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BIOREGENERATIVE SPACE AND TERRESTRIAL HABITAT

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ABSTRACT

For fifteen years, NASA at the John C. Stennis Space Center has been involved in bioregenerative component development for air, water, and waste treatment. Through funding from the NASA Technology Utilization Office, technology developed by this project has been transferred to single homes, small communities, and large municipal users such as San Diego, California, as well as commercial investors interested in capitalizing on the air purification spinoff products. The products of this project have now been integrated into a unique, bioregenerative habitat with a self-contained waste treatment and water reclamation system. Biological processes are used in the energy-efficient living quarters for air reclamation and revitalization. Food products will also be produced in the waste treatment train. This integrated "living" system, which minimizes the use of mechanical and energy-consuming treatment systems and maximizes the use of bioregenerative processes, is the culmination of the component development work and the beginning of a more complex and detailed project. The development, test, refinement, and verification of this unique bioregenerative habitat will yield information necessary for the safe and efficient use of biological processes in closed habitats both in space and on Earth.

Background

For many years, NASA has had parallel programs in closed system habitability. One was based on developing physico-chemical processes to largely meet near-term space needs, especially with Space Station.[1] A second program is concentrating on edible product production from inorganic nutrient supplies with water and air reclamation achieved through condensation collection and photosynthesis, respectively.[2] The third program is based on the development of bioregenerative processes which could have immediate application for wastewater treatment in the United States, through the NASA Technology Utilization (TU) and Spin-off Programs, due to less spacial restraints on earth. Long duration space missions involving interplanetary exploration will possibly benefit from a combination of the latter two programs, by relying almost exclusively on bioregenerative processes to provide air, water, and food for humans.

The products and benefits of the program sponsored to date by the NASA TU Office are the subject of this paper. In April 1989, the efforts of this program culminated in the completion of a novel facility, referred to as BioHome, which incorporated all of the TU-developed bioregenerative components for air, water, and nutrient recovery into a single, integrated habitat. BioHome promotes the concepts of self-reliance and individual responsibility for environmental conservation. Its evaluation and refinement of integrated component efficiencies will also provide a test bed for future biological-based systems to be used in long-term space travel.

BioHome

BioHome was architecturally-designed with a modern, futuristic look and was engineered to achieve maximum air and energy closure. As shown in Figure 1, its exterior is covered with special molded plastic panels designed to resist normal weathering conditions with minimal maintenance. Both the inside and outside are shaped in parallel arches spanning 14.5 ft at the base and rising to 9.5 ft inside and 10.5 ft outside due to the 11 in thick walls filled with fiberglass insulation and creating a R-40 thermal insulation value. BioHome is 43 ft long and contains 640 ft^3 of interior space of which 344 ft^3 have been equipped to provide a fully functional, one-person habitat. (See Figures 2-4). The remainder of the interior space houses a network of bioregenerative components whose basic end products are reclaimed wastewater and

Presented at:

Ninth Biennial Princeton Conference on Space Manufacturing
Space Studies Institute
Princeton, NJ
May 11, 1989

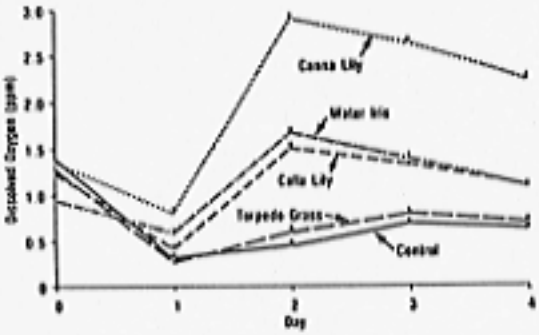

Figure 7. Effects of plants on dissolved oxygen concentration.

