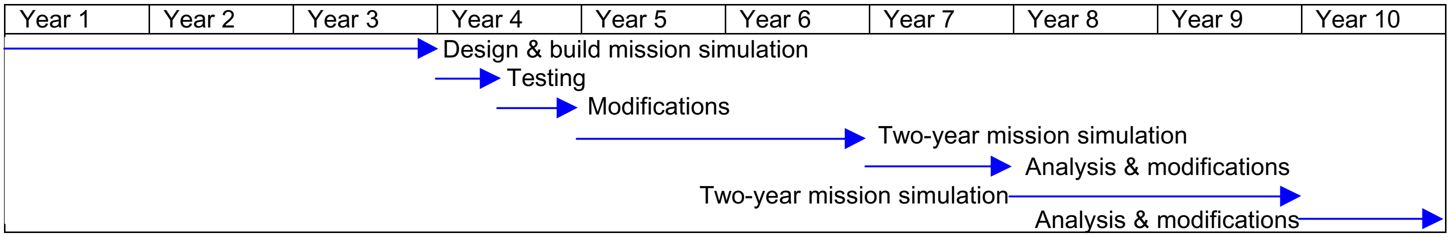

Figure 1. A ten-year schedule for a full end-to-end simulation for a human Mars mission using a single facility.

If we accept that full end-to-end mission simulations are required to adequately test and prepare for a human mission to Mars and back, then time becomes the significant program driver. For example, let's examine the following scenario, illustrated in Figure 1. Three years are required to develop and build a full mission simulation, followed by six months of short term testing, then six months of modifications based on initial test results, and then a two-year end-to-end mission simulation test. Now we have a long list of things that need changing, and at least a year is required to implement all system modifications based on the two-year test results. A second two-year test is now required to validate all the modifications made after the first test. At the end of this second full up test, six to twelve months are required to analyze all the data and extensively evaluate systems and materials performance. Using this scenario whereby all phases are conducted sequentially with a single facility, it will take **ten years** to create the technical basis and engineering and management capability with which to begin the design of a manned mission to Mars. This schedule could be significantly compressed with several facilities running in parallel where lessons learned on the "leader" are used to make adjustments on the "follower". A similar approach has been taken with Mars Rover landings. Clearly the need to begin working with full-scale ground simulations is evident, as is the need to glean lessons learned from past and analogous efforts.

Past and current analogs for long duration human space exploration and settlement are studied as a means of identifying potential risks, ranging from technical to programmatic, that would be faced in developing a ground simulation of a human space mission. Biosphere 2 lessons learned are therefore presented in the context of risks that a ground simulation program may need to mitigate. Thus, the two-year closure of Biosphere 2 is viewed in this paper as both a simulation of a long duration space mission, and as a long duration mission in need of a simulation itself, or at minimum extensive system testing (which was precluded due to budgetary and scheduling constraints). Although the first two-year closure of Biosphere 2 ended ten years ago, it is still the longest duration and possibly the highest fidelity simulation of a self-contained space base-like environment.

DESCRIPTION OF BIOSPHERE 2

Figure 2. Biosphere 2. The Human Habitat is in the foreground. The rainforest is pictured on the left.

Biosphere 2 is a privately financed, closed ecological system, located near Tucson, Arizona. Biosphere 2 supported eight humans and over 3000 documented species of plants and animals, in seven biomes – rainforest, savanna, desert, marsh, ocean, intensive agriculture and a human habitat – for two years.

With a footprint of 14 thousand square meters, Biosphere 2 has an atmospheric volume of 161 thousand cubic meters. A stainless steel liner seals the structure from below, while a space frame and glass glazing above contain the atmosphere while allowing 45-50% of ambient sunlight to enter. Two variable volume chambers compensate for variations in atmospheric volume due to changes in temperature or other factors.

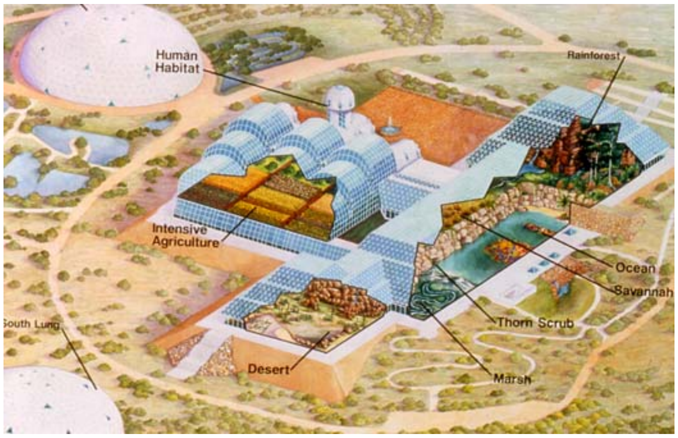

Figure 3. Floor plan of Biosphere 2.

