SUSTAINABLE WATER IN CLOSED BIOSYSTEMS:
Preliminary Design Considerations

William J. Jewell, Professor
Cornell University

Introduction

The future of the Earth's population and long-term space flights have major challenges in common - life is dependent upon sustainable water, food, and energy systems. Successful long-term space flights will require absolute sustainable technologies for all critical life support systems. Top priority must be given to living environments with sustainable water supplies. Today, almost all human water systems are not sustainable, and freedom from pollution still depends on "dilution as the solution to pollution."

This paper is a summary of the preliminary design considerations of a test system that is intended to examine several limitations of closed biosystems that could support long-term sustainability. Many simplifying assumptions have been made to enable the components of such a system to be defined.

Goals and Objectives

The goal of this design is to show the feasibility of innovative biological wastewater treatment systems to serve as the basis for a complete recycle and sustainable water system.

Specific Objectives are to:

1. design a sustainable living system that would account for 100 percent of all major material flows, assuming a constant solar energy source - water, food, nutrients, associated solid wastes, etc. ;

2. define minimum size and minimum resource-consuming sustainable water and energy requirements with the potential to achieve one hundred percent recycle of critical items - water, nitrogen, etc.;

3. emphasize in the above design new technologies that have been fully documented to have sustainable characteristics, but are not necessarily in commercial application - high rate anaerobic conversion of biodegradable organic carbon, hydroponic treatment of wastewaters in the Nutrient Film Technique, recycle of refractory organics to topsoil applications, recovery of refractory materials in useful by-products, and biological reduction of refractory organics to basic elements using higher organisms (insects, worms, and/or mammals); and to

4. estimate the minimum size of living systems that have the potential to achieve 100% recycle of water and other materials using solar energy.

Living System Requirments

A closed biosystem must include sustainable water to support not only human needs, but water for living systems required to support human life (see overview in Figure 1). Sustainable water requirements in closed systems incorporate information on diet, nutrient flows, and solar energy. Critical values assumed in modeling the closed biosystem include (all values expressed per adult male per day unless stated otherwise): dietary energy requirement of 3,500 kcal per person per day, an energy to mass ratio in food of 4.5 cal/g dry matter, biomass nitrogen and carbon content of 2.2% and 40% of the dry weight of the biomass, respectively (see Table 1 in the Appendix for listing of all closed biosystem assumptions). The totally closed sustainable system is composed of four main subsystems and 20 separate processes. A summary of these components is shown in Figure 2.

Water Requirements and Wastewater Treatment.

Minimum water requirements are reported to vary from 2.3 to 4.0 liters per day for drinking and another nine liters for hygiene uses (Eckart 1996). This compares to an average of around 380 liters per person per day that is used in design of domestic sewage treatment facilities. Note, however, that plant water needs are more than 100 times minimum human needs.

Initial thoughts of developing a complete water recycling system often focus on complicated processes that convert sewage directly to drinking water quality. Such emphasis may be misplaced in closed systems since plant water requirements are so large. If food production via photosynthetic processes is included in the closed system, extensive treatment of human wastes is eliminated as a condition of operation of the system. Instead, recycling carbon and mobilizing nutrients contained in the wastes becomes the focus of wastewater treatments. Far more water is evapotranspired than is needed by humans. Sustainable water in closed biosystems is provided by management of the quantity and quality of condensed evaporated water. It is likely that volatile matter that may be absorbed into the condensed water will be a larger long-term problem than ultra-efficient sewage purification.

A two stage wastewater treatment systems is recommended for rapid conversion of biodegradable carbon and mobilization of nutrients in human wastes. The first stage is anaerobic treatment followed by aerobic polishing. Contaminated solids and other organics that cannot serve any other purpose can be added directly to the anaerobic reactor. A schematic of the wastewater management system shown in Figure 3.

In order to provide extensive treatment capacity in as small a volume as possible, the empty tank reactors are supplemented with small biofilm reactors. These biological treatment units provide a reservoir of organisms, and a greatly enhanced treatment capacity.

After wastewater is treated, it is transferred to a reservoir that serves as the source of mobilized nutrients to feed the hydroponic plant systems. Nutrient concentrations are estimated to be in the range acceptable to hydroponic systems.

Food Production and Water Requirements.

The size of plant biomass production system is based on average food and energy requirements. Two simplifying assumption are made to estimate total surface area of plant production systems - total dry matter needs are less than 800 g/person-d (approximately 320 g C/person-d) and of the total biomass harvested, only one third is human edible carbon. If the average photosynthetic process fixes carbon at a rate of 5 g C/m^2-d, the total plant production area would be 190 m^2. This is subsequently reduced to a hydroponic area of 160 m^2 because of other sources of human food carbon from other processes.

As noted above, two dry mass units of organic matter is produced for every unit of human food. This organic material can be used for a number of purposes - structural, aesthetic, chemical, etc. In this project it will be assumed that food is the highest priority followed by a need to recycle the basic elements of which this "waste" biomass is composed. Options to process this material rapidly into food and/or to be exposed to a decomposing environment, or preferably both, is the direction pursued here.

Non-human food organic carbon is diverted to food production units referred to as "Regeneration" units. Of the non-human plant carbon produced, 640 g C/d, it is assumed that 75% can be used as animal food, and the remaining 25% has substantial energy, but is not compatible with animal digestive systems (materials such as roots, stalks, etc.).

Carbon Recycling and Nutrient Mobilization.

High protein plant leaves and other digestible material is available to produce animal protein such as fish. Since it is anticipated that a fairly large water reservoir will be required for security, the backup water storage system is combined with an aquaculture unit. This is referred to as Regeneration Unit #1.

Two additional regeneration units are added to recycle nutrients and carbon - Regen #2 is a vermiculture unit where biosolids from both waste treatment and aquactulture are added as food for worms. Regen #3 is the final stage for fairly rapid regeneration of nutrients and carbon. Biological processes that assist in this regeneration process in the third unit are fungi and/or mushrooms. A summary of carbon flows in the three Regeneration units are summarized in Figure 4.

Material that leaves Regen #3 is estimated to be 9% human food, 9% carbon dioxide, 82% humus or top soil-like material, and a liquid leachate generated intermittently that carries mobilized nutrients to the nutrient storage tank and subsequently to the hydroponic system. Two options for handling stable organic material generated in Regen #3 are: (1) incineration for rapid regeneration of elements and,
(2) accumulation in a topsoil unit. Obviously, some combination of Regeneration units #2 and #3 are possible. Accumulation of soil-like material in a plant production module is recommended since certain plants may be resistant to healthy and continuous production in a hydroponic system. Also, seed production may be easier in a soil-based system.

Nitrogen Management.

The previous estimates focus on water, mass and carbon flows. A third element of great concern in closed systems is nitrogen. It must be carefully managed because of its critical role in living metabolism and the many forms that this element can assume. The hydroponic system (160 m^2 growing area)combined with products from the regeneration units and the humus-based plants produce adequate protein food. The efficiency of recycling of nitrogen may be far from perfect in this system.

Previous work on hydroponic systems have shown that nitrogen balance cannot be achieved, especially with systems that involve organic matter (Jewell et al. 1993). Some nitrogen "leaks" from hydroponic systems, most likely as a result of micro anoxic environments where conditions for microbial denitrification are favorable. These conditions include zero dissolved oxygen and the presence of biodegradable organic matter. When these conditions occur many bacteria have the capability to use electrons from oxidized forms of nitrogen [NO_3^- (nitrates) and NO_2 (nitrites)] and reduce these valuable plant fertilizers into unavailable nitrogen gas. In sewage treatment hydroponics, between 25 and 50% of nitrogen has been observed to be unaccountably, presumably because of denitrification.

Hydroponic systems that maintain water free of biodegradable organics, high oxygen levels, and low oxidized nitrogen concentrations will discourage loss of nitrogen via denitrification. A conservative design would assume that as much as a quarter of the cycling nitrogen will be converted to nitrogen gas (N_2), or a total mass of 15 g of nitrogen must be transformed from N_2 to organic nitrogen each day in a closed biosystem.

A sustainable system must replace this nitrogen fertilizer loss via nitrogen fixation. Two biological options are available to convert N_2 to organic nitrogen which can be subsequently biologically regenerated as ammonia-nitrogen or nitrate-nitrogen- symbiotic N_2 fixation in legumes and N_2 fixation in blue-green algae. An option that could be used to generate useful biomass with minimal side affects would include symbiotic N_2 fixation using legumes, possibly food producing legumes such as soybeans.

Unfortunately, nitrogen fixation is a highly energy intensive process, and rates are relatively slow. Depending on the length of growing season, documented fixation rates vary from 0.008 to 0.18 g N/m^2-d. Growing areas to make up a 25% loss would be 83 m^2 to 1,900 m^2. This nitrogen management plant area could be equal in size to hydroponic food production. It will be assumed that no human food results from the nitrogen fixing hydroponics.

A summary overview of the closed biosystem for one adult is shown in Figure 5. Total plant growth area is 290 m^2.

Construction of a pilot test sub system will attempt to follow the relationships developed here. Initially, the system will be open with synthetic wastes incorporated. After preliminary testing, human waste will be included, and the system will begin to be closed, insofar as resources permit.

Limitations of Closed Systems Studies

Research into closed biosystems has been on-going for many decades beginning with brine shrimp ecosystems and gradually increasing in size and ambitions to the largest ever created - Biosphere 2 in Arizona(Allen 1991). The physical challenge of obtaining a completely closed system of any size is substantial. Most efforts with only modest budgets must conduct studies in relatively open systems and attempt to extrapolate to closed effects. Biosphere 2 is a "first approximation" of Earth's biosphere with the following characteristics: a materially closed, energetically open 1.28 hectare life support system with a total volume of around 180,000 m^3... with 16,000 m^2 of glass surface. It started with 20 tons of living biomass distributed in about 4,000 species. Eight adults have lived in the closed system and have attempted 100% recycle of water, food, waste, and air (less a leakage).

Two other limitations significantly alter the attempt to measure real "closed system" effects - presence of gravity and absence of humans. Obviously, eliminating gravity is not possible for Earth research. In addition, long-term enclosure of humans is not practical at this time.

Finally, all Earth biological systems of any size depend on a myriad of biological interactions from hundreds, if not thousands of living species. Existence of a fully closed system for years at a time depends on whether an equilibrium can be created that will be free of significant population explosions and crashes of unwanted or desirable species.

Discussion

Several limitations of these preliminary design considerations are obvious. First, the plant growth surface areas are large. Sufficient food production can be obtained from a much smaller photosynthetic surface area. This assumes that plants can be managed to grow at high rates, and that other mechanisms, such as atmospheric nitrogen can be managed and recycled efficiently.

Loss of nitrogen fertilizer via denitrification in hydroponic systems and recovery in symbiotic nitrogen fixing plants results in a surprising increase in plant surface area requirements. It is possible that nitrogen fixing plants can be used to do multiple service and produce food, purify the atmosphere, etc. This would decrease overall surface area requirements.

Large masses of water have been included to provide minimum quantities needed for security purposes. The largest water storage tank has been combined with a food production module, i.e., fish production and biomass decomposition. Whether smaller or larger water storage is needed and when and where the water is obtained remains to be defined.

Finally, it should be noted that developing even a one-person module for test purposes using artificial light will consume large amounts of energy. Using high artificial light intensity (around 1.0 kW/m^2, around 1.4 kW/m^2 is available in outer space) for 18 hours per day would result in energy consumption value equal to around $250,000 per year. An additional amount of energy would be needed to manage humidity and recover condensate.

References

Eckart, Peter. 1996. *Spaceflight Life Support and Biospherics.* Space Technology Library, Volume 5. Published by Kluwer Academic Publishers. ISBN 1-881883-04-3. 444 pages.

Allen, J. 1991. *Biosphere 2 - The Human Experiment.* Penguin Books. New York.

Jewell, W.J., R.J. Cummings, T.D. Nock, E.E. Hicks, and T.E. White. 1993. "Energy and Biomass Recovery from Wastewater: Piloting Resource Recovery Wastewater Treatment." Final Report, September 1986-December 1990. (GRI-93/0192.2) Gas Research Institute. April.370 pages.

APPENDIX

Table 1. Summary of unit processes, sizes of units, and assumptions used to design the modules. These units are considered to be necessary to provide 100% recycling of water, carbon and plant nutrients in a closed system using only biological natural processes in sustaining one adult male person.

UNIT PROCESS IDENTIFICATION	SIZE OR LIMIT OF PROCESS	Assumptions Relating to Unit Process Requirements
1. Potable Water Storage	210 liters (55 gallons or 7.35 ft3).	Water Requirements = 30 liters per day, with a seven day storage volume.
3. Temporary Waste Storage.	210 liters.	Storage of waste equal to potable water storage volume, or 30 day.
3. Waste Treatment System.	Main Objective is to recycle carbon and mobilize plant nutrients. Efficiency of cycles is not important. All biological processes, minimum energy consumption, simple, automatic, energy production, odor and pathogen elimination.	System is capable of processing liquid and solid wastes. Takeoff or effluent areas for both liquids and unconverted solids. Each biological system have associated biofilm reactors to increase microbial mass by two orders of magnitude, and treatment surface area by four orders of magnitude to provide stability and redundancy. Two stage system - anaerobic followed by aerobic biological treatment. Liquid is recycled from the main empty tank to the biofilm reactor to turn over the main reactor once per day.

Table 1. Continued.

4. Anaerobic Waste Treatment .	Main unit =300 liter volume (79 gal)	Provision for 10 day hydraulic retention time.
5. Biofilm Reactor Booster units - anaerobic and aerobic.	Anaerobic biofilm unit = volume to give HRT = 6 hr. flow rate, or volume of 25 liters. Aerobic biofilm unit vol. to give HRT of one hr.	Biofilm reactors are off-line, i.e., only receive influent from main on-line anaerobic and aerobic treatment systems. Both anaerobic and aerobic units turn liquid over on-line unit once per day.
6. Biogas holder	Volume = 100 liters (40 gallons).	Total expected gas production from human waste is 70 liters CH_4/d. Methane is used to support single cell protein production via methanotrophs or for combustion needs.
9. Aerobic Treatment Processes.	Sludge blanket process with volume of 15 liters. Off-line biofilm reactor.	Use "bubble-less" oxygen transfer to eliminate volatile problems (H_2S, for example).
10. Mobilized Nutrient Storage.	Volume = 1,050 liters. May need to add bubble-less aerator to this unit as well.	Storage volume equal to 7 days of treated wastewater (<30 liters/d + excess nutrient leaching drainage from system (120 liters per day in excess of ET).

11. Food Production.	Total biomass production of 2,400 g(dry)/d. Hydroponic productivity required to produce the bulk of food mass at rate of 12.5 g (dry)/m^2-d or 5 gC/m^2-d Surface Area = 160 m^2(1,700 ft^2).	Example channel dimensions of 2ft wide by 25 feet long, liquid nutrient feed to one unit, gravity flow to next five channels, then recycled. Liquid level contained with automatic pumping from aquaculture unit (Regen #1). Intermittently fed with mobilized nutrients on a daily/weekly basis.

Table. 1. Continued.

12. Water transfer to Hydroponic units and other plant production.	Assumed evapotranspiration rate is constant related to mass production at 250 g H20 evaporated per gram of dry matter produced. Volume transfer to satisfy ET = 600 liters per day average ET. Add 120 more liters to leach nutrients from other process to recovery plant fertilizer.	Total water recycled to plants is 720 liters per day.
13. Nitrogen Considerations and N_2 fixation	Total nitrogen availability is 60 grams N/d, with total human food containing 15 g N/d. Oxidized forms of nitrogen are lost via microbial denitrification in the hydroponic channels at the rate of 25% per day. Nitrogen gas (N_2) must be fixed using legumes. Assume rate of fixation is 0.15 g N_2-N per m^2 per day. Surface Area requirements = 100 m^2 (1,080 ft^2). Use same type of NFT channels as in food production NFT. Air stripping system applied to this unit to clean volatiles from the air with plant roots.	This unit is required to recover nitrogen lost as N_2 via denitrification in waste treatment and hydroponic units.
14. Humus/soil plant growth units	Surface Area Requirements = 30 m^2 (323 ft^2), depth of 6 cm. Incinerator is used as a backup for this unit in carbon recycling.	Recirculation of carbon shows a buildup of refractory carbon that could be used to support a small soil-based food production unit. It is possible that this unit can also double as a vermiculture unit.

Table 1 continued.

15. Regeneration Unit #1. Aquaculture unit combined with water storage.	Volume = 5,000 liters (1,320 gallons). This unit's main purpose is water storage for a today of 10 days supply. Other purposes of Regen#1 are food production/biomass conversion system that receives edible food not desirable as human food.	This unit receives 600 liters per day of condensate from the plant food production units. Approximately 600 liters is pumped from this unit to plant systems. Biosolids are removed intermittently from this unit and fed to a vermiculture unit.
16. Regeneration Unit #2. Vermiculture unit.	Surface Area = 5 m^2. Depth depends on availability of humus - around 30 cm (12 inches).	This unit is fed with wet biosolids from Regen #1. Some pretreatment of these solids may be necessary to prevent this unit from being too wet, or cycles are maintained.

17. Food Production Requirements.	Avg. harvest requirement= 2,400 g(dry)/d [5.3 lb(dry)/d],@ 10% dry 24,000 g (wet/d) [53 lb(wet)/d]. Division of edible Biomass:onethird of total harvest is human edible food, remainder is fed to other food production/regeneration units. 800 g/d(1.74 lb/d)[8,000 g(wet)/d] (18lb[wet/d]) 1,600 g/d(3.65 lb/d)	Human Food from total harvest is one third of total mass = 800 g(dry)/d, non-edible biomass = 1,600 g(dry)/d fed to aquaculture units, and some stalks, roots to vermiculture unit.

18. Harvesting requirements - storage/drying/plant processing.	Dry storage volume for unused biomass = 0.23 m3 (8 ft^3) per wk of harvest stored.Wet volume = 1.76 m3 (62 ft^3).Total drying surface area = 5.8 m^2 (62 ft^2)with a one third meter deep biomass.	Assume wet density of 96 kg/m^3 (6 lb/ft^3), dry density of 80 kg/m^3 (5 lb/ft^3). Use stacked surfaces for drying.

Table 1 continued.

19. Harvesting requirements - transfer to food/regeneration units.	Of the two thirds of biomass not human edible, divert 75% to aquaculture units as dried and palletized matter. Include vermiculture products in feed to aquaculture units. 25% directly to vermiculture unit.	Assume that three quarters of non-human edible food is acceptable as fish food. Increase protein content using vermiculture products.
20. Condensation Units.	Temperature of plant growth areas are maintained between 30°C and 40°C, humidity between 50% and 80%. Total condensate recovery is assumed to be 600 liters per day.	

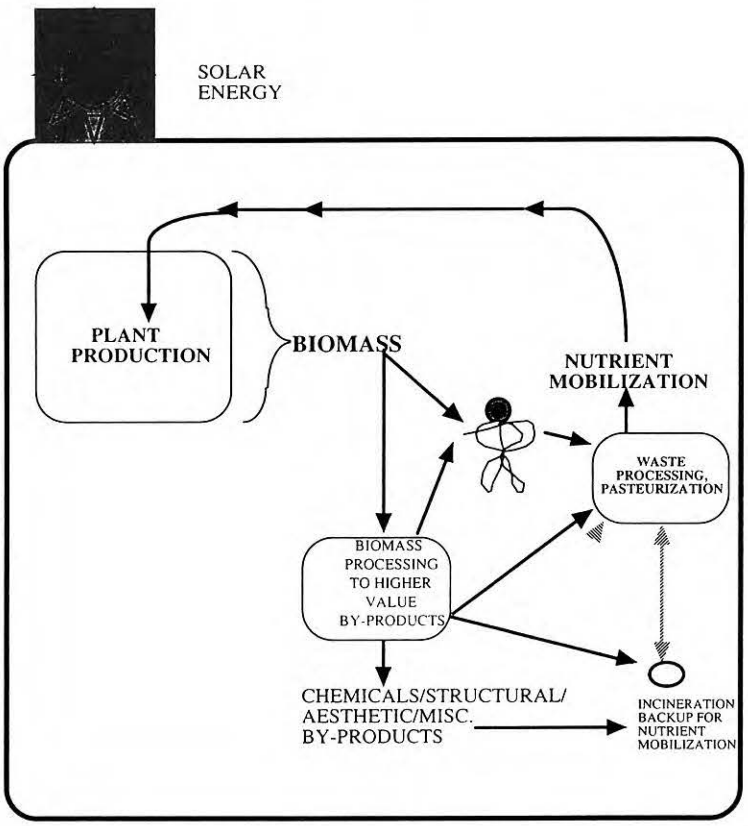

Figure 1

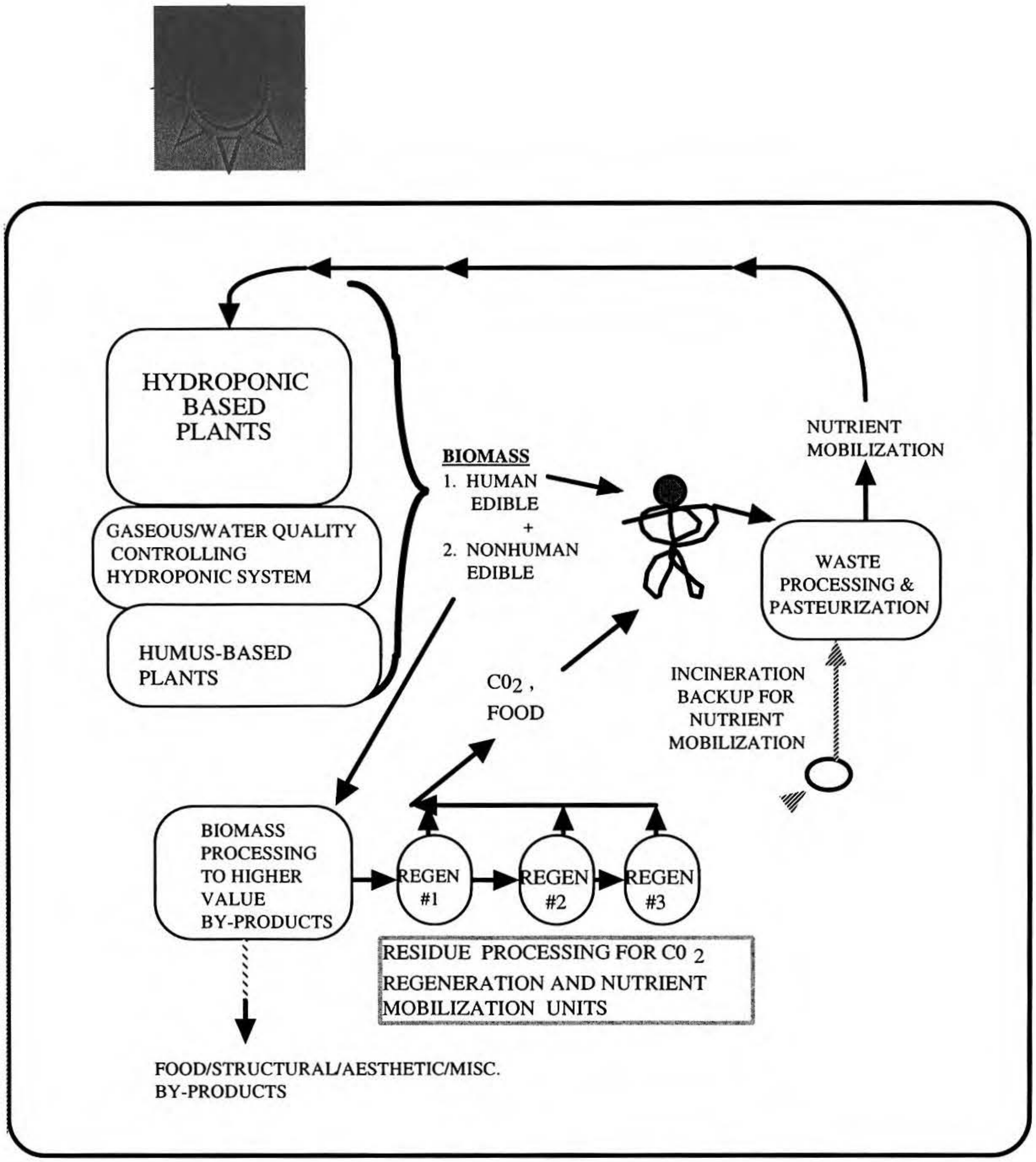

Figure 2. Schematic of flow materials and processes involved with closed biosystems.

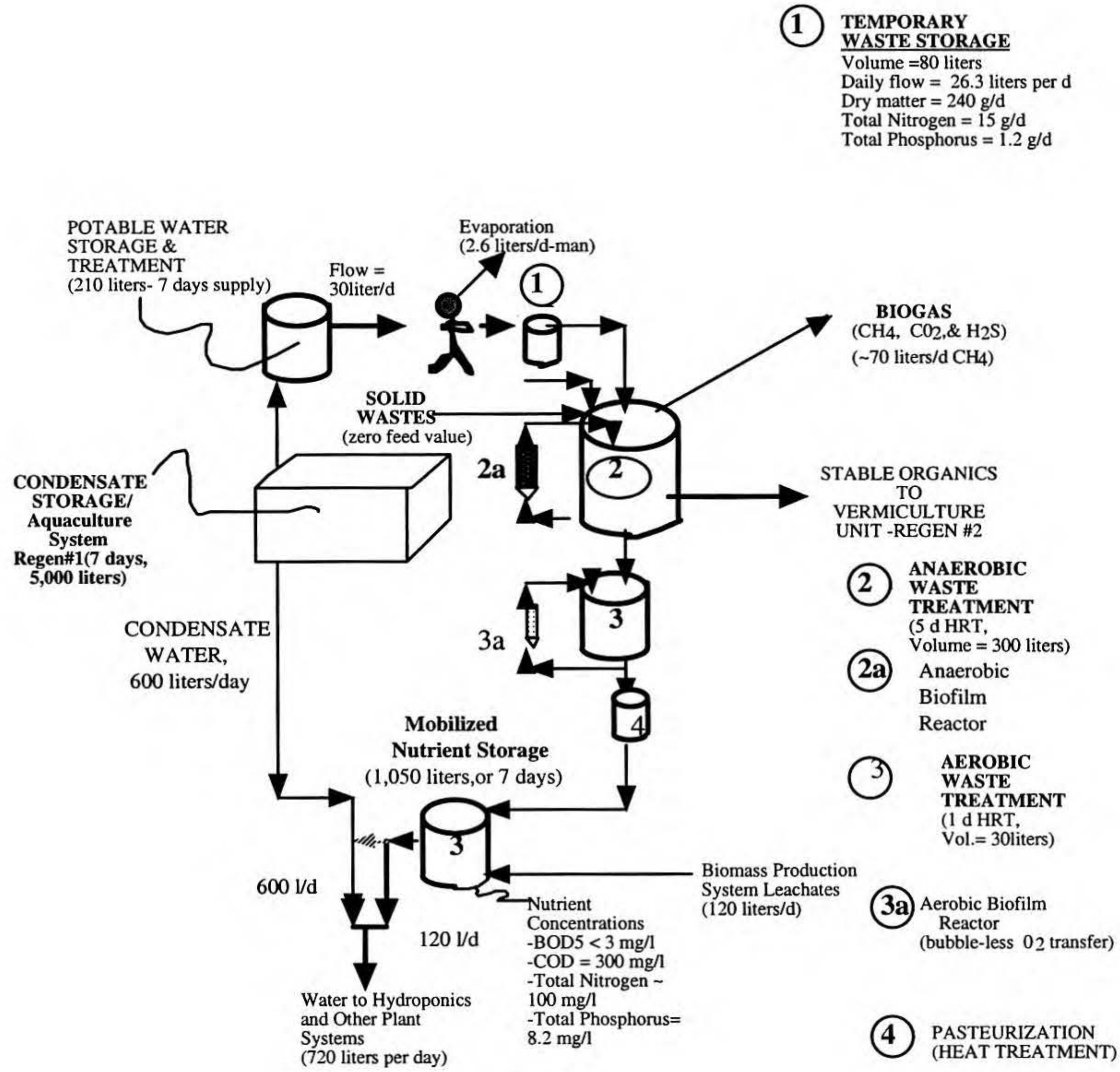

Figure 3 . Flow of water in closed biosystem and estimates of biological waste treatment processes required to control human pollutants and to assist in nutrient mobilization. Values per adult male.

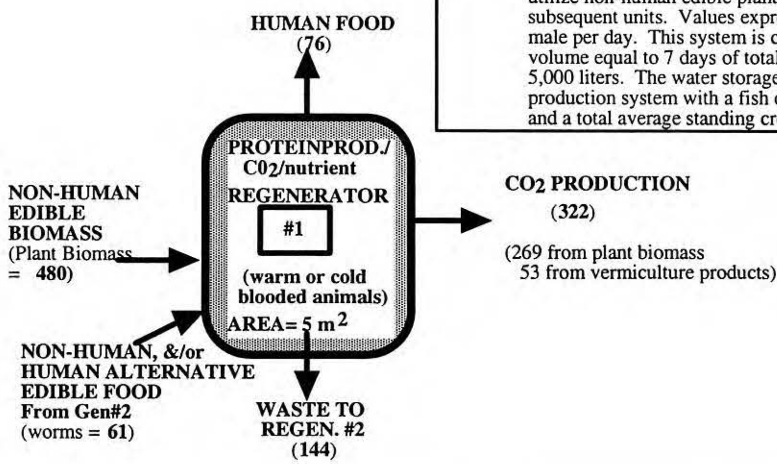

Figure 4a. Regeneration Unit #1. Aquaculature.
Summary flow of materials in the first biomass processing system to utilize non-human edible plant material and alternative products from subsequent units. Values expressed as grams of carbon per human male per day. This system is composed of backup water storage volume equal to 7 days of total system water usage, or a volume of 5,000 liters. The water storage system is also an aquaculture production system with a fish density of 11 g fish per liter of storage, and a total average standing crop of fish equal to 56 kilograms.

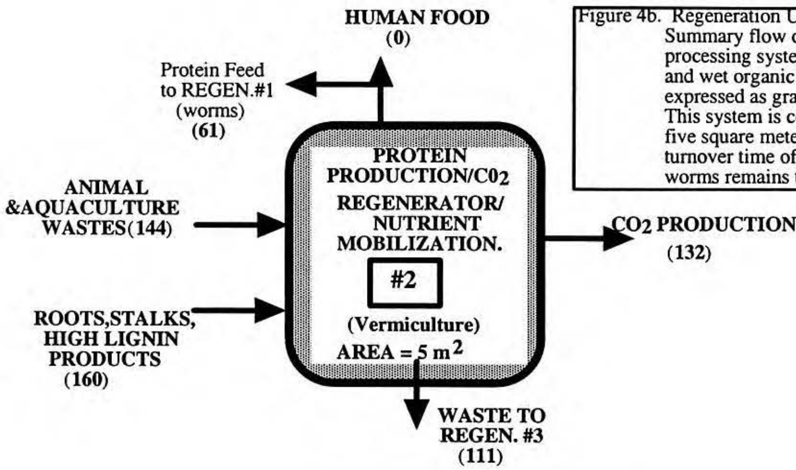

Figure 4b. Regeneration Unit #2. Vermiculture.
Summary flow of materials in the second biomass processing system to utilize non-human edible plant material and wet organic waste from the aquaculture unit. Values expressed as grams of carbon per human male per day. This system is composed of surface area of approximately five square meters, depth of humus of 6 cm, and a turnover time of once per year. Total standing mass of worms remains to be determined.

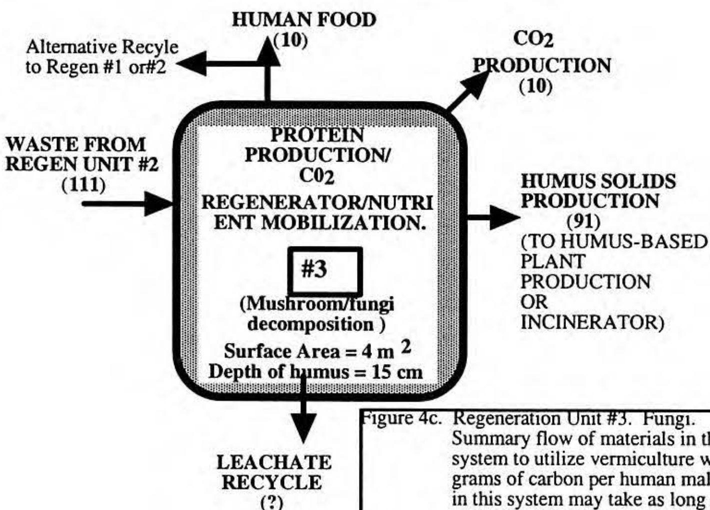

Figure 4c. Regeneration Unit #3. Fungi.
Summary flow of materials in the third biomass processing system to utilize vermiculture wastest. Values expressed as grams of carbon per human male per day. Humic materials in this system may take as long as ten years to recycle all carbon and nutrients. This system is composed of about a 4 square meter surface area of humus, 15 cm deep.

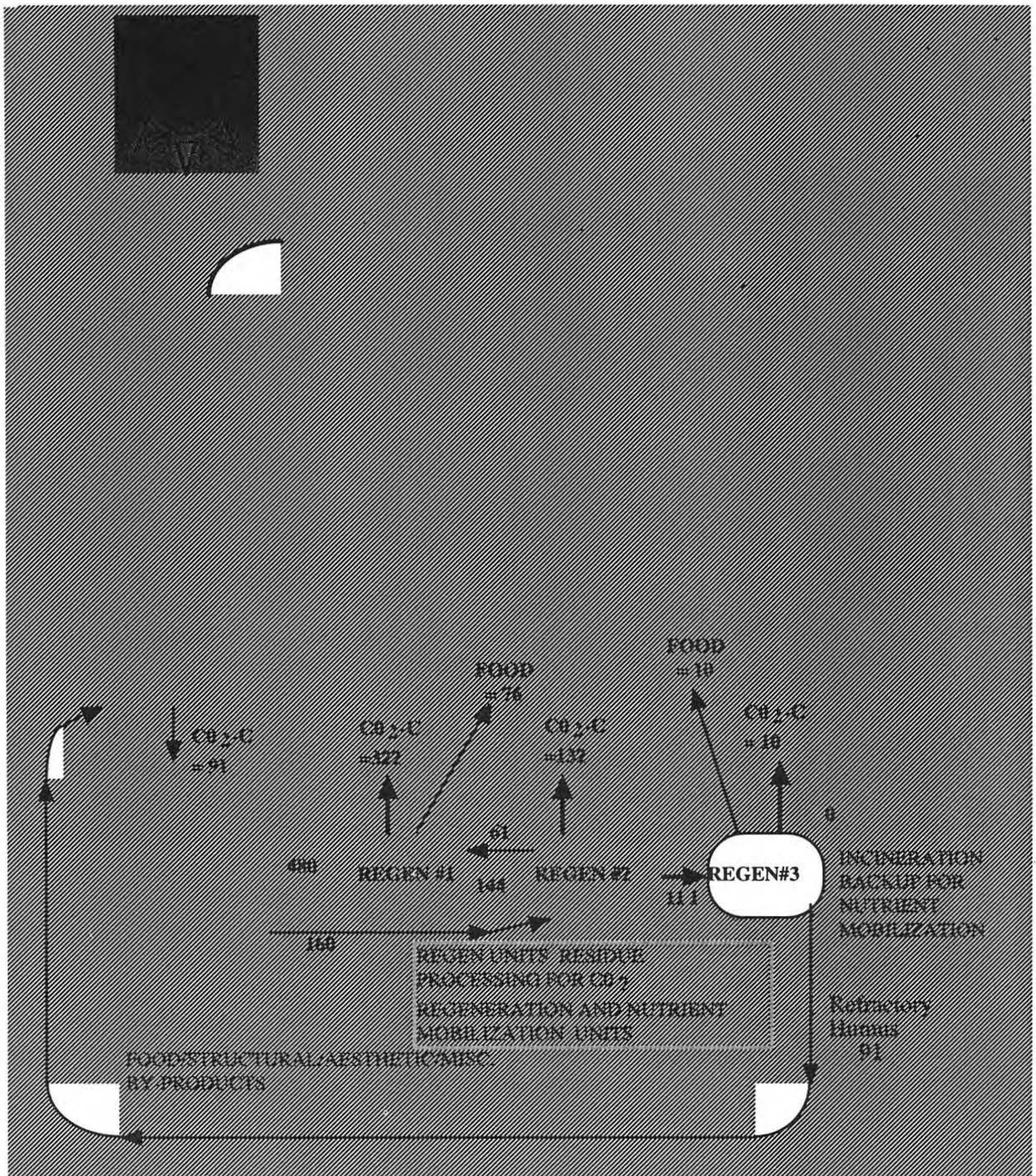

Figure 5. Schematic of flow of food carbon and carbon dioxide (as carbon) with closed biosystems using three different carbon and nutrient mobilization regeneration units.