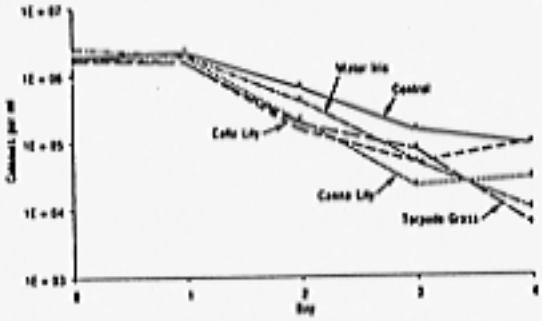

Figure 8. Effects of plants on fecal coliform count.

resolved. We intend to repeat the experiment with a few modifications in an attempt to resolve these discrepancies. Among the changes planned at the present time are use of two plants of each species, an increase in the volume used at the beginning of each testing period, such that the evapo-transpiration rate will not cause a significant decrease in the volume over the testing period, identification and enumeration of the protozoan flora present, and determination of the parameters such as biological oxygen demand and dissolved solids. The final results from this series of experiments will give a much better understanding of which plants will function best in the waste recycling system of the BioHome.

Potable Water Reclamation

Potable water will be obtained from a dehumidifier and the air conditioner condensing atmospheric moisture produced via evapotranspiration from the plants in the treatment system. In addition, extraneous atmospheric moisture will be condensed due to some air exchange with the outdoors. The ambient relative humidity in SSC area is always high. The condensates will be combined and treated with GAC and an ultraviolet disinfection unit and tested extensively for water quality, including organic chemical contamination and indicator microorganisms. In the future, it is the goal of this project to provide all the potable water needs of the BioHome occupant by this process.

Since plant evapotranspiration rates are important to the success of this proposed process, screening experiments have now been initiated to provide data for retaining or revising the selection of aquatic species used in this wastewater treatment network.

An example of data from the first screening experiment is shown in Figure 9. Plants of approximately equal biomass of each species were placed in 1800 ml of freshly collected domestic wastewater, and the water volume monitored daily. This experiment clearly indicates that canna lily is very efficient at transpiring water with water iris, calla lily, and torpedo grass in decreasing efficiency. Much more work in this area is planned.

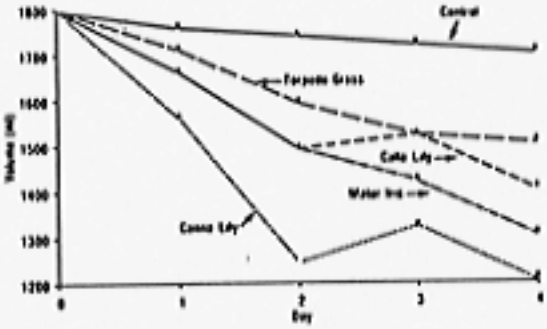

Figure 9. Transpiration rate of water plants.

Air Revitalization

The photosynthetic process that allows plants to live and grow requires continuous exchange of gaseous substances between plant leaves and the surrounding atmosphere. The most common gaseous substances exchanged are carbon dioxide, oxygen and water vapor. The plant leaves normally give off water vapors and oxygen and take in carbon dioxide. However, it appears that plant leaves can also take in other gaseous substances from the surrounding atmosphere such as formaldehyde, benzene, toluene, and other undesirable organics.

Foliage plants are placed throughout the living quarters of BioHome in order to abate the buildup of any toxic organics outgassing from the newly constructed and furnished facility. Air quality will be closely monitored for trace organics.

In addition to conventional foliage plant arrangement, a special, newly designed GAC/plant air filter will also be used in BioHome. This unique system is shown in Figure 10. Data demonstrating the utility of this system in controlled, screening experiments is shown in

of pipe with no plants or other media; its purpose is to encourage further solids settling and minimize downstream clogging problems. Each of the remaining segments contains biofilm support media and either 5 or 6 vascular plants. At present, four different species of water plants are being evaluated: water iris (Iris pseudacorus), calla lily (Zantedeschia aethiopica), canna lily (Canna flaccida) and torpedo grass (Panicum repens). Segments 2 and 3 are filled with lava rock to provide a high surface area, light weight biofilm support. Segments 4, 5 and the first half of 6 contain 4 x 14 mesh granular activated carbon (GAC) obtained from American Norit Company. The second half of Segment 6 contains the mineral zeolite a hydrated sodium (or calcium) aluminosilicate used for ammonia removal. Located at the effluent end of each segment is a small sampling port from which water samples can be drawn for analysis.