During the two-year mission, the habitat contained a kitchen, apartments, analytical laboratory, workshop, library, command room, animal bay, storage, medical facility, recreation and living rooms. Food was grown and essentially all the air, water and human, animal and plant wastes were recycled and purified by plants, microorganisms and a physical/chemical carbon dioxide scrubber. With a leak rate of less then 10% per year, Biosphere 2 was operated as essentially materially closed while open to energy and information, so that data (computer, video, etc.), electricity, light and heat were transferred in and out as needed.

A two-year test run of Biosphere 2 was completed on 26 September, 1993. Biosphere 2 was operated by a crew of four men and four women that lived inside the structure without leaving for the duration of the mission, with the exception of one medical emergency when a crew member left for five hours to undergo hand surgery. The crew maintained, operated and depended on Biosphere 2 to support their lives, while using it as a tool for ecological research and for studies of possible future applications in space. Currently Biosphere 2 does not sustain human populations, and most recently was used for global change and biogeochemical experimentation.

LESSONS LEARNED

Extensive computer modeling and subsystem testing must begin early in any complex human mission program. The time required to conduct an end-to-end mission test is so long that a Long Duration Human Space Exploration Program (such as to Mars) is critically dependant on the tests being successful. <u>Extensive computer modeling and ground-based physical simulations are the most effective risk mitigation methods available.</u>

This paper does not attempt to capture all the issues that arose in the course of the Biosphere 2 project. Numerous scientific findings of the two manned-missions (two-year, followed by an eight-month mission) were published in a dedicated journal of Ecological Engineering, June 1999 and elsewhere. Rather, it is intended as an overview of challenges encountered that are pertinent to long duration space missions, particularly to bases on the Moon or Mars.

PLAN FOR PERFORMANCE SHORTFALLS - It is often the case that systems, once integrated, do not perform as expected. A rigorous design, simulation and test program at a subsystem level does not always account for interactions that manifest themselves in adverse or unexpected ways at the system level. Biosphere 2 was, for the most part, a novel combination of known technologies that were adapted to the particular application. The project attempted where possible to avoid risks associated with specific technologies by using tested, off the shelf technologies where possible. The “technology” under development was the closed loop system itself. While the project was never in a situation where testing was delayed due to the implementation of a specific subsystem, there are many instances of performance reduction and operational problems due to under performing subsystems. Performance shortfalls generally occurred in subsystems that had conflicting requirements and did not receive sufficient analysis early in the design process.

Problems encountered during the two-year closure of Biosphere 2 demonstrate that, when integrated, the system will not necessarily perform exactly as expected. Moreover, system-level problems may only manifest themselves with a full-up operational demonstration. Synergetic and compounding effects are elucidated that would not have been under subsystem level testing only. Histories of a system (especially biological systems) also affect the performance and must be considered in a test plan. Furthermore, the test plan must include end-to-end testing as aging of all components typically cannot be accelerated, and compounding effects of the system may only become evident late in the mission. Insufficient testing and system experience allows mission critical problems to go undetected.

An example that supports this thesis was oxygen decline that became evident late in the two-year mission. During the first 16 months of closure the O_2 in the atmosphere decreased from ambient 21% to 14%. The oxygen loss was initially inexplicable as the rate of loss was greater than the rate of CO_2 increase, usually correlated in previous experiments in the project’s Test Module. A research program was initiated to ascertain the cause. Carbon isotope data, soil and atmospheric analysis determined that CO_2 microbial decomposition of the large amount of organic matter incorporated into soils was subsequently absorbed into the internal concrete structure (Severinghaus et al, 1994). The oxygen loss problem was subsequently solved in later missions by coating the concrete to prevent CO_2 absorption. The continuing CO_2 problem was likely avoidable had atomic level computer modeling been done of major atmospheric constituent cycles as part of the design process, resulting in less organic matter being incorporated into the soils to balance the carbon cycle.

Another contributing factor was the glass and steel structure covering the Biosphere, which had to accommodate ancient architectural forms such as stepped pyramids and barrel vaults while transmitting sufficient light for the plants. Due in large measure to insufficient analysis of the light transmittance through the as-designed structure, by the time the low light transmission problem was identified it was too late to change the structure and sealing technology, or the architectural forms. The anticipated light levels at the soil surface was 65% of ambient, however, the actual level was 45 – 50% of ambient. The lower than expected light transmittance was in part responsible for the low oxygen levels and food production.

Figure 4. An early construction shot of the Biosphere 2 rainforest showing artificial rockwork made of concrete.

SIMULATE THE OPERATIONAL ENVIRONMENT - The two-year "simulation" mission of Biosphere 2 elucidated several design flaws that failed to take into account variability of environmental factors, some of which could have been eliminated had more integrated system modeling and subsystem testing been accomplished prior to the mission start. Bases on the Moon or Mars will undoubtedly encounter situations where uncertainty in the operational environment will dictate that robustness needs to be built into the design and its test program.

A noteworthy example of unexpected environmental inputs in Biosphere 2 was lower than expected levels of food production. The agriculture was designed to be a regenerative, non-polluting, intensive, soil-based agriculture system, providing a fully nutritious diet, with a wide variety of crops. Approximately 85% of the food consumed by the crew was produced inside Biosphere 2 during the 2 years. The remainder came from stored beans and wheat and excess seed stock. All amino acids, minerals and vitamins (except B12 and D which were supplemented) were successfully provided by the Biosphere 2 agriculture. However the production of calories was low.

One of the primary causes of reduced yields was low light levels during the two winter seasons of the two-year enclosure from El Nino-Southern Oscillation events. A second cause was inadequate modeling of the interaction of the truss-glass structure with light, which showed flux estimates that were higher than what was actually experienced. The low light weakened plants, thereby encouraging the development of pest infestations that devastated some crops. Broad mite, not experienced on any crops in any previous tests, killed the white potato crop, requiring the crew to plant sweet potatoes instead.

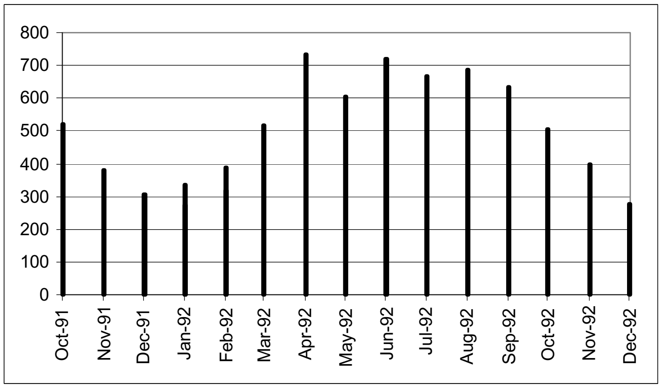

Figure 5. Light received at plant height in the agriculture from 26, September, 1991 to 28 February, 1993. Data shown as monthly quantum light totals (E/m^2).

While it is likely that any base on the Moon or Mars would exclude agricultural pests, the need to have multiple species serving the same function within the diet (sweet potato and white potato, for example, or wheat and rice) is clear. Unforeseen environmental conditions can cause one species to respond better than another. With the addition of high-pressure sodium lighting the second crew that was enclosed in Biosphere 2 for 8 months was able to produce 100% of their food on the half-acre agriculture, demonstrating the viability of a fully regenerative agriculture system for permanent space bases.

Another operational factor was workload. As was the case for the International Space Station, the time required for maintenance activities was dramatically underestimated. Despite being a new facility with little equipment maintenance required, labor was insufficient to answer research and development questions while conducting all required maintenance. The workweek comprised 60 – 80 hours, and was towards the lower end of the range during times of extreme hypoxia from the low atmospheric oxygen levels. On average, nearly 50% of each person's time was spent growing and preparing food. This percentage is somewhat higher than for other studies performed by NASA and Russian scientists, which showed that approximately one third of the time was required. With increased automation in the agricultural systems the labor hours would have been reduced, but budgetary and construction schedule constraints precluded it. 20% of labor hours were on maintenance of the wilderness and equipment. Another 20% was spent communicating, e.g., writing e-mails and reports, talking with consultants and giving interviews. Six percent was on analytical laboratory and sensor maintenance and operations, leaving only 5% of time for research related activities.

The designers and operators of Biosphere 2 thought they understood the basics of how to respond to problems, though lacked sufficient preparation of mission rules. While sufficiently prepared for short time frame events (fire, mechanical failure, etc.), the team was not well prepared to deal with changes that occurred slowly. This may have partly been due to the idea that slow changes would allow rules to be established on the fly, and knowing that the crew could always leave if the conditions were not safe. As will be shown later, slow changes, combined with a lack of planning can lead to potentially dangerous situations. In retrospect, we believe that integrated system computer modeling and physical simulations, emphasizing scenario generation, probably would not have predicted the combination of medical and environmental control issues that occurred, though the crew and mission control would have been far better prepared to deal with issues as they arose.

Some crewmembers thought communication with “mission control” was difficult (despite video conferencing, e-mail, phone etc.), a feeling that was exacerbated by frustration over a perceived insufficient level of support from the outside. We believe that the effects of store-and-forward communication are probably not well understood, and note that a long duration space mission has never been conducted with significant communications delays. Computer modeling and ground-based physical simulation efforts need to include the human aspects of communication difficulties as well as the latency in communications. These time delays and miscommunications are especially important in emergency management. Scenarios where time to action is dependant on communication with mission control should incorporate miscommunication and delays.

A significant risk is presented where nominal operations are well understood by the flight and ground crews, but the equipment and training required to handle emergencies may be inadequate due to a limited understanding of failure scenarios and a lack of developed and trained response options. In a more general sense these examples elucidate the need to design for robustness against uncertainties in the operational environment. In addition, an extensive ground-based physical simulation and test program that includes off nominal cases may help identify design flaws early before they become a problem to be dealt with during the operational phase.

ESTABLISH A TEST BASELINE - Full up end-to-end testing becomes particularly critical when preparing for a complex mission with many mission phases, such as the installation of a Moon base. Performance degradation can occur as the result of a series of events over a long period of time over several mission phases. Because much of such a mission is simulated with computers and induced conditions, the know-how required to conduct such a complex long duration test must be developed. Improper testing is often cited as a cause of failure in much simpler robotic missions (e.g., the Mars ’98 Lander failed due to lack of end-to-end test on entry, descent and landing system). When developing test protocols, the program is not only at risk because the systems being tested may fail, but the testing protocols, the very design and conduct of the test may be discovered to be at fault, invalidating the test results. This issue is especially important when testing complex biological systems that involve human crewmembers because the range of possible problems and results is so large.

One way this was manifested in the Biosphere 2 project was the failure to establish baseline physiological values for the crew in the years leading up to the two-year closure, as well as an explicit agreement from crewmembers to make themselves available for long-term physiological evaluation after the mission. The crew’s physiological and emotional response to the low oxygen, high stress, and low caloric intake during closure was a unique opportunity. For example, no increase in hemoglobin was observed in the crew despite an oxygen partial pressure equivalent to 15,000 feet for a long duration. The crewmembers’ base metabolic rate was also observed to drop significantly during closure. However a lack of measurement before closure, and the refusal of several crew members to be tested after closure, made the significance of this observation more difficult to evaluate. This and other phenomena would have been better understood with a longer duration pre-closure evaluation period with collection of archival samples. As a rule of thumb, the pre and post evaluation period should be at least as long as the planned test, and a multiple if the test duration is less than 90 days.

SCALABILITY AND COMPLEXITY OF ANALYSIS AND COMPUTER MODELING - For Biosphere 2, an under appreciation for early total system analysis and computer modeling, especially after preliminary results were inaccurate or unfavorable, resulted in management ignoring the results and under funding or eliminating computer modeling and physical simulation efforts. The need to conduct early analysis with detailed computer modeling is unfortunately under appreciated by many program managers. This becomes a self-fulfilling prophecy where insufficient computer modeling and analysis efforts lead to inconclusive results, which are then ignored. This phenomenon occurred through the design process as well as during operations within Biosphere 2.

Computer modeling is dependant on an accurate understanding of the component technologies. While collections of subsystems were tested in a “Test Module” that was 1/300th the volume of Biosphere 2, these tests failed at the time to elucidate many of the problems encountered in Biosphere 2. So, in this case management was given a false sense of security by tests that appeared to be successful. With *20-20 hindsight* it is the authors’ assertion that if the test module experiments had more rigorously mimicked the materials and processes in Biosphere 2 and the data had been combined in computer models, along with small closed chamber testing of the interaction of individual materials with the atmosphere, the oxygen loss problem, for example, may have been identified early enough to have been prevented. This lesson is clearly applicable to establishment of Moon or Mars bases because the ability to scale up infrastructure while maintaining a safe environment for the occupants will be paramount. Latencies in being able to respond to problems or send resources, for example, as imposed by planetary alignments or trip time, make a detailed understanding of all elements even more important.

Figure 6. The Test Module was 1/300th the volume of Biosphere 2.

A complicated relationship exists between complexity (the number of interdependencies), safety, and redundancy. For example a system that has three truly redundant systems based on different strategies (chemical, biological, flow through) for life support is perceived as "safe" but is also difficult to test. Furthermore, use of redundancy may introduce additional failure modes that in the end may outstrip the perceived benefits of utilizing redundancy. It is often more difficult to design a simple solution than a complex one. Complexity management entails simplifying every aspect of the spacecraft, life support and mission wherever possible. Biosphere 2 was very complex, though to a degree the occupants were able to take advantage of that complexity to change operating strategies and reconfigure the system to address issues as they arose. An example of this is managing the atmospheric carbon dioxide initially by optimizing plant growth. When biomass was not maintaining the level low enough during the darkest months of the year, a physical/chemical scrubber was initiated to assist. Also, when the white potato crops were compromised by pest infestations, the planting plan was altered to replace them with another starch crop, sweet potatoes, that did not succumb to the pests. And finally, a liquid oxygen generator, intended for use with analytical systems in the laboratory, was modified to provide breathing oxygen to treat sleep apnea in crewmembers due to the reduced atmospheric oxygen levels late in the mission.

UNDERSTAND MATERIALS ISSUES AND INTERACTIONS - Several unanticipated issues arose due to materials choice and lack of testing in a like-environment. All materials included in Biosphere 2 were screened prior to installation to ensure that out-gassing of toxic substances would be kept below acceptable limits. Lifetime exposure standards for airborne toxins and carcinogens, developed by US Environmental Protection Agency (US EPA) and The State of California, were used as the principal criteria for determining if the air in Biosphere 2 was safe for the two-year mission. Using these standards it was estimated that if a person were exposed to the Biosphere 2 atmosphere for a lifetime, it would increase the odds of contracting cancer by one in one hundred thousand.

Drinking water was obtained exclusively through condensation of atmospheric moisture. Without treatment the condensate water met all US EPA potable water standards. Though the Biosphere had an ultraviolet light / peroxide water treatment system, it was never used. The water also met all US EPA microbial standards as long as dust and debris was regularly removed from the condensate collection system. No disinfectants or anti microbial agents such is iodine or chlorination were required. However, a side effect was that the high humidity environment also caused extensive corrosion of electrical boxes and equipment, which was enhanced by the unusually acidic condensate caused by elevated atmospheric CO_2. Condensate on structural material was measured at pH ranges of 4.5 to 5. The acidic moisture also led to extensive corrosion of bi-metallic junctions.

Within two months materials off-gassing products and bioorganic hydrocarbons reached values in the air and condensate water that remained relatively constant for the remainder of the two years and under required levels. Two notable exceptions to this were Methane and Nitrous Oxide (laughing gas). Methane reached an equilibrium concentration after approximately a year, reaching an asymptote of 120 parts per million (ppm), still below operational limits. Nitrous Oxide and Nitrogen gas (products of nitrification and denitrification) rose steadily through the course of the two years, and did not exceed any published standards. Ethylene remained below 5 ppb. The outside air exchange rate averaged 8% per year.

A particularly vivid example of the need for materials testing in like environments was the extensive use of concrete in Biosphere 2 and its unexpected interactions with the sealed atmosphere. As discussed above, the concrete absorbed CO_2, thereby acting as a CO_2 sink and indirectly lowering atmospheric O_2. This issue also has implications for the use of in situ concrete in building habitats on the Moon or Mars, and its direct contact with the base's internal volume. Another materials interaction problem was high heavy metal levels in the ocean and other waters due to leaching from exposed steel structural parts, particularly the steel liner.

A minor materials-related lesson worth reporting regards the use of sulfurhexafluoride (SF6) for leak detection. All the seams in the biosphere's stainless steel liner had gas collection systems on the outside. The atmosphere was dosed with SF6 so that if leakage occurred through a fault in a seam, the presence of SF6 could be detected using an electron capture detector and the leak repaired from the inside. A significant amount of SF6 was released after closure. Several of the analytical systems in the biosphere used high temperature metal catalysts. These catalysts were poisoned by acids that formed as a byproduct of SF6 decomposition on the hot catalyst. The SF6 was also a problem for the liquid nitrogen plant. It froze out on internal components, requiring a monitoring and blow-down system to be improvised that would clean the SF6 out of the system periodically.

MEDICAL FACILITY AND ISSUES - The medical facility inside Biosphere 2 needed to be non-polluting, and would need to be able to deal with ills in a tiny facility, as any space base would require. Contrary to situations in Antarctic bases where facilities can be basic, Biosphere 2 had a well-outfitted diagnostics laboratory, and Dr. Roy Walford, the doctor on the crew, anticipated that he would be able to deal with about 75% of possible maladies encountered during the two years. He wanted to ensure that no one would exit unnecessarily. Equally, he needed to be certain that no person would be erroneously kept in the Biosphere when he or she should have been released to more specialized care outside.

Biosphere 2 was humid; there were many species of bacteria, fungi and other organisms living inside; and, a large amount of industrial equipment was housed in its basement. The medical team anticipated that three major physiological problems would become evident during the two-year mission: infection and allergies; trauma; and toxic exposure from build up of outgassing and organic emissions (Walford et al, 1996). No significant infections occurred, and the few allergies encountered were treatable. A partial amputation of a digital phalanx that occurred during the first month of closure was the only acute trauma. No trace gas contaminants were ever measured that exceeded permissible levels. However, concerns about elevated levels of nitrous oxide in the atmosphere became evident towards the end of the two-year mission as literature references citing the possible suppression of "B" vitamin metabolism in people repeatedly exposed to elevated levels of nitrous gas overlong periods or time. Nitrous oxide is a byproduct of nitrification and de-nitrification, principally in soils. A two-year mission had been chosen as the experiment's length as it was considered the likely length of a mission to Mars. The systemic nitrous problem would not have been elucidated in a shorter simulation.

Unanticipated medical challenges were faced, however, that were caused by a life support system that was not adequately functioning. Because of the lower than expected yields in the agriculture, the diet was low in fat and calories. Calorie intake was approximately 1780 kcals/person/day for the first six months, which subsequently increased to 2200 kcals during the remainder of the two-year closure (Nelson et al, 1993). Fat intake accounted for approximately 12% of the energy intake. Weight loss was considerable. By 8 – 10 months the men had lost 18% of their total body weight on average, and the women lost 10%. Mean body fat, measured by skin-fold measurements, indicated 8% for the men and 13% on average for the women. No significant weight gain or increase in body fat was measured even with the increase in calories (Walford et al, 1996). This prompted unexpected monitoring of crewmembers to ensure that each person was receiving enough protein and other vital macro- and micro-nutrients.

Dr. Walford has written extensively about the health benefits of a nutrient dense, low calorie diet like the one eaten by the eight-person crew of Biosphere 2 (Walford et al, 1992). However, most crewmembers commented on feeling hungry, irritable, and fatigued from the low calorie diet. It is the authors' opinion that it reduced crew efficiency, and possibly safety, and added to the stress experienced by the crew.

A second unexpected medical condition arose during the two-year closure on account of depleting oxygen. As described above, during the first 16 months of closure the O_2 in the atmosphere decreased from 21% to 14%, equivalent to 15,000 ft elevation (although pressure remained constant), declining at the slow rate of the equivalent of 750 ft / month in elevation. Symptoms from the reduced O_2 were considerable below 16% (Walford et al, 1996), and Dr. Walford directed O_2 to be injected into the biosphere raising the level to 19%. Symptoms included fatigue, decreased work capacity, sleeplessness, shortness of breath and sleep apnea (Leigh, 1993; Alling and Nelson, 1993). The symptoms were all similar to high-altitude sickness as the crew was not adapting normally, possibly due to the low calorie diet.

The reduced O_2 required extra crew health monitoring, including taking arterial blood for gas testing. The analytical laboratory shared many functions with the medical facility. The flexibility of both labs was utilized many times. For example, as the oxygen partial pressure (ppO_2) began to drop, a range of analytical procedures were developed / improvised using materials inside the biosphere in order to determine the cause of the oxygen loss and to analyze crew member respiratory function and adaptation to the lowered oxygen.

In response to the low ppO_2, the total 2,3-diphosphoglycerate (2,3-DPG) level in the crewmembers' blood increased. 2,3-DPG controls how much oxygen is released once the blood reaches the tissues. An increase in 2,3-DPG shifts the disassociation curve so hemoglobin has a reduced affinity for oxygen. This is the normal adaptation to a rapid decrease in ppO_2, and is followed by an increase in red blood cells and return to normal levels of 2,3-DPG. Such an adaptation to high altitude occurs in the course of weeks. In Biosphere 2, the slow oxygen loss produced a ppO_2 change equivalent to an 18-month climb to 15,000 feet. The crewmembers exhibited no significant increase in red blood cell count or total hemoglobin, and the 2,3-DPG remained elevated. It is thought that this response was due to the low calorie diet. Due to the limited life span of a red blood cell, it is energetically expensive to increase and maintain a higher red blood cell count. Therefore, we hypothesize that the crewmembers' bodies conserved energy by not increasing production of red blood cells, but maintained the change in the disassociation curve with the elevated 2,3-DPG.

The lack of adaptation by the crew also demonstrates the synergetic or compounding effects of technical and management issues, and in this incidence, something that had not before been witnessed in human populations. Any medical team on a long-duration mission must be able to develop ad hoc research programs to maintain the health and safety of the crew. The flexibility to answer such unforeseen questions must be considered in the design of monitoring and analysis systems for future space missions or bases.

For example, the medical team developed innovative respiratory system analyses to measure alveolar gas composition, conducted unplanned blood analysis, and pieced together oxygen delivery system using analytical system spare parts and subsystems. The system extracted and concentrated oxygen from the Biosphere 2 atmosphere and delivered 90% oxygen in tubes to crewmembers' sleeping quarters in the Habitat. This supplemental breathing oxygen was used at night, in order to alleviate sleep apnea caused by the lack of adaptation to the reduced ppO_2.

The lowered-oxygen incident also underlined a particularly important aspect of a mission's medical team structure. Hypoxia can produce difficulty in clear thinking and lack of judgement (Ward et al, 1989), reported in several biospherians when the O_2 was near its lowest level. The crew's primary physician was inside Biosphere 2, undergoing the same environmental stresses as the remainder of the crew. Clearly, there needed to be a physician outside Biosphere 2 that was overseeing, and if necessary, over-ruling the crew's physician under such circumstances, which is particularly true when considering psychological stresses and social conflict (see below).

The combined effects on the crew from psychological stress, the low calorie diet, lowered-oxygen, and the inability of the crew to adapt to the low ppO_2 with a hemoglobin increase were certainly not anticipated. This slow accumulation of stressors made each day seem essentially like the last. Like a frog in slowly warming water, the cumulative effect of many slowly changing factors can lead to a dangerous situation. The principal danger in this case was the increased likelihood of an accident due to reduced mental capacity and impaired communication among crewmembers. The impaired communication is principally a byproduct of the psychological issues associated with the isolated and confined environment, exacerbated by the oxygen and food issues. Some crewmembers reported (and sought treatment for) mild clinical depression, believed to be a result of these combined factors, as they reported no previous history.

CREW SELECTION, TRAINING AND PSYCHOLOGICAL ISSUES - The management as well as the crew and mission control personnel must be trained to conduct extended missions. The root cause of failures during early robotic Moon missions was determined to be bad management of the mission control room and support personnel. NASA screens astronauts extensively prior to choosing candidates for the Astronaut Corps.

The selection process at Biosphere 2 was somewhat unorthodox. The crew was partly self-selected, in that they underwent grueling experiences during training in the Australian Outback and on a research vessel at sea, and during the design and build of Biosphere 2. Those candidates that were not dedicated simply quit under the pressure. The crew of the first mission was also selected from within the project's management. Selecting the first crew from the projects top management and technical leads had many advantages in the staffing required to move into operations as well as a motivated crew that knew every technical detail of the project. The major disadvantage was that very little cross training occurred. The crew was not selected for compatibility, which certainly enhanced many of the inter-personal problems that arose during the mission. However, the eight-person crew did manage to stay in Biosphere 2 for the entire two years, and maintained and operated their life support system successfully. The second crew went through even less selection process.

No formal psychological screening or psychometric testing was done either before or during the mission, with the exception of one examination towards the end of the two-year stay. The crew received the Minnesota Multiphasic Personality Inventory, revised version (MMPI2), which was scored at the Arizona Center for Clinical management, by Michael Berren. No psychological pathologies were evidenced by the MMPI2 test (Walford et al, 1996). Of note is that, where normally the profiles of men and women are very different, the profiles in this case were almost indistinguishable in key areas. Moreover, when correlated with profiles of astronauts and people that winter over in the Antarctic, the women showed particularly close correlation, while the men showed some correlation, suggesting that a certain type of person signs up for missions of this nature (Bechtel, 1994).

Several crewmembers reported that the psychology of groups in Isolated Confined Environments (ICE) such as Biosphere 2 was one of the more difficult aspects of living inside the enclosure for two years. As astronauts on Mir attested, private communication with loved-ones and others outside the enclosure was considered very important by all biospherians. The authors propose that the interpersonal problems that arose (the crew broke into two factions after six months) significantly compromised crew efficiency and safety, although the crew succeeded in completing the two years in spite of deep-seated communication barriers.

ICE psychology is being increasingly recognized as a medical issue that arises during long-duration missions. Crew factionalism and depression are two such effects (Pierce, 1991). Research on Antarctic winter-over crews, on Mir, and during numerous recent ground-based seven to 240-day experiments, underscores the difficulty that humans can encounter when enclosed for long periods of time. Unfortunately, a space-based mission cannot be simulated on the ground with 100% fidelity, not only because of the lack of gravity-based stress in a ground-based physical simulation, but also because on the ground the test subjects are aware that help and safety are very close at hand, altering the psychological dynamic. On the other hand, the very fact that a crewmember is enclosed voluntarily in a ground-based experiment increases certain psychological strains, as astronauts and winter-over crews have no choice but to keep going. Several astronauts have commented on this to the authors. Regardless, many aspects of ICE have been well documented, which can only be simulated under long-duration mission simulations, and six months is generally considered as the point beyond which ICE issues are encountered. Such physical simulations are a vital aspect of any crew training.

It is the authors' belief that the effects of ICE cannot be adequately communicated, and the mitigation of their effects adequately trained without potential mission crewmembers experiencing it during long-duration physical simulations. "Test like you fly, and fly like you tested" also applies to crew psychology and training. A series of short duration tests does not adequately prepare a crew member or ground control for a long duration mission.

CONCLUSION

Biosphere 2 and the two manned missions demonstrated the technical feasibility of using bioregenerative systems for life support in long duration scenarios, such as a Moon or Mars base. While there were considerable problems encountered during the first two-year mission, such as food production and oxygen loss, they are not inherent to bioregenerative systems but are attributable to the specific design of Biosphere 2. Many useful lessons can be learned from the number of problems that arose during the mission. Even though the first two-year manned mission ended ten years ago, it is still the longest duration, and possibly the highest fidelity, ground-based physical simulation of a space base environment. The experience of conducting mission simulations within the Biosphere 2 facility elucidated issues that were not even considered before end-to-end testing, and may represent one of the best training analogs available for space mission design and operations. Designed in the mid and late 1980's, most of the problems were unforeseen, and in some instances unforeseeable at that time. They were systemic, synergetic and compounding and only evident when a long duration, all-up test was performed. Furthermore, it is not enough to perform end-to-end testing of the technical systems, but the human element must be included to allow for adequate experience and training in confined environment psychology and social inter-relations. Maybe one of the most pertinent lessons is that the adage "Test like you fly, and fly like you tested" also applies to crew psychology.

Biosphere 2 created as many questions as it answered, though demonstrated that the long duration testing requirement, as well as the complexity of a Moon or Mars base requires a Simulation Based Acquisition strategy with Integrated Systems Computer Modeling.

Columbia University has managed Biosphere 2 for the past five years to conduct global climate change experimentation. Consideration may be given to the use of Biosphere 2's agriculture and habitat, now isolated from the wilderness biomes, as a test bed and ground simulation facility directed to supporting the President's Vision for Space Exploration. While Biosphere 2 is a facility that can address a variety of operational scenarios, the lack of a specific mission analog make the lessons learned a step removed from a space mission. However, with specific scenarios, we would have a better understanding of the range of applicability and operational conditions that have been addressed by Biosphere 2 or could be addressed in future experiments and simulations within the facility.

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