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**SOLID-PHASE THERMOPHILIC AEROBIC REACTOR (STAR) PROCESSING OF FECAL,
FOOD, AND PLANT RESIDUES**

Principal Investigators: Dr. James E. Alleman, Dr. Cary Mitchell, Purdue University
Co-Investigators None

Background

The Solids Thermophilic Aerobic Reactor (STAR) was investigated for the initial treatment of all biodegradable solid wastes that would be generated in a crewed mission, including inedible plant wastes, paper, fecal matter, and food wastes. STAR operates similarly to the autothermal thermophilic aerobic digester (ATAD) currently in use in a number of wastewater treatment plants. The projected advantages of the STAR system include a reduced retention time, increased rapid pathogen inactivation, lower reactor volume requirements, and ease of automation as compared to other biological waste treatment systems.

The system operates under thermophilic, microaerobic high moisture conditions. Temperatures are maintained at 55-65°C. ATAD has been shown to inactivate indicator bacteria, thermotolerant coliforms and enterococci, and *Salmonella* spp., and has proven capable of producing Class A biosolids suitable for agricultural land application when operated at stable and appropriate operational parameters, which mainly include temperature, mixing and retention time. The STAR system includes the EVAC toilet, which is plumbed to a storage tank where waste is transported via vacuum. The reactor is batch fed from the storage tank once per day, and consists of a stainless steel tank with a heating band, an air diaphragm pump to circulate the sludge, piping for mixing and aeration, and a scrubber system. A visual sight gauge as well as pressure sensors allow monitoring of volume, and online monitoring includes pH, ORP, CO₂, temperature, and O₂.

Operational parameters were evaluated to optimize solids degradation and resource recovery while minimizing ESM within the system. Recycling of effluent supernatant was evaluated, studying the effects of recycling of supernatant and the affiliated enzymes and thermophiles both to increase degradation and reduce the amount of water added to the influent to increase moisture levels. Lignin degradation was evaluated in STAR, as this organic component is typically the most recalcitrant. The knowledge gained in the completion of the work contained herein will benefit other downstream technologies and ALS systems, and will continue progress on the path to a regenerative long-term habitat.

Project Goals and Objectives

The primary goal of this project was to develop a novel high-temperature solids digestion system for processing biodegradable wastes within a sustainable closed-loop ecosystem. The residual streams generated by this process would be amenable to direct water and nutrient recovery. Associated objectives are:

- 1- To create a thermophilic reactor system mechanically able to suitable mix and aerate high input solids levels at an expected range of 6-10% solids,
- 2- To maximize the positive ESM-enhancing attributes in terms of gas transfer rates to maximize performance, solids shear to reduce particle size, solids and organic destruction performance to reduce waste volume and enable further recovery of water, nutrients and carbon, and pasteurization to prepare the product for further use or storage,
- 3- To minimize ESM-degrading attributes, in regard to mass and volume, crewtime, noise generation, vibration, energy consumption, and heat loss,

4- To evaluate the system's performance utilizing a long-term mission waste stream including human fecal matter, paper, food residuals, and plant materials.

Research Progress

1. *Oxygen Transfer, Solids Loading, and Sensitivity Analysis:* The reactor design was further improved and evaluated over the last year. A schematic of the final design is shown in Figure 1. An evaluation of oxygen transfer, solids loadings, and a sensitivity analysis were completed on the final design.

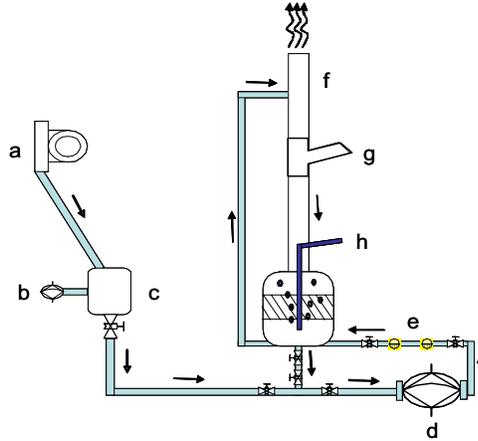


Figure 1: Schematic of digestion reactor. [a: EVAC toilet. b: vacuum pump. c: storage vessel. d: air diaphragm pump. e: online monitoring sensors. f: countercurrent air supply (sludge flows down, air flows up, off-gases exit the system). g: feed port. h: influent air.]

Oxygen transfer in the system was considerably improved by the enhancements to the reactor design (Figure 2). Initial transfer rates were consistent up to the saturation levels expected at the temperatures of testing. The improvements also impacted the ORP levels, raising the minimum ORP levels reached after a feed event (approximately -260 mV) and also raising the maximum ORP levels during the recovery period (approximately -40 mV). These improvements likely impacted the solids degradation potential of the reactor by improving oxygen availability. Further enhancement of the system and reduction in associated ESM could be investigated by variance of the air supply to match the demands during times of high metabolism after a feed event. This could not only improve the cost efficiency of the system relative to the oxygen supply mechanisms, but also would impact the heating energy required by the system and affect evaporation rates.

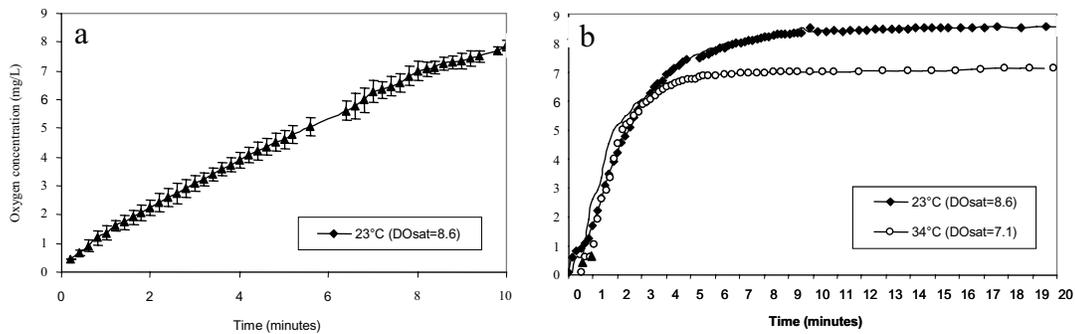


Figure 2: Oxygen transfer evaluation of previous design (a) and current design (b).

The K_{1a} values were estimated for the reactors at each temperature using nonlinear regression analysis. As shown in Table 1, the K_{1a} values did increase with the temperature increase for the 23°C study compared to the 34°C study using the final reactor design. These results would imply that although a complete offset of the lower $DO_{saturation}$ at increased temperatures due to subsequently increased K_{1a} did not occur, a sizable offset was in fact attained. Additionally, the K_{1a} value from the previous reactor design (0.11) was essentially tripled at 23°C, indicating a considerable design improvement.

Table 1: K_{1a} estimations for 2 temperatures in final reactor design.

Temperature	K_{1a}	r-squared	F-value
23°C	0.33	0.98	3700
34°C	0.48	0.96	1500

Evaluation of the influent solids loading utilizing relatively low HRT (13 days or less) showed the highest degradation at an influent solids loading of 6%, as shown in Table 2. However, there was only a minimal (~1%) loss of efficiency by increasing to the 8% loading. Degradation was decreased to 63% total solids loss at the 10% influent loading with an HRT of 11 days, likely due to limitations in mixing and aeration. This degradation was enhanced by operating with a much longer HRT, regaining 74% reduction in total solids, which is near the maximum percentage (75-80%) that can theoretically be oxidized, with the remaining 20-25% generally estimated to be inert and non-biodegradable. However, with a primary goal of reducing the energy and mass of the spaceflight system, this longer HRT would require a much larger system, resulting in higher operational costs. Depending on the length of operation and the post-treatment technology selections of the utilization scenario, the cost of essentially doubling the costs due to the additional mass, energy and volume requirements of a larger reactor vs. the savings in storage of the difference in total solids degradation would have to be calculated to determine the break-even point. For these reasons, the 8% solids loading with a 9 day HRT was selected as the optimum operating scenario for further research in the system as currently configured. This selection was deemed appropriate for further research goals; however, mission architecture and post-treatment technology selection would dictate the outcome of this decision for long-term missions. While the reactor was operated at 8% influent solids/9-day HRT, a sample was analyzed for BOD. Feedstock levels were 48,100 mg/L and effluent levels were 7,860 mg/L which was an 83.7% reduction.

Table 2: Solids degradation (\pm standard deviation).

Influent Solids %	HRT	Average Total Solids Loss (%)
4	10	74 (\pm 0.8)
6	13	75 (\pm 1.3)
8	9	74 (\pm 3.7)
8	18	78 (\pm 1.3)
10	11	63 (\pm 4.2)
10	22	74 (\pm 2.0)

A sensitivity analysis was completed on the reactor to determine the most statistically significant parameters for degradation of solid waste and the concomitant generation of CO_2 . This ordinary least squares analysis, utilizing White's HCCM method, was executed on a data set containing 303 observations. There were 5 parameters chosen, resulting in 298 degrees of freedom. Both the r-squared and adjusted r-squared values were 0.976, which is excellent. Significant parameters were determined to be pH, ORP, temperature, and time. Higher pH resulted in high CO_2

generation, as would be expected due to the increase in biological activity at the higher levels as compared to the acidic levels. ORP in the higher micro-aerobic zone was found to be the most conducive to degradation, presumably due to the increased supply to meet microbial demand and the increase in lignocellulose degradation at these more aerobic levels. Lower temperatures (which must still be maintained above 55°C due to pathogen inactivation issues) were found to be best, which would indicate that the physical-chemical conditions at these temperatures, the lower thermal impacts on enzyme systems, and the proliferation of the widest consortium of microorganisms likely all benefit the system. Finally, time to peak CO₂ generation was found to be statistically significant, indicating that elimination of lag time before onset of the burn phase would merit further research.

2. *Nitrogen Pathways and Attainment of Stable Cycling:* Within the reactor proteinaceous materials are degraded, releasing NH₃ and NH₄⁺. Additionally, cell lysis occurs in thermophilic aerobic systems as cells acclimated to mesophilic temperatures enter the high heat, high shear conditions in the reactor. Bacteria are comprised of roughly 60% protein, 10% lipids, 5% carbohydrate, and 25% DNA/RNA material which would become available for degradation upon lysis of the cells. There will still be undigested proteins and organic nitrogen, minimal amounts are expected to be utilized for cell growth, and some of the NH₄⁺ will be present in soluble form, or in struvite/dittmarite. Due to considerable changes in pK_a of ammonium at increased temperatures, the majority of NH₄⁺ will be volatilized as NH₃ in the off-gas. In summation, the nitrogen pathway is expected to proceed as follows (Figure 3). Initially, the influent sources of nitrogen are dominated by particulate organic nitrogen as part of cellular composition, both as microbial biomass and feedstock particulate matter. This particulate organic nitrogen is rapidly released into the bulk solution as the cellular solids lyse and decay and proteins are denatured. The soluble organic nitrogen, largely from amino acid degradation, is hydrolyzed into soluble inorganic nitrogen. Finally, the inorganic nitrogen strives for equilibrium in the bulk solution via stripping (primarily NH₃, potentially as NO₂), and as soluble inorganic nitrogen. Increases in pH and alkalinity are largely due to stripping of CO₂ and NH₃, and the formation of carbonates.

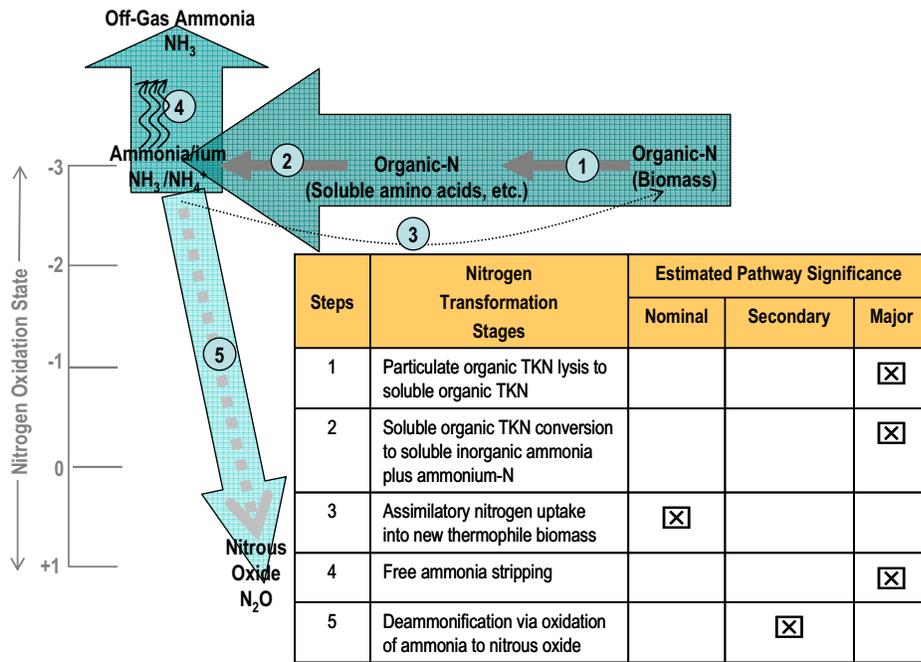


Figure 3: Likely primary nitrogen transition pathways.

Start-up behavior of a thermophilic aerobic reactor was assessed. The utilization of pH adjustment by addition of base was evaluated to reduce the amount of time required for start-up by the addition of sodium hydroxide (NaOH) for the first few hours only of start-up, and the response of the 8% loading study is shown in Figure 3. The grey line denotes the run not utilizing pH adjustment and as illustrated in Figure 4, the pH dropped in the first few hours as fatty acids and NH_4^+ were generated, and the system remained in acid hydrolysis conditions. In contrast, the run utilizing pH adjustment for the first hours was able to attain stable cycling and did not require further control after 24 hours. Both the 2% and 8% solids loading levels showed the same behavior (data not shown). At both solids loading levels evaluated the total solids degradation rates were ~50% under acid hydrolysis conditions when pH adjustments were not utilized. When pH adjustment was utilized during the first day of start-up and the system was operated under slightly basic conditions, total solids degradation increased to 72-78%. The results of this study indicate that by forcing start-up using initial pH control, stable cycling conditions can be attained in as little as 3 days. Depending on the initial pH of the feedstock, pH control may or may not be necessary. Prior studies on the digester system at 6% influent solids with higher pH feedstock did not require pH control to attain a stable cycle. However, from the standpoint of potential failures and/or contingencies, this scenario of a restart under low pH conditions should be prepared for and understood. Simple standard monitoring and controls can be implemented for this type of start-up scenario. Start-up protocols should be investigated to determine if initial loadings should delay the addition of low pH constituents, adding them after the buffering capacity has been developed in the system, or if initial pH control is the best protocol. If required, this intervention could be easily automated.

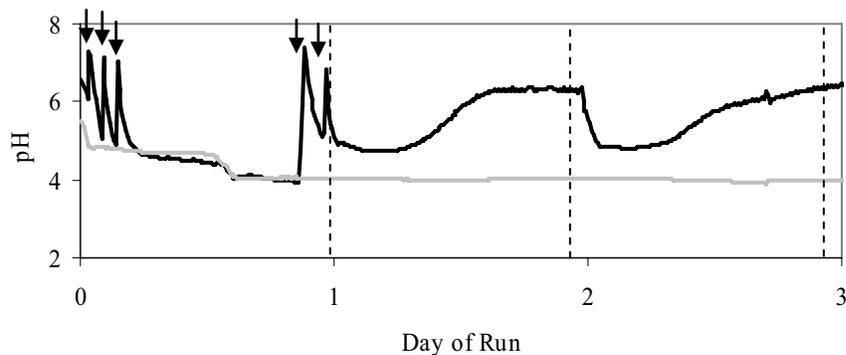


Figure 4: Start-up pH behavior at 8% solids loading (adjusted pH = black, unadjusted = gray; pH adjustments noted with arrows; feed events noted with vertical lines).

Evolution of fatty acids, alkalinity, ammonia-nitrogen, and pH during the start-up of the system were tracked over 4 days. Each of these parameters was shown to attain near stable cycle conditions by day 4 of start-up (Figure 5a). Adjustments to pH were utilized in the first 24 hours only and are indicated by arrows. After the start-up period, a stable cycle pattern can be observed. The behavior of fatty acids, alkalinity, ammonia-nitrogen, and pH during the 24-hour cycle of the established system were also evaluated (Figure 5b). Results of this study showed low levels of total ammonia nitrogen in the effluent, indicating extensive volatilization. Alkalinity values drop after a feed event when volatile fatty acids and NH_4^+ are generated as a result of degradation processes. These levels recover after approximately 12 hours, indicating both volatilization of ammonia and further degradation of volatile fatty acids to CO_2 . Total ammonia, pH, and temperature along with the dissociation constant must be considered to determine ammonia speciation. Due to conditions in the reactor, it is assumed that the major pathways for nitrogen compounds under the parameters of the system include the extensive stripping of NH_3 into the gas phase, soluble NH_4^+ and undegraded

nitrogenous materials, and the production of struvite/dittmarite which will likely precipitate. More research is needed to identify ammonia speciation in thermophilic aerobic digesters, particularly in regards to speciation within the off-gas. The data substantiates the premise that the majority of activity occurs within the first 12 hours after a feed event. Further research would be advisable to investigate the optimization of the feeding cycle, and to evaluate cost savings based on control of air supply to match the demands of the system.

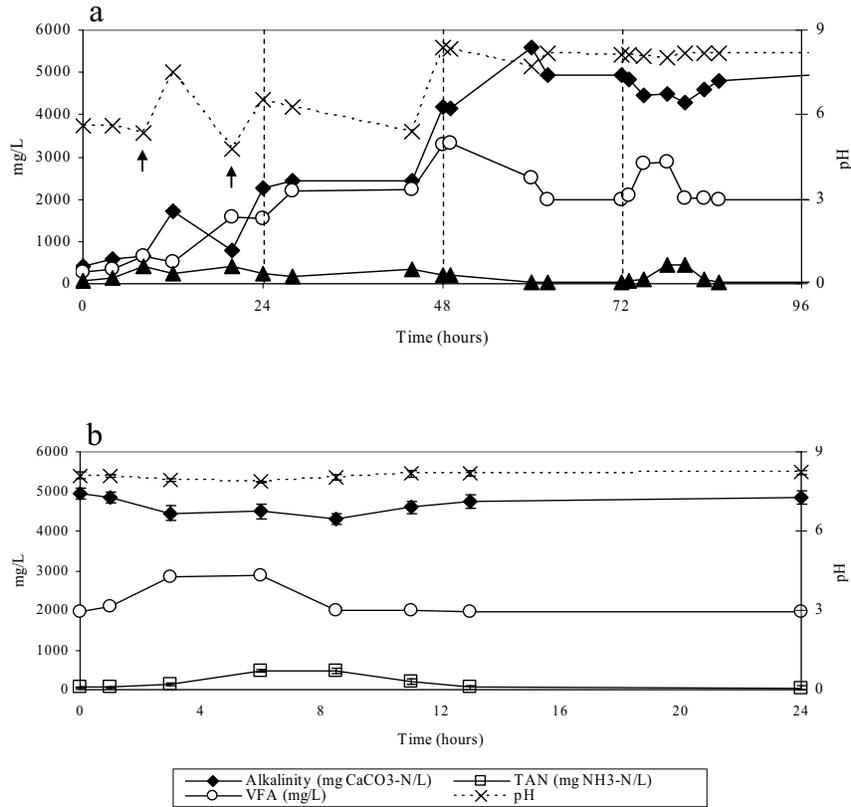


Figure 5: Start-up (a) and stable-cycle (b) conditions (error bars = standard deviation).

Relative enzyme activity during start-up and stable cycling was evaluated in the system as well. Over a seven day period from the initial start of the reactor, the enzyme activity evolved as shown in Figure . The average enzyme activity for the established reactor is also shown in red. As easily degradable organic material is initially high, enzyme levels drop accordingly, then are induced as this material is degraded. It is interesting to note that with only 2 exceptions out of 19 enzymes (alkaline phosphatase and leucine arylamidase), the relative activities on day 7 match those of the stable cycle enzyme levels tested several weeks into the operation of the reactor, and the variance of both alkaline phosphatase and leucine arylamidase was only one activity unit. In most cases the levels matched stable cycle levels by the 5th day.

Phosphatases, Esterases, Amino-peptidases, and Proteases

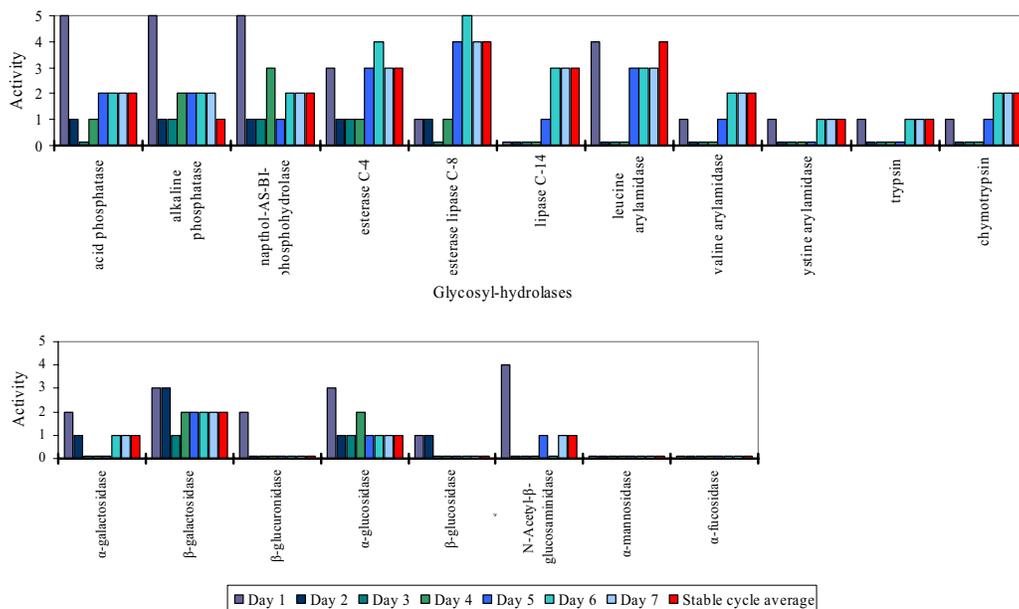


Figure 6: Enzyme evolution over 7-day start-up with average stable cycle activities shown in red.

3. *Lignin degradation, bench-scale filtrate recycling and enzyme activity study:* Due to the physical structure of lignocellulosic materials, degradation of lignin is important to allow access to the other organic components and enable subsequent degradation of cellulose and hemicellulose to proceed. Lignin is often considered to be recalcitrant to biological degradation. Lignin degradation in the pilot-scale reactor was 81% (Table 3). This is an excellent result for a biological, low HRT process, as most biological technology researchers report levels of lignin degradation of up to 70%.

Table 3: Lignin reduction in the pilot-scale reactor.

	Average (%)	Standard deviation
Untreated Feedstock	18.1	0.29
Effluent	16.67	0.06
Percent Reduction	81.2	0.24

In the final design of this investigation, the pilot-scale reactor was operated using water to dilute the influent raw waste stream to the desired solids level. Filtrate recycling would contribute to operational cost reduction by reducing or eliminating the need for addition of clean water to the system to increase moisture levels, and was also proven to increase degradation in the system. Another option for investigation would be the utilization of grey water from the system as a wetting agent. In order to reduce the influent solids from the raw value of 25% to the optimal solids loading of 8% for the reactor, 1-L of clean water must be added per person per day. Over the course of a long-term implementation this reduction would be substantial. Filtrate recycling was evaluated at bench scale for a matrix of all combinations of influent, water, filtrate, solids from filtrate, and effluent. Filtrate recycle was not shown to have a significant impact on lignin degradation in the system, but significantly higher total solids degradation was reported when utilizing filtrate as the wetting agent both in combination with food only and in combination with food and effluent. No significant correlation was found for this system between

initial lignin content and total solids degradation, but the correlation for % lignin degradation and % total solids degradation was 0.74.

Relative enzyme activities for all combinations of influent, water, filtrate, solids from filtrate, and effluent were determined. Overall enzyme activity for all combinations showed the highest relative activity for the phosphatases. Alkaline phosphatases have been shown to have multifunctional properties that can alter both organic phosphorus decomposition and carbon and nitrogen mineralization from dissolved organic compounds. Esterases showed the second highest activity; these enzymes have been utilized for the determination of overall potential activity of microbial enzymes in biochemical transformations of organic matter in environmental samples. Aminopeptidases, important in protein degradation and induced when carbon sources are not readily available, showed the third highest relative activity. Glycosyl-hydrolase relative activity was detected on a relatively low level, and protease activity showed the lowest relative activity. Thermophilic organisms generally produce relatively low levels of the proteases trypsin and chymotrypsin than mesophilic organisms. ATAD sludge typically shows poor dewatering characteristics, and it has been shown that extracellular proteins play a role in this issue and that supplementation of protease can increase dewaterability. Glycosyl-hydrolase relative activity at the end of the 24-hour feed cycle had the most significant effect on lignin degradation.

A further evaluation of enzyme activity in the system using a direct comparison of filtrate vs. water as a wetting agent was performed. These bench-scale studies compared the enzyme activity every 4 hours over a 24-hour period, beginning with a feed event, for the current combination of food, water and effluent, and the water-saving combination of food, filtrate, and effluent. The majority of enzymes showed a significant increase in relative activity when filtrate was used as the wetting agent. In Table 4, enzymes showing significant differences are indicated by plus-signs (+), and non-significant differences are indicated by minus-signs (-) along with the p values (Wilcoxon Matched-Pairs Signed-Ranks Test). Although the cystine arylamidase and proteases do not show a statistically significant increase, it is interesting to note that they each increase at the end of the run utilizing filtrate.

Table 4: Significance of enzyme activity in study of filtrate vs. water as wetting agent.

Enzyme	Significant	p
alkaline phosphatase	+	0.031
esterase C-4	+	0.018
esterase lipase C-8	+	0.00049
lipase C-14	-	0.43
leucine arylamidase	+	6.1×10^{-5}
valine arylamidase	+	0.0039
cystine arylamidase	-	0.25
trypsin	-	0.25
chymotrypsin	-	0.25
acid phosphatase	-	0.43
naphthol-AS-BI-phosphohydrolase	+	0.0039
α -galactosidase	+	0.0039
β -galactosidase	+	6.1×10^{-5}
β -glucuronidase	+	0.031
α -glucosidase	-	0.93
β -glucosidase	+	0.00049
N-Acetyl- β -glucosaminidase	+	0.0039
α -mannosidase	+	0.031
α -fucosidase	+	0.0039

The 24-hour evaluation of enzyme activities is presented in Figure . As degradation proceeds, enzymes may be induced as needed, and the relative activity will change with the conditions within the reactor. The enzymes exhibited similar activities at time 0; only esterase C-4, acid phosphatase, α -galactosidase, β -glucuronidase, and α -glucosidase show any variation, and these only by 1 activity unit. However, the relative activity levels are typically sustained for a longer duration in the samples containing filtrate. This would be a further benefit to the utilization of filtrate rather than clean water to attain desired moisture levels in the reactor.

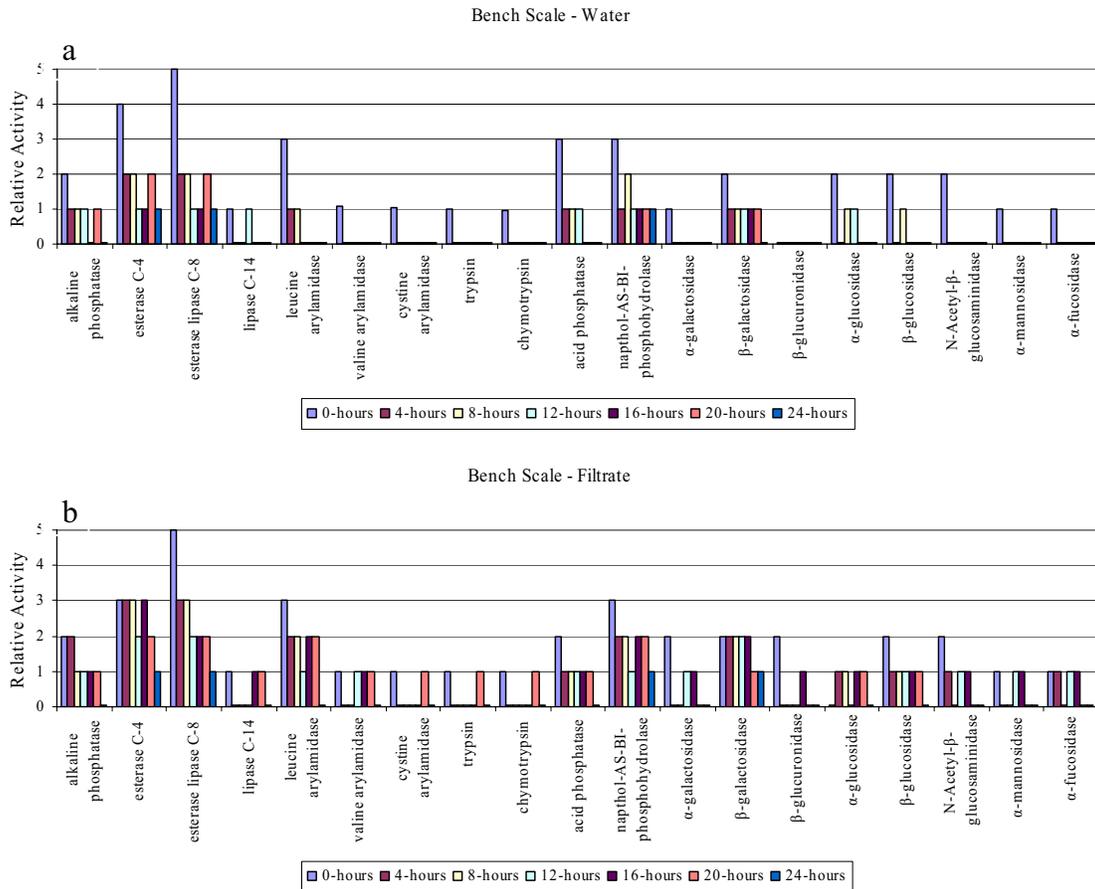


Figure 7: Enzyme evolution over 24-hour time period (a: water; b: filtrate).

Future Research Directions

Aerobic thermophilic digestion shows promise for utilization in a long-term closed-loop system. Biological treatment of wastes becomes more feasible as the duration of utilization increases. The system described herein will provide significant reduction in waste volume and will enable the recovery of resources. Future research recommendations include further optimization of the system as well as enhancing basic insight into the biology and chemistry of the system. A pilot-scale evaluation of the behavior and long-term performance of the system utilizing filtrate as the wetting agent instead of clean water is recommended. Optimization of the feeding cycle by evaluating shorter time intervals between feedings, as well as optimization of the aeration of the system by monitoring and controls based on degradation rates is suggested by the results of this research. Investigation into the microbial community would be desirable. A detailed off-gas analysis would enable further evaluation of speciation within the reactor, as well as provide

insight for downstream technologies. For incorporation into closed-loop ecosystems, bioaccumulation within the system of contaminants, salts, etc. should be investigated for long-term utilization. Pharmaceutical degradation and organic contaminant destruction should be evaluated. For space utilization, microgravity compatibility must be addressed. Additionally, a Hazard/Failure Analysis should be performed on the system.

Trainees

Post-Doctorates- None

Ph.D. - Dawn Whitaker, Purdue University (0.5 Research Assistant), Graduated 8/06

Undergraduates – R. Ellis, S. Muhammad, B. Walker, J. Lukens, G. Conyers, E. Barton

Research Collaboration

- STAR researchers participate in SIMA telecons, and the Solid Waste group telecons. Participation is ongoing in the Solid Waste Working Group.
- Dawn Whitaker continued working with Julie Levri at NASA-ARC on the OPIS project, part-time during the school year and full-time during the summer, ending December 05.

Publications and Presentations

2005-2006 Continued participation in outreach activities for K-12

Several papers in preparation for submission to peer-reviewed journals

Whitaker, D.R., and Alleman, J.E. (2006). “Thermophilic Aerobic Solid Waste Processing for Long-term Crewed Missions”. *Earth and Space 2006, 10th ASCE Conference on Engineering, Construction, and Operations in Challenging Environments*, Houston, TX

Whitaker, D.R. and Alleman, J.E. (2006). “Lignin Degradation in Solid Waste Treatment Systems”. *Habitation Conference*, American Institute of Aeronautics and Astronautics, Orlando, FL.

Whitaker, D.R., Invited Speaker, W1170: Chemistry, Bioavailability, and Toxicity of Constituents in Residuals and Residual-Treated Soils Group Meeting, “Solid Waste and Biosolids in Space”. January 2005, Las Vegas, NV.

Whitaker, D.R., Staton, K.L., Alleman, J.E., Lane, J.W. (2005). “Loading Balance and Influent pH in a Solids Thermophilic Aerobic Reactor”. *International Conference on Environmental Systems*, Society of Automotive Engineers, Aerospace Division, Rome, Italy, Paper # 2005-01-2982.

Kuo, Y., Whitaker, D., Chiu, G., Alleman, J. (2005). “System Level Design and Initial Equivalent System Mass Analysis of a Solid-Phase Thermophilic Aerobic Reactor for Advanced Life Support Systems”. *International Conference on Environmental Systems*, Society of Automotive Engineers, Aerospace Division, Rome, Italy, Paper # 2005-01-2983.

Whitaker, D.R., Lane, J.W., Alleman, J.E., Riano, R. (2004). “Solids Thermophilic Aerobic Reactor for Solid Waste Management in Advanced Life Support Systems”. *International Conference on Environmental Systems*, Society of Automotive Engineers, Aerospace Division, Colorado Springs, CO, Paper # 2004-01-2467.

Whitaker, D.R., Alleman, J.E. (2004). “Solids Thermophilic Aerobic Reactor (STAR) Treatment of ALS Solid Wastes”. Poster Presentation, NSCORT Executive Advisory Committee Meeting, Washington, D.C.

Alleman, J.E., Whitaker, D.R., Riano, R. (2004). “Solid-Phase Thermophilic Aerobic Reactor (STAR) Processing of Fecal, Food, and Plant Residuals”. Purdue Environmental Review Research Poster Session, West Lafayette, IN.

Principal Investigator: Charles C. Glass, PhD

BACKGROUND

Currently, NASA employs physiochemical technology to purify water for “short” space journeys. Conversely, this process is expensive and less than ideal for long voyages where optimally a significant portion of the waste products must be regenerated, especially the recovery of potable water from wastewater. If NASA plans to sustain long-term human voyages into space, to achieve this goal, most of the waste generated should be recycled. This project will contribute to the knowledge base focusing on sustaining human life for longer periods of time in space, specifically a Mars Mission.

This research focused on converting a concentrated ammonia-rich liquid, which includes trace organics and hydrogen sulfide from the Sequential Thermophilic Aerobic Reactor (STAR) Gas Scrubber, into a form that would be conducive for downstream processes of gray water treatment and plant growth. We identified the optimum zeolite to effectively treat ammonia rich wastewater and convert it to a form appropriate for plant uptake, while developing a regenerative process for the zeolite.

PROJECT GOALS AND OBJECTIVES

- To effectively treat ammonia rich wastewaters from various process streams inside of the ALS system.
- To convert concentrated ammonia to a form for uptake by plants or other unit operations in ALS.

RESEARCH PROGRESS

Adsorption of Ammonia on to Zeolites. Natural zeolites have been researched extensively for their use in nitrogen removal from wastewater from industrial and domestic waste sources (1-9). At concentrations greater than 100 mg/L NH₃-N the ion exchange process, using the ammonium selective ion exchange media, become feasible for use in comparison to biological nitrification (10-14) and other methods such as ammonia stripping and breakpoint chlorination followed by treatment on activated carbon (1).

Ammonium removal by clinoptilolite has been found to be a cost effective method in wastewater treatment over the last three decades. Clinoptilolite, a naturally occurring zeolite, has been found to be selective for ammonium ions in the presence of other cation concentrations commonly found in wastewaters (1-4, 6-8). Various reports in the literature (9) have also documented the influence of pretreatments on increasing this zeolites adsorption capacity and selectivity, which ranges widely depending on the type of pretreatment. The purpose of the project was to find a suitable means of decreasing the concentration of ammonia-rich brine fluid, which includes some organics and hydrogen sulfide from condensate from the STAR Gas Scrubber.

Adsorption of ammonium is well reported for the two (1-8) zeolite types, clinoptilolite and chabazite, and was carried out in both batch and column reactors to evaluate the effective adsorption capacity of these zeolites at high concentrations of ammonia in simulated wastewater.

In Figure 1 the results of the equilibration of ammonium ion onto the three zeolites in the presence of sodium and potassium ion, when treated with simulated wastewater (1000 mg/L NH₃-N) in a batch reactor setup. The data is presented as solid phase ammonium ion concentration at equilibration (mg of NH₄⁺ per gram of zeolite) plotted against the zeolite used. The chabazite was found to be the most stable and had a maximum adsorption capacity at equilibrium (32.73 mg NH₃-N/ g_{zeolite}) as compared to the commonly used clinoptilolite. The chabazite at an initial concentration of 1000 mg/L NH₃-N attained 90% removal in less than one hour with only one gram of the respective zeolite. However, a maximum adsorption capacity was higher for clinoptilolite 2 (36.20 mg NH₃-N/ g_{zeolite}) in comparison to that of clinoptilolite 1 (34.40 mg NH₃-N/ g_{zeolite}). But the most important property of retention capacity at equilibrium differs largely in the case of clinoptilolite 2 (25.82 mg NH₃-N/g_{zeolite}) than in case of chabazite. The adsorption capacity of clinoptilolite 1 was also found to be consistent with the general capacity of clinoptilolites in the literature (5) of 18 mg NH₄⁺/g of zeolite.

A column study was also performed with synthetic wastewater to determine the breakthrough curves for the three zeolites. Figure 2 shows the results of the column study. The chabazite was found to outperform the other forms of zeolite which was consistent with the results of the batch reactors. This may be due to the presence of easily exchangeable sodium ions. Ming et. al (14) and Lahav et. al (15) observed that the affinity of clinoptilolite and chabazite was greater for K⁺ than NH₄⁺. This affinity for potassium cations over ammonium can explain the poor adsorption of ammonia for the other zeolites. The breakthrough curves were steep which is very important for process application and represents an effectual media.

The optimum zeolite screened from the above experiments was tested over a range of concentrations of ammonia (Figure 3) to determine its maximum capacity for lower concentrations and how it behaves over various concentration ranges. At the 400 mg NH₃-N/L concentration the retention ability of chabazite for ammonia was comparable with a maximum adsorption of 22.57 mg NH₃-N/g_{zeolite} to an equilibrium adsorption capacity of 21.81 mg NH₃-N/g_{zeolite}. It was observed that an increase in initial concentration 500 and 1000 mg NH₃-N/L, resulted in an effectual increase in the adsorption capacity, 31.93 mg NH₃-N/g_{zeolite} and 40.87 mg NH₃-N/g_{zeolite} for chabazite, respectively. However these values were misrepresentative since the equilibrium adsorption capacities were 66% and 63% respectively, of the original aqueous ammonia retention.

To increase the adsorption capacity by adjusting the various parameters responsible for adsorption, different pretreatment techniques were carried out for the best zeolite and at 400 ppm concentration of the ammonia solution, as shown in Figure 4. It was found that the heat treatment for one hour at 600 °C showed the best results. Based on the observations of Klieve et. al, the heat treatment for one hour was carried out. This heat treatment resulted in weight loss due to evaporation of water and some organics which opened channels for better ammonia adsorption. During the initial five hours, the untreated chabazite had the best adsorption capacity but maintained a very low retention value, while the one hour heat pretreated sample had comparative adsorption and retention capacities. Cartlidge et. al. observed that Na-exchanged natural chabazite showed solid-state transformation to a sodalite structure at 600 °C, whereas K-exchanged natural chabazite did not transform. However, the XRD spectra taken after the heat treatment of the samples under study did not show any such structural changes as compared to untreated samples.

A pretreatment process involving an acid treatment may result in dissolving alkali impurities which can block pores and channels within the zeolitic framework, hence promoting adsorption deep within the pores. However, zeolites with lower Si/Al ratio have been found to be unstable at

lower pH, probably due to the loss of aluminum from the framework and thus, resulting in lower adsorption capacity. This can be seen from Figure 4, where at an initial concentration of 400 mg NH₃-N/L, the untreated zeolite performs better than the acid pretreated.

Another pretreatment aimed at increasing the ammonia adsorption capacity of the zeolite was treatment with sodium hydroxide. Heating in the presence of salt for varying time periods did not improve the adsorption capacity. In Figure 4, chabazite base treated had a maximum adsorption capacity (27 mg NH₃-N/g_{zeolite}) that surpassed that of the untreated zeolite (15 mg NH₃-N/g_{zeolite}) and one hour heat treated also. But the retention capacity of one hour heat treated chabazite was the best among all the other pretreated samples.

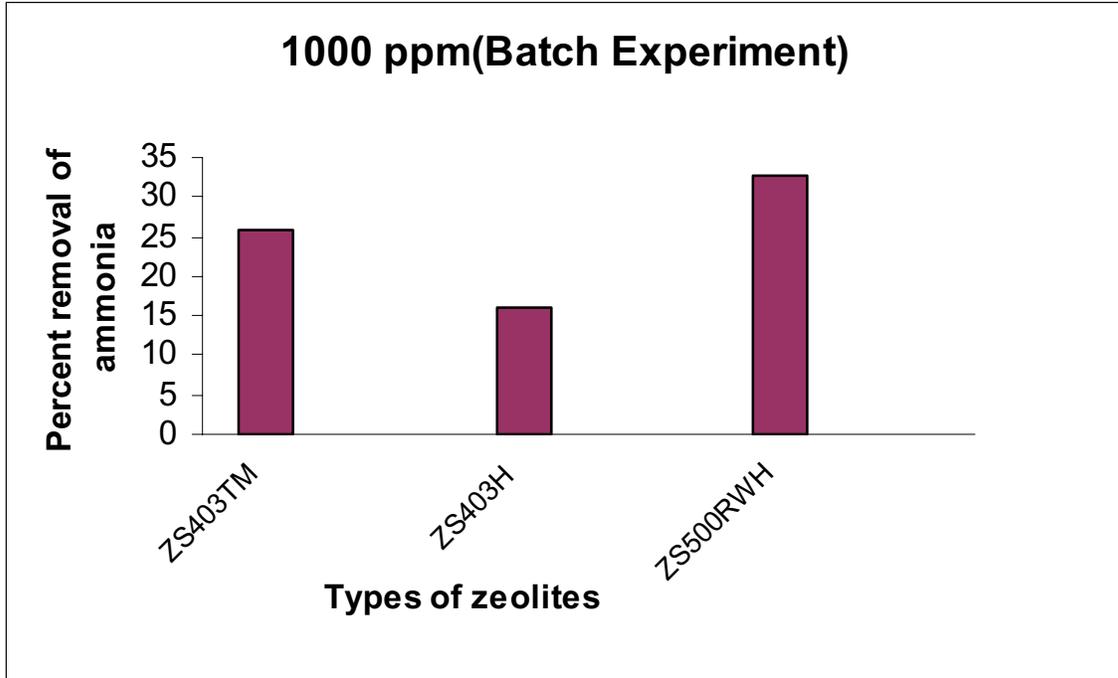


Figure 1. Adsorption capacity of various zeolite at a concentration of 1000 mg NH₃-N/L in a batch reactor.

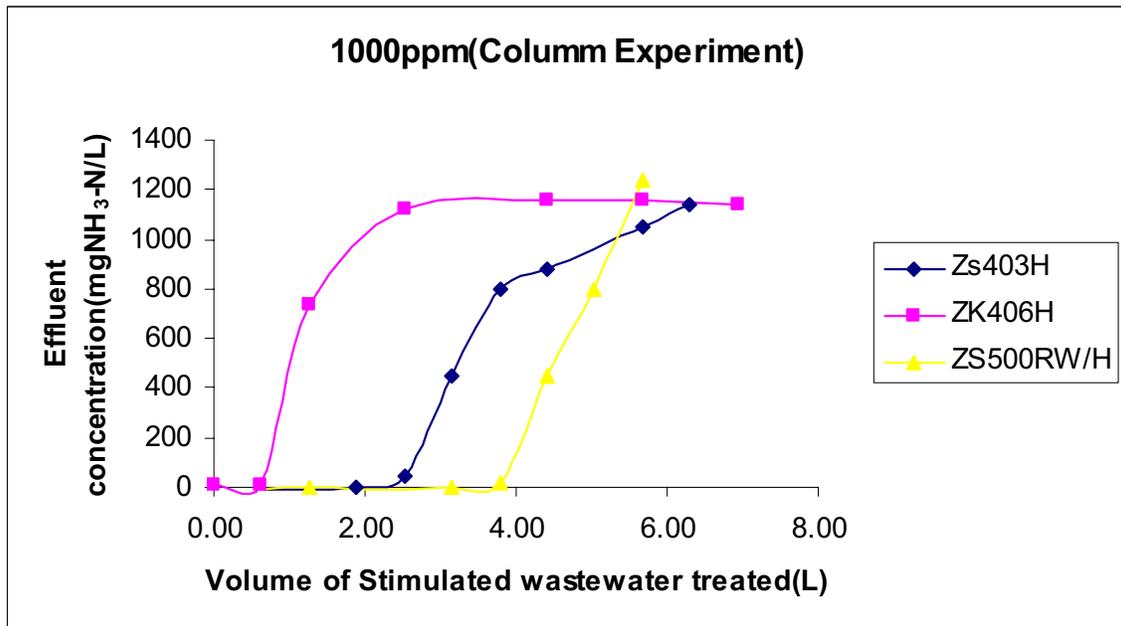


Figure 2. Adsorption capacity of various natural zeolites studied at a concentration of 1000 mg/L in a column experiment.

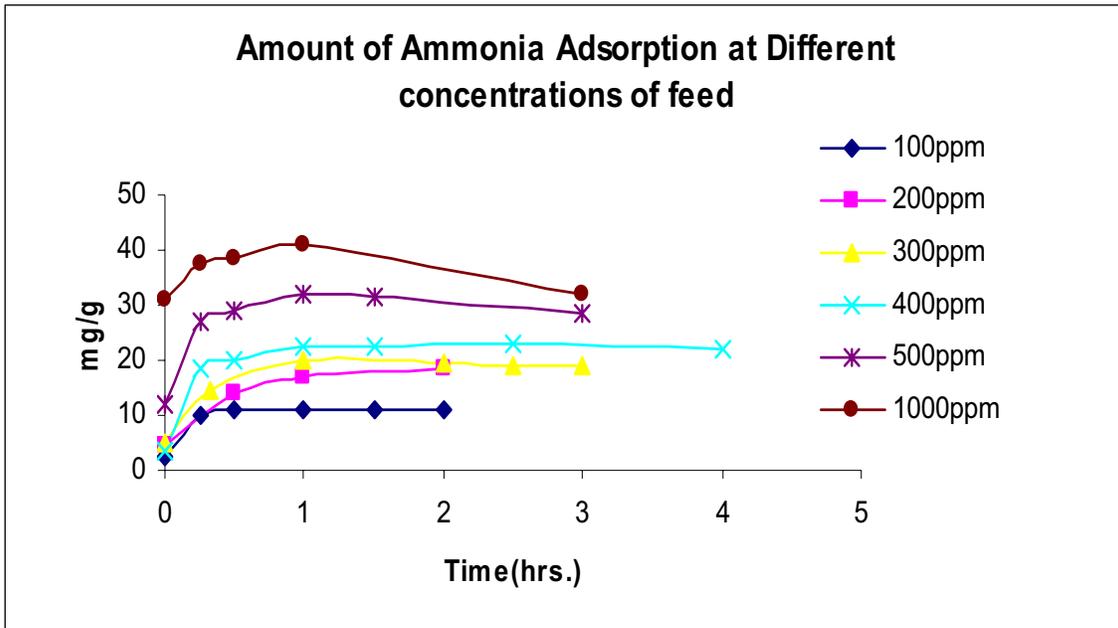


Figure 3. Extent of adsorption of ammonia over chabazite(ZS500RW/H) at different concentrations of ammonia solution.

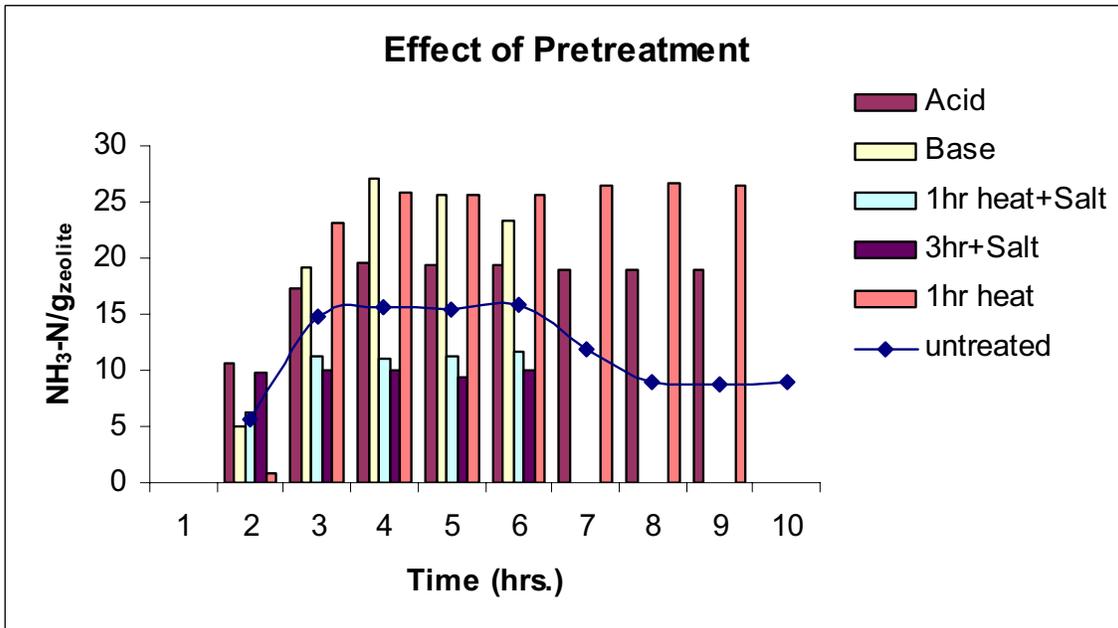


Figure 4. Comparison of the effect of various pretreatments carried out over chabazite (ZS500RW/H) with a concentration of 400 mg/L of ammonia solution.

Nitrification and Denitrification. In the phase III Lunar-Mars Support Test project ammonium ions were removed using a column in series system packed with clinoptilolite, a naturally occurring zeolite material. Clinoptilolite removes ammonium ions through ion exchange with calcium. The system worked well, however the clinoptilolite was never regenerated and the nitrogen sorbed was never returned to the system. This would not cause a problem in a 91-day experiment, or any other short term mission, however over time nitrogen would accumulate in this phase and an unstable system would result. In this project a nitrification/denitrification reactor is being used to regenerate the clinoptilolite and return a liquid product that can be used as a nutrient supplement for the plant systems in the ALS. Nitrification refers to the oxidation of ammonium or organic nitrogen compounds to nitrite or nitrate, while denitrification is the anaerobic respiration of nitrate and nitrite to nitrogen gases, through nitric oxide and nitrous oxide. Nitrification and denitrification have been shown to convert nitrogen at the concentrations greater than 1000 mg/L as N (Mahne et al., 1996, Glass et al, 1997, Glass and Silverstein, 1998, Glass and Silverstein, 1999). The conversion of nitrogen at these concentrations requires physical conditions that are different from natural water concentrations and care is taken to ensure that nitrogen oxides are not released during the regeneration of the clinoptilolite. An important portion of this experiment is determine, through mass balance of measured products, that the ammonia is being converted to nitrate and nitrate is being converted to nitrogen gas. This will have to be in conjunction with the mass balance of nitrogen in the ALS. The portion of nitrogen to be returned to plants as nitrate or ammonium and the portion of nitrogen that should be returned to the atmosphere will be determined as the second objective of this project.

Plant community patterns are strongly related to N availability and the form of nitrogen that is used is highly variable (Pastor et al., 1984) and different plant communities will display distinct patterns of nitrification and denitrification. Numerous studies have attempted to quantify rates of denitrification in relation to moisture status, fertilizer additions, cropping systems, and other field variables (Colbourn and Dowdell, 1984; Tiedje, 1988). Most of these studies have been hindered by high spatial and temporal variability in activity, with coefficients of variation frequently exceeding 100%, even with intensive sampling of small field plots (Parkin et al., 1987). Soil water, nitrate, and organic carbon supply all exhibit variability in time and space in soil, or any non-completely mixed environment. A more accurate quantification will be necessary for the

plant systems in the ALS because return of nitrogen to the growth of plants will provide oxygen for the system.

Nitrogen exists in many forms in the environment and can enter aquatic systems from either natural or human-generated sources. Some of the primary direct sources or transport mechanisms of nitrogen from sewage include:

- Untreated sewage—direct discharge.
- Publicly owned treatment works (POTW) effluent—direct discharge, land application.
- POTW waste solids—direct discharge, land application.
- Septic tanks and leaching fields—groundwater movement.

Untreated sewage flowing into a municipal wastewater facility has total nitrogen concentrations ranging from 20 to 85 mg/L. The nitrogen in domestic sewage is approximately 60 percent ammonia nitrogen, 40 percent organic nitrogen, and small quantities of nitrates (U.S. EPA 1993).

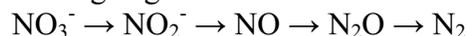
Wastewater treatment plants are required to significantly reduce the level of ammonia that comes into the plant. The presence of ammonia nitrogen promotes eutrophication of water bodies such as algae which decreases the dissolved oxygen due to bacterial oxidation. High levels of ammonia can be very toxic to living organisms, promote additional oxygen demand on receiving waters, adverse public health effects, and decreased suitability for reuse. Industrial activities and human handling produce ammonia concentrations that are well over 1000 mg/L – N.

Most wastewater treatment plants use the combined processes of nitrification and denitrification to oxidized ammonia to harmless nitrogen gas. Nitrification is defined as the biological process during which nitrifying bacteria is used to convert toxic ammonia to nitrate, once the proper conditions are present for the nitrifying bacteria to thrive. In nitrification, there are two main bacterial species involved; Nitrosomonas and Nitrobacter. Their reactions are simplified as follows:



Essentially, in reaction 1, ammonia is combined with oxygen and hydrogen carbonate to produce bacterial cell mass, nitrite (NO_2^-), water and carbonic acid. While in reaction 2, ammonia, hydrogen carbonate, carbonic acid and oxygen combines with the nitrite to produce bacterial mass, water and a large amount of nitrate.

Denitrification is an anaerobic biological process by which denitrifying bacteria reduce nitrates to inert atmospheric nitrogen gas.



Denitrification is an essential part of nitrogen removal and it is used more extensively than any other type of biological treatment process because in addition to nitrification it is more cost effective. Denitrification enables transformation of oxidized nitrogen compounds by bacteria into harmless nitrogen gas. Because of its availability and price, methanol is more commonly used as a carbon source for bacterial denitrification (Foglar

2004 et al 2004). One of the problems with high levels of ammonia is the formation of free ammonia. Ammonia concentrations at 10 - 150 mg NH₃ – N/L begin to inhibit the growth of Nitrosomonas bacteria (Christian et al 2002). Similarly, Casten and Rozich (1986) observed a decrease in nitrification rate as ammonia concentration was increased. Therefore with respects to the process design, it is essential that the nitrifying bacteria be able to withstand the high ammonia concentration levels. Other major factors that influence the kinetics of nitrification are temperature, pH and dissolved oxygen concentration.

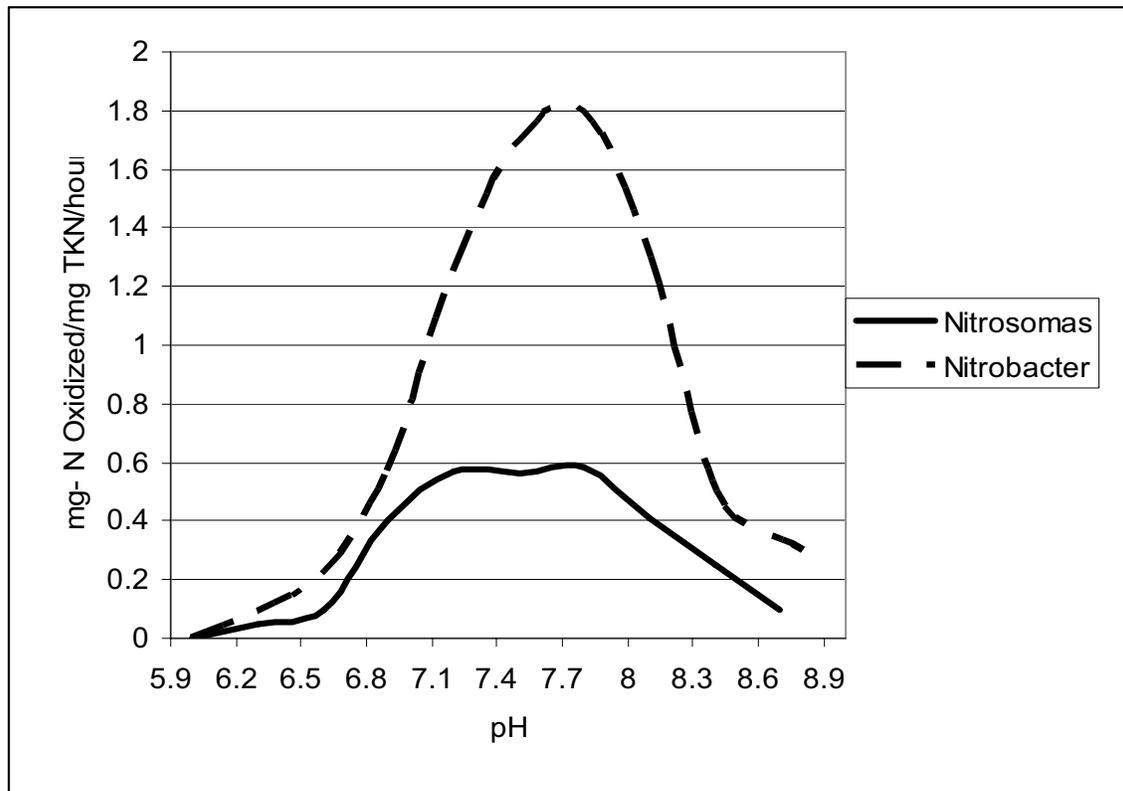


Figure 5. Effects of pH on nitrifying bacteria.

Dissolved Oxygen. Figure 6 shows the effect of dissolved oxygen (DO) on nitrification efficiency. DO concentrations above 1 mg/l are essential for nitrification to occur. If DO levels drop below this value, oxygen becomes the limiting nutrient and nitrification slows or ceases.

The maximum nitrifying growth rate is reached at a DO concentration of 2 to 2.5 mg/L.

Denitrification is performed in anoxic conditions, where the DO is zero. Research has shown that acclimating the bacterial population to strong specialized environmental stresses will result in a growth of specialized bacteria (Antileo et al. 2002).

Fundamentally, nitrogen-rich supply such as activated sludge could be a potential source of nitrifying bacteria that could be acclimatized to deal with high concentrations of ammonia wastewater.

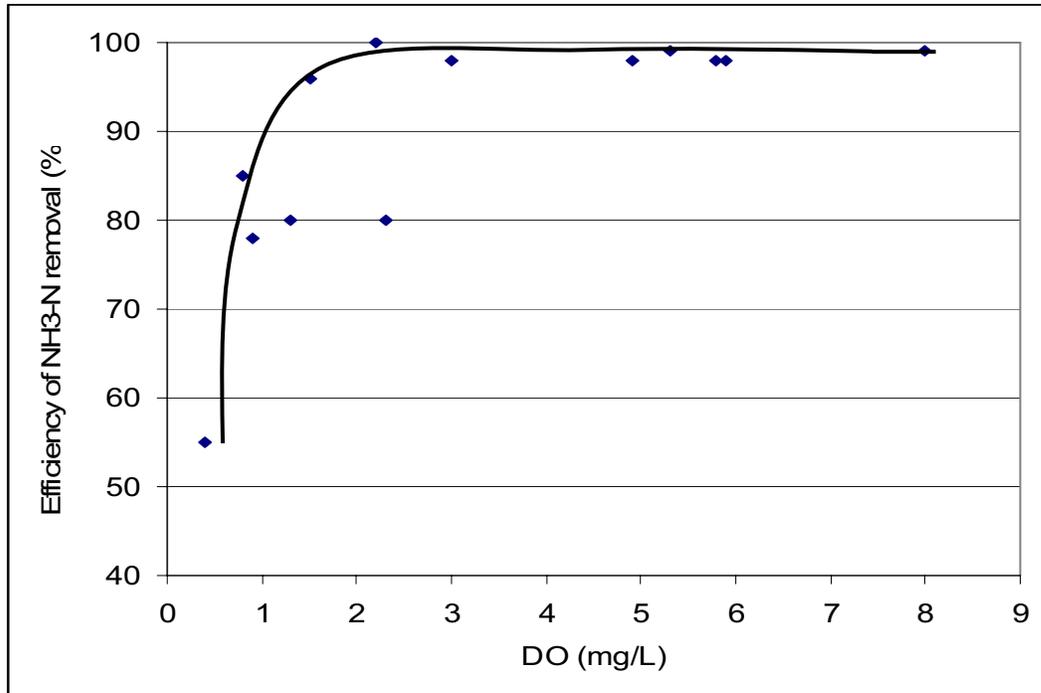
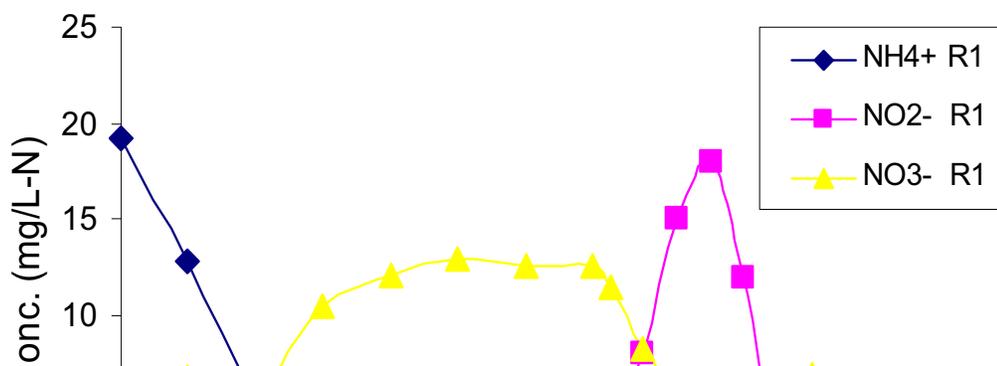


Figure 6. Nitrification versus DO

Based on kinetic modeling done for the nitrification and denitrification phase of wastewater treatment of high concentration ammonia and using the assumptions and conditions stated, it was found that nitrification of high strength ammonia of 1000 mg-N/L to below 10 mg-N/L can occur, under aerobic conditions, in a period of 4 hours. While removal of nitrate at a high concentration of 1000 mg-N/L to a concentration below 10 mg-N/L requires a period of 8 hours. Below is tabled the conditions and cycle schedule for an initial TAN of 1000 mg-N/L. Since the nitrification and denitrification process would take the longest periods in this case, the reactor schedule could be used for the essential nitrification and denitrification of lesser concentrations of TAN.

In Figure 7 preliminary data is presented showing nitrification and denitrification in a SBR. This system did not contain zeolite, however it performed well. In the future the ammonia concentration in this reactor will be increased in steps allowing for acclimation of the consortium of microorganisms to increasing free ammonia toxicity.



uptake by plants; and to quantify the dynamics, transformations, and mass balance of nitrogen throughout the ALS. The sources of ammonia will include the off-gas from the ATAD operation, