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PRELIMINARY EVALUATION OF WASTE PROCESSING IN A CELSS

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ABSTRACT

Physical/chemical, biological, and hybrid methods can be used in a space environment for processing wastes generated by a CELSS. The waste materials in a bioregenerative life support system will be generated by numerous sources. Representative examples of waste components include: the inedible materials from higher plants; volatile organics produce by humans, plants, algae, fungi, and bacteria; CO_2; water vapor; urine; feces; waste water from washing and hygiene; and trash that includes a wide variety of solid materials. To develop systems that are capable of recycling these materials it is necessary to know their composition, the rates at which they are produced, the advantages to be gained in separating them before processing, and the fates of their constituents during various oxidation regimes. Two recycling scenarios, derived from qualitative considerations as opposed to quantitative mass and energy balances, tradeoof studies, etc., will be presented; they reflect differing emphases on and responses to the waste stream formation rates and their composition, as well as indicate the required products from waste treatment that are needed in a life support system,. The data presented demonstrate the magnitude of the challenge to developing a life support system for a space habitat requiring a high degree of closure.

INTRODUCTION

Renewed interest in long duration human space missions, particularly the establishment of a Lunar base or a mission to Mars, has prompted a critical evaluation of advanced life support systems (1). This evaluation has revealed that current methods available for nearly complete recycling of water, oxygen, and food in space are technologically and economically impractical. Such limitations will prevent humans from spending long periods of time in space. Therefore, research emphasis should be placed on developing improved recycling techniques to overcome these limitations.

Nearly complete recycling can be theoretically accomplished by life support subsystems which are dependent either on physical or chemical (P/C) principles or by subsystems which include a living or biological component, such as a Controlled Ecological Life Support System (CELLS). A subsystem which is based on a physical or chemical principle, for example, is a water electrolysis unit which provides oxygen for respiration by using electrical energy to decompose water into hydrogen and oxygen. Higher plants are an example of a biological sybsystem that produces oxygen for respiration through photosynthesis, using sunlight for its source of energy. If a high degree of closure of the life support system is required, wherein most of the water, oxygen, and food is recycled, then a hybrid system consisting of a combination of P/C and biological subsystems will undoubtedly be needed.

Recycling in a space habitat implies the conversion of waste streams derived from several different sources into useable products. Some of the waste streams are common to both the P/C and CELSS based life support systems. For example, all of the wastes derived from a human are common to both systems. Certain waste streams are present only in space habitats that use living subsystems as an integral part of the life support system. To illustrate: if higher plants are used to produce food, then inedible biomass (in substantial quantity), water derived from the transpiration of plants, and the spent, plant nutrient solution are wastes not found in a solely P/C life support system.

Not only are the input waste streams different in P/C and biological systems, but the required outputs are also different. A CELSS requires plant nutrients as an output stream, a requirement unique to a photosynthetic-based food production and life support system.

For either the development of a computer model of a waste treatment or recycling subsystem or the functional design itself, it is desirable to have well defined input feed streams, including production rates and composition. Recent data are presented, as specifically as possible, on the nature of the waste streams that could be encountered in a human space habitat. Those streams that are characteristic of a given type of life support system are identified, and two representative scenarios for recycling wastes and nitrogen in a bioregenerative life support system are described.

WASTE SOURCES

In determining the treatment to be applied to any waste stream of a life support system, at least three factors must be considered: 1)stream composition, 2) rate of stream production, and 3) required end product(s).

WASTES FROM GENERAL HUMAN ACTIVITIES

Parker and GAllagher (2) reported results from a comprehensive study of human wastes in which over 25,000 person-days of data was analyzed. They reported mean values for the dry and wet weight of human feces, the volume of human urine (2,066 milliliters/person-day), solids per menstrual period (10 grams), the average number of pads or tampons used per period (15.2), the average weight of pads (10.65 grams) and tampons (2.60grams) from different manufacturers, and the total amount of toilet paper usage for women for bowel movements and urination (41.1 grams/woman-day). The solids content of human urine was obtained from previous work (3). It should be noted that the values reported by Parker and Gallagher are mean values and they emphasize that a space habitat waste handling and treatment subsystem must be designed to accomodate extremes and should not be designed on the basis of mean values.

The type and amounts of organic and inorganic constituents in human urine can be identified in previous work (3 and 4). The elemental composition of human feces derived from subjects fed a specified diet is also available (3).

The amount of urinal flush water shown in Table 1 is being used for designing or sizing the environmental control and life support system (ECLSS) for the US Space Station (5). The volumes of dish, laundry, shower, and hand wash water were obtained in a private communication (6) and these amounts are also being used for designing the Space Station ECLSS. The amount of cabin humidity condensate and its contaminant concentration were derived from Space Shuttle data and are also part of the design load for the Space Station ECLSS.

The amount of food preparation waste and details concerning its composition are available (3). The work of M. Karel of the Massachusetts Institute of Technology, was employed for designing a model food processing and preparation waste for the US CELSS program (3). In designing this model waste, it was assumed that

Table 1. Waste Feed Stream Production Rates and Solids Content in a Manned Space Habitat containing a Higher Plant Growth Chamber			
Stream ID	Wet Weight Formation Rate, lb/person-day	Dry Weight Formation Rate, lb/person-day	Weight Percent Solids, %
Toilet Waste			
Urine (2, 3)	4.59 (a)	0.14	3.1
Feces (2)	0.21	0.0452	21.4
Wipes (2)	0.091	Unknown	Unknown
Urinal Water (5)	1.09	NA	NA
Hygiene Water			
Dish (6)	12	2.6 x 10-3	0.022 (b)
Shower & Hand (6)	12	3.4 x 10-3	0.028 (c)
Laundry (6)	28	1.5 x 10-3	0.0054 (b)
Humidity Condensate (6)	8.26	1.3 x 10-3	0.016
Food Preparation Waste (3)	0.13	0.044	34
Trash	2.2	Unknown	Unknown
Respired CO2 in Air (5)	NA	2.2	NA
Contaminated Cabin Air (11)		See Table 3	
Inedible Biomass (Wheat Chaff)	14	1.4	10
Transpiration Water (7)	136 - 678	See Note (d)	

Footnotes

(a) The density of urine was taken as 1.008 g/ml (4) to convert urine volume to weight.

(b) Detergent only; sodium dodecyl benzene sulfonate (an anionic detergent).

(c) Cleansing agent only; Economics Laboratory Cleansing Agent Formulation 6503.54.4 (an anionic detergent).

(d) The contaminant load in transpired water from plants is unknown.

the CELSS population would be small, that plants would be grown hydroponically, and that animals would not be part of a CELSS.

In 1985, the NASA-Ames laboratory analyzed the trash brought back to Earth aboard Space Shuttle Flight 51D. The objective of this analysis was to gain insight into the composition, amount, and volume of trash produced during a representative human space mission. This type of information will be needed for the design of a long term human space mission waste handling and treatment subsystems. The results from this analysis are shown in Table 2.

Table 2. Composition and amount of trash derived from Space Suhuttle Flight 51D (49 person-day flight)

Trash Constituent	Weight, lbs	Volume, ft3
Food Containers [(a)]	50.8	3.3 [(b)]
Paper	14	1.3
Boiomedical	14	1.0
Leftover Food & Garbage	10.5	0.3
Plastic Bags	7	2.2
Grey or Duct Tape	3.5	0.3
Cans, Aluminum $ Bimetallic	2.8	0.5
Miscellaneous	5.8	0.8
Total	108	9.9

Footnotes

(a) Includes 27 lbs of uneaten food and beverages.
(b) After cleaning and stacking.

AIR CONTAMINANTS

Contaminated air from crew quarters is another waste stream that must be treated in the closed environment of a space habitat. Wastes in cabin air include water and carbon dioxide from perspiration and respiration, volatile contaminants from people and equipment, and airborne particles. The average amount of carbon dioxide produced by an adult each day is shown in Table 1 (5). A contaminant load model (including contaminant type and concentration) is a prerequisite for the design and sizing of the contaminant control subsystem for a space habitat. The load model being used for designing the Space Station contaminant removal subsystem has been developed (11). An extensive list of representative volatile contaminants illustrating the broad spectrum of compounds one can expect to find in a closed habitat is described. Specific information also includes the space maximum allowable concentrations (SMAC) for continuous exposure to a given contaminant.

The estimated concentration and size of airborne particles which are expected to be found aboard the Space Station are given in Table 3 (11). These estimates are being used for the design and sizing of the contaminant control subsystem. In estimating the rate of generatioon of airborne particles expected aboard the Space Station, it was assumed that about 90 percent of the particles would be derived from humans and their activities. To obtain the total generation rate of particles or dust expected aboard the Space Station, the numbers in Table 3 must be multiplied by the crew size and the factor 1.1 to account for particle generation by sourcess other than people (assumed to be 10 percent of the total).

Table 3. Estimation of Space Station Particle or Dust Generation Rate by Humans (11)	
Particle Size, (microns)	**Particle Generation, (particles/hr/person**
0.3 - 0.5	81,341,426
0.5 - 1	34,570,164
1 - 2	4,270,366
2 - 5	1,565,870
5 - 10	211,548
Above 10	40,626

WASTES FROM PLANT PRODUCTION ACTIVITIES

In estimating the amount of inedible biomass and transpiration water (Table 1) that must be handled by the waste treatment subsystem in a CELSS, the following assumptions were made: a) the average amount of dry food required by each adult per day is 0.617 kilograms (5), b) wheat alone can meet a person's daily caloric but not necessarily nutritional requirement, c) only 50 percent of the dry mass of a mature wheat plant is inedible (i.e., an optimistic harvest index of 50 percent), d) 90 percent of the wet weight of the inedible portion of a wheat plant is comprised of water, and e) depending upon carbon dioxide concentration, the amount of transpired water ranges from 50-250 grams per gram of plant (edible plus inedible) dry weight (7).

Transpiration water may contain volatile organic compounds that must be removed before recycling the water. These compounds may come from plants or materials in the plant growth chamber. Currently, the type and concentration of contaminants in transpiration water are poorly defined and therefore this stream must be considered as a waste stream that will require some processing.

WASTES FROM EXPERIMENTAL SYSTEMS

Experiments being conducted in a space habitat will also contribute waste of varying types and amounts that will require handling and treatment. The broad spectrum of wastes that might be derived from experiments precludes this source of waste from being considered here. However, a study has been conducted in which waste derived from potential flight experiments is defined (8).

WASTE PROCESSING

Given the quality and quantity of the waste streams presented in Table 1, there are a number of different waste processing methods that one might consider for handling and treating these wastes. These methods include both biological and phyical/chemical processes. The optimum combination of processing technologies remains to be determined. However, a scenario based on qualitative considerations (as opposed to detailed mass and energy balance calculations, tradeoff studies, etc.) is shown in Figure 1.

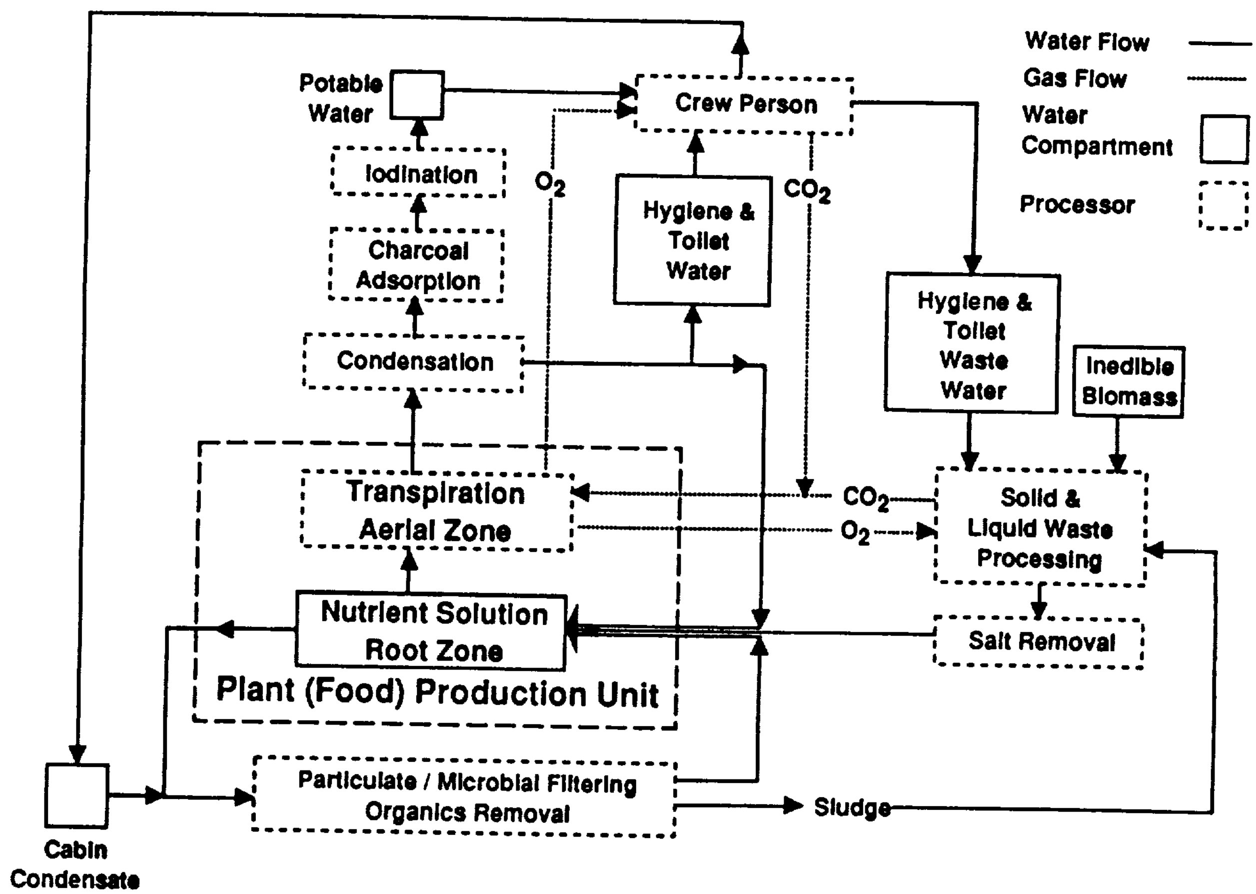

Fig. 1. Representative Water Pathways in a CELSS.

GENERAL WATER AND GAS PROCESSING SCENARIO

Figure 1 graphicallly depicts a water pathway scenario in a CELSS. The scenario shows how water may be processed or treated in order to attain the required quality standards of each of the depicted water compartments. The different sizes of the solid boxes in Figure 1 reflect proportional volumes (derived principally from Table 1) of the major water compartments on a per day per person basis (actual sizes are dependent upon the rate of throughput and storage considerations).

It should be noted that the range for transpiration water production set forth in Table 1 is determined by the environmental conditions, predominantly the concentration of carbon dioxide in the plant growth chamber. Transpiration water production is inversely proportional to the carbon dioxide partial pressure. When the CO_2 pressure is low, the stomates, openings in the leaves through which gas and water exchange occur, open, and the transpiration rate is high (up to 250 grams water transpired per gram of dry biomass produced); the reverse is true for high CO_2 concentrations.

The ability to change the transpiration rate by varying the CO_2 concentration can be an important control factor in a CELSS. For example, under optional plant growth conditions, more than enough water is provided to meet crew requirements even though the transpiration rate is low. Should an emergency occur whereby more water is needed by the crew, the transpiration rate and the amount of water provided to the crew could be quickly increased, by merely decreasing the CO_2 concentration in the plant growth chamber.

It is expected that transpiration water, having been derived from a phase change process, will be relatively clean. Therefore, this waste stream may need only minimal filtering and bacterial control to yield high quality water for drinking and other applications. However, most of the condensed transpiration water will be used to replenish water lost from the plant nutrient solution. This cycle as illustrated in Figure 1 shows nutrient solution make-up water also being introduced from other processors.

The condensate collected from the cabin environmental control system, having passed through a phase change, is also expected to be quite clean (see Table 1). However, humidity condensate may contain a high population of microbes derived from microbial growth on the condenser or heat exchanger. Although the amount of the condensate collected is not enough to meet the hygiene and toilet water requirement, the water recovered can be combined and treated along with transpiration water and spent nutrient solution. The nutrient solution will contain an unknown number of microbes as well as organic compounds produced by root metabolism and detritus breakdown. These contaminants can be filtered out and useable salts can be returned to the nutrient solution. The filtrate or sludge would be treated in the solid waste processor.

Toilet water containing feces and the inedible biomass waste streams have relatively high solids concentrations and also may contain potentially harmful microbes. Therefore, these streams will require a more rigorous treatment. High temperature and pressure processes, such as wet oxidation or supercritical water oxidation may be used to treat these more concentrated streams and to assist in closing the water cycle between the crew person and the plant production unit. The water produced by the solid and liquid waste processor (see Figure 1) includes the yield from inedible biomass, hygiene and toilet water treatment, and also from a certain amount inherent in some of the items listed in Table 2, as well as from the root zone filtrate. This water is not necessarily potable, but after salts and potentially toxic metals (derived from corrosion) are removed, it is benign to the plants growing from the nutrient solution to which it is returned.

Gas exchange between the plant growth chamber and other parts of a CELSS is also an important part of recycling. For example, oxygen produced by photosynthesis in the plant growth chamber may be used for oxidation in the waste processor and for respiration by the crew. Likewise, the CO_2 produced by both crew and waste oxidation is needed by the plants for their growth.

The crew consumes water-containing edible biomass, drinks potable water, and produces waste. Consequently, the crew closes the life support loop in this generally described scenario.

NITROGEN RECYCLE THROUGH A HYBRID WASTE PROCESSING SYSTEM

Figure 2 illustrates a more specific waste recycling scenario which includes methods for recycling nitrogen and converting it into forms desirable for plant metabolism. In this scenario, organic nitrogen is converted into ammonia (NH_3) and nitrate ions (NO_3^-) which are species desired by plants for their nutrition.

As mentioned previously, waste processing, applied to closing

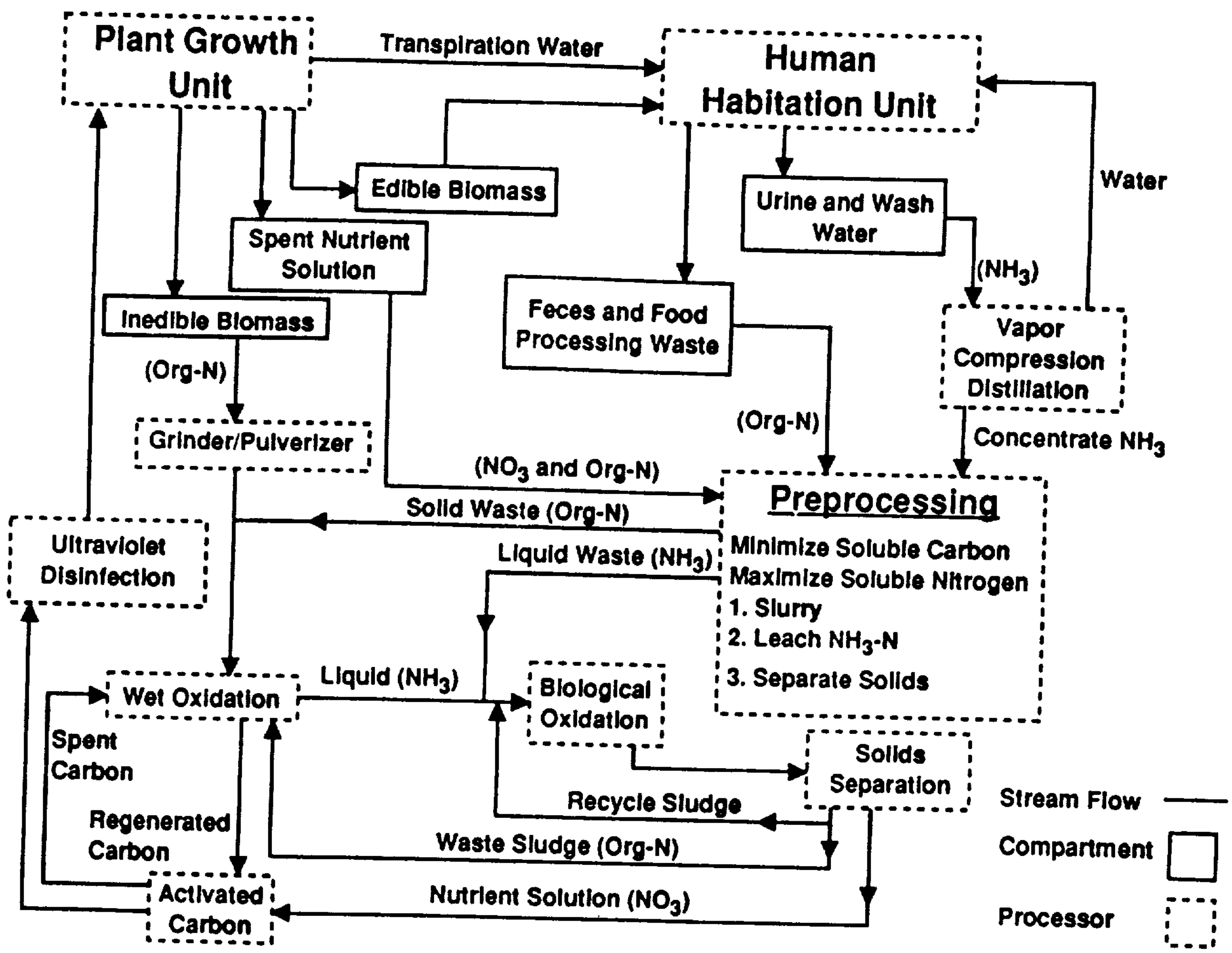

Fig. 2. Waste Processing in a CELSS: Nitrogen Recovery.

a life support system, can be achieved by three basic methods. Physical/chemical methods are directly applicable to handling liquids as well as large quantities of solid materials, but suffer a significant limitation; the inability to produce a form of nitrogen which is reuseable directly by higher plants. The physical/chemical waste processing methods characteristically produce nitrogen gases (N_2 and N_2O) while growing plants for a CELSS require either nitrate or ammonium ions (NH_4^+) as a source of nutrition. Aerobic biological waste processing systems can produce either or both ions as a final end product but do not handle solid wastes efficiently. With the above requirements and characteristics in mind, a scenario of an integrated waste processing system is discussed below. The hybrid system includes vapor compression distillation, wet oxidation, biological oxidation, activated carbon adsorption, and ultraviolet disinfection. A schematic diagram of the proposed system is presented in Figure 2. The treatment scheme is simplified to show the flow of nitrogen only.

The treatment scenario assumes processing of wastes generated by the plant growth and human habitation units. Wastes from the plant growth unit include the inedible biomass and the spent nutrient solution. The inedible biomass is principally solid waste (wheat chaff, etc.) low in organic nitrogen (Org-N) content (3) but overall represents a potentialy high mass of nitrogen due to the large amount of material generated. The inedible biomass would first be ground and pulverized to reduce the total volume and particle size. Final processing could be handled by wet oxidation operated at a temperature less than 300 C and a pressure of 1500 psig to minimize loss of nitrogen as N_2 gas and maximize recovery of ammonia nitrogen (NH_3-N) (9). The spent nutrient solution is primarily water, inorganic salts, and organic residues exuded by the plants. The spent nutrient solution would be sent to the preprocessing stage to act as a wetting agent to slurry and maximize leaching of Org-N and NH_3-N from the solid wastes generated at the human habitation unit. Nitrogen leaching can be accomplished through a combination of physical solids disintegration and an anaerobic fermentation-like process.

The solid wastes from the human habitation unit include feces and food preparation or processing waste. After preprocessing of the solid wastes, the slurry would be physically separated into liquid and solid streams. The solid portion containing Org-N could be further processed by wet oxidation to convert the Org-N to NH_3-N. Liquid wastes from the human habitation unit include urine and hygiene or wash water. These two waste streams would be combined for processing by vapor compression distillation (VCD). The final product of vapor compression distillation could be returned to the human habitation unit as drinking and hygiene water. Current state-of-the-art vapor compression distillation technology requires that pre- and post-treatment be implemented to optimize treatment efficiency and insure potable water quality (10). Pretreatment by pH adjustment will maximize separation of NH_3-N and other salts while post-treatment by ultraviolet (UV) disinfection will significantly improve the bacteriological quality of the final product. Additional potable water could be supplied by water condensed from the evqaporation/transpiration process occurring in the plant growth unit. The concentrate from vapor compression distillation would be sent to the preprocessing stage to be combined with the concentrated NH_3-N liquid leachate. The liquid leachate from the preprocessing stage as well as the liquid effluent from the wet oxidation step, both of which will contain highly concentrated NH_3-N, could be processed by biological (microbial) oxidation such as suspended growth (activated sludge) or fixed film (rotating biological contactor, trickling filter, etc.) systems. Carbon and nitrogen oxidation would occur, transforming the majority of the organic carbon to CO_2 and water and the NH_3-N and Org-N to nitrate nitrogen (NO_3-N). Following separation of the microbial solids, the liquid effluent from the biological oxidation unit would be returned to the plant growth unit to supply water, as well as nitrogen and other necessary nutrients. The microbial solids could be processed by wet oxidation to convert Org-N to NH_3-N. Due to the incomplete oxidation of carbon and separation of microbial cells during biological processing, the liquid effluent will require additional polishing by activated carbon adsorption and UV disinfection before being transferred to the plant growth unit. The activated carbon system would remove residual carbon which can stimulate the growth of bacteria while UV disinfection would destroy bacteria and viruses including potential plant pathogens. The wet oxidation system would also be used to regenerate the spent activated carbon.

CONCLUSION

The production rate and solid content of waste streams found in a life support system for a space habitat (in which plants are grown for food) have been discussed. Two recycling scenarios (Figures 1 and 2), derived from qualitative considerations as opposed to quantitative mass and energy balances, tradeoff studies, etc., have been presented; they reflect differing emphases on and responses to the waste stream formation rates and their composition, as well as indicate the required products from waste treatment that are needed in a life support system. The data presented here also demonstrate the magnitude of the challenge to developing a life support system with a high degree of closure.

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