The final effluent from the above system flows through an ultraviolet unit to assure complete kill of all microorganisms, especially those potentially pathogenic to humans, from the stream. The final effluent is pumped into a 100 gal aquarium, currently used as a holding tank and buffer. Future plans include use of this tank for fish production. Catfish will be studied first. When the system plumbing is completed, water from the aquarium will also be used to operate the toilet and for watering vegetables.

Introduction of water into Segment 1 is controlled by a set of level sensors located at the influent end of this pipe. Water can be pumped either from the initial holding tank or the aquarium. When the liquid level in Segment 1 falls below 4 in, both are turned on, and water enters at equal flow rates from the holding tank and aquarium until a level of 7 in is reached, then both pumps are turned off. A separate float switch, located in the holding tank, senses the level in it, such that during periods of insufficient volume, all influent originates from the recirculated water in the aquarium. The rise in Segment 1 is much faster than that in the remainder of the system due to the hydrostatic pressure created by the media in the other segments, therefore dampening the pulse effect of the pumps and creating a more even system flow.

Screening Experiments--
Dissolved Oxygen and Fecal Coliform

Two important parameters which are indicators of the microbial profile of the biofilms in the wastewater treatment network are dissolved oxygen, an indicator of aerobic or anaerobic conditions, and fecal coliform, an indicator of potential human pathogen contamination. It is desirable to maintain aerobic conditions in order to reduce hydrogen sulfide and noxious odors. Consistent removal of fecal coliform also reduces the possibility of pathogenic microorganism survival in the system.

An experiment to determine the relative ability of the plants selected for initial screening in the recycling system in the BioHome is currently being conducted. Results of the first five weeks from this experiment are presented herein. The plants previously mentioned, water iris, calla lily, canna lily, and torpedo grass, were used for the experiment. The individual plants chosen for use initially had approximately equal root masses. After removal from the medium in which each was growing, the roots were rinsed thoroughly in tap water before beginning the experiment. Five beakers with a capacity of 2000 ml each were used. Each was covered on the sides and bottom with aluminum foil to exclude as much light as possible.

Domestic wastewater was collected from one of the facultative sewage lagoons at SSC. Approximately 1400 ml of water was placed into each beaker and a different plant placed into each of four beakers. The fifth beaker was used as a control. It contained the same volume of sewage as the other four (excluding the volume occupied by the root mass of each plant), but no plant was placed in it. The dissolved oxygen and fecal coliform count was determined in each beaker immediately after setup and at multiday intervals following. The shortest period was 4 days and the longest was 9 days. All beakers were left undisturbed during this period except when testing was being conducted. Care was taken during these episodes to minimize the agitation and aeration of the liquid.

After the first week of testing, each plant was removed from its beaker and the root mass thoroughly rinsed and replaced into the beaker. Freshly collected wastewater was introduced into each beaker to a level of 1800 ml and 1800 ml was placed into the control. The DO and fecal coliform counts were determined in each beaker at intervals over a period of 7 days.

In order to assess the ability of the different plants to encourage growth of various beneficial microorganisms and protozoans, the plants were not removed from the beakers at the beginning of the third week of testing. Instead, water was withdrawn from each of the beakers until only 200 ml remained in each. Freshly collected sewage was then introduced into each up to the 1800 ml mark. This procedure was used in an attempt to preserve protozoa and other microflora which might be enriched from one week to the next. Sampling was conducted as in the previous weeks. Two more 7 day periods of testing were conducted in a manner identical to that described above. Data in Figures 7 and 8 show the results of this experiment. Overall, the canna lily appears to be the most efficient at both increasing the dissolved oxygen and decreasing the number of fecal coliforms present in the sewage. The results of this experiment are only preliminary. At this time, discrepancies exist that must be

potable water, edible plant products, and revitalized air.

Wastewater Treatment/Food Production Network

Since aquatic and semi-aquatic plants can utilize domestic sewage as a complete growth media while assimilating minerals, the scheme used at the John C. Stennis Space Center (SSC) for waste recycling and food production is using aquatic and semi-aquatic plants for wastewater treatment, and the harvested plant material then becomes a complete growth media for food plant production. Conventional food plants such as tomatoes, sorghum, corn, potatoes, cucumbers and squash have been successfully grown on composted aquatic plant materials produced in a similar wastewater treatment process.[3]

The estimated daily wastewater volume for BioHome is 50-60 gallons, generated by one person on a normal daily routine. The wastewater will be treated in a system housed in one end of the BioHome and accessible by a door from the habitable section as well as the outside. The network is a composite of systems developed by NASA at SSC over the past 15 years using sorptive and high surface area support media for an integrated system of vascular plants and suspended and attached microorganisms.

Past research at SSC has demonstrated that aquatic and semi-aquatic plants such as water iris (Iris pseudacorus), cattails (Typha latifolia), duckweed (Lemna, Spirodela, and Wolffia spp.), bulrush (Scirpus californicus), torpedo grass (Panicum repens), canna lily (Canna flaccida), calla lily (Zantedeschia aethiopica), etc. can utilize raw human sewage as a complete growth media.[3,10] When sewage is slowly filtered through an aquatic plant root filter system, complex biological processes take place during wastewater treatment and purification. The symbiotic relationship that is normally established between the plant roots and microorganisms living on and around these roots is very complex and important in the wastewater treatment process. See Figure 5. This process not only removes organic chemicals, but is also thought to contribute to the reduction of other polluting substances including pathogenic bacteria and viruses.[11,12] It has been shown that roots of aquatic plants such as bulrush, reed, soft rush and water iris excrete substances that can either partially or completely kill pathogenic bacteria while not harming beneficial bacteria.[8] The aerobic zone around the aquatic plant root system can also support, in addition to bacteria, the growth of large numbers of protozoa which feed on bacteria, viruses and particulate organic matter.

A flow diagram of the BioHome wastewater treatment network is shown in Figure 6. All wastewater and sewage, including vegetable waste, macerated by a

Figure 5. Wastewater treatment/food production network in BioHome.

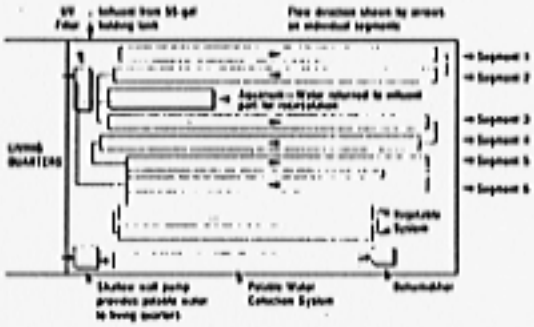

Figure 6. A flow diagram of the BioHome wastewater treatment network.

garbage disposal in the kitchen sink, is initially collected outside the facility in a 55 gallon plastic tank. This holding tank permits solids settling and subsequent digestion. Its effective volume can be maintained at a variable level in order to hold excess wastewater during periods of high usage. It is the only component of the system physically located outside of the BioHome facility and subject to ambient thermal fluctuations.

The biofilm/plant system is constructed of Schedule 40 polyvinylchloride (PVC) pipe, 8 inches in diameter. Ports are provided at regular intervals along each PVC segment in which plants are inserted. Six segments, varying from 10 to 12.75 ft in length and with an effective hydraulic volume of approximately 61 gal are used for the wastewater treatment portion of the system. The segments are connected in series by sections of 1 in diameter PVC pipe as shown in Figure 6. Segment 1 is an empty section

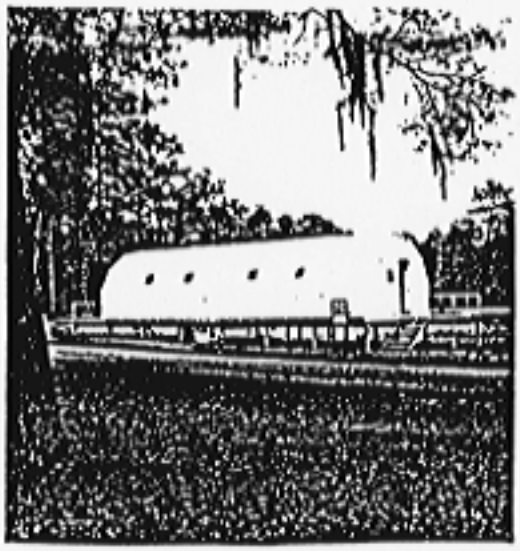

Figure 1. Exterior view of NASA BioHome at SSC.

Figure 3. Bedroom area in BioHome.

Figure 2. Bioregenerating closed habitat.

Figure 4. Dining and entertainment area in BioHome.

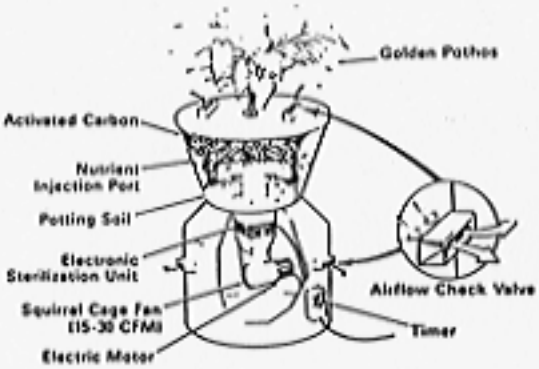

Figure 10. Air purification system combining houseplants and activated carbon for gravity-free environments.

Figure 11. The GAC enhances the sorptive properties of the system and also provides a biofilm support media for enhancing bioregeneration of the sorption sites.

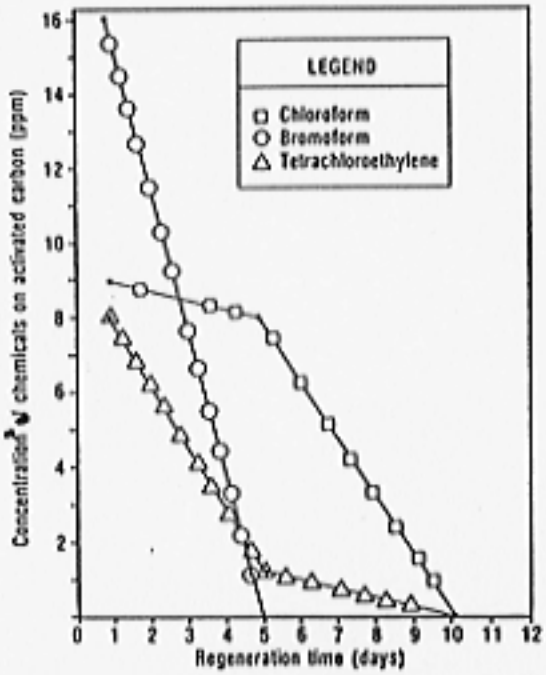

Figure 11. A bioregenerating activated carbon/plant system for removing toxic chemicals from indoor air and contaminated water. The detection limit is <1 ppm.

Summary

BioHome is a unique tool for the spatial refinement of a biological-based network of components for wastewater treatment, water reclamation, edible product production, and air revitalization. Vegetable production will begin as soon as sufficient aquatic plant biomass has been generated and composted to provide a nutrient-rich media for this activity. It is the goal of this project for all components to be working in harmony by 1990 and for the extensive monitoring and data analysis of this network to provide direction for final refinement and verification of the integrated system effectiveness. Results from this project will be widely disseminated to potential users to encourage its use and the promotion of individual environmental health and conservation.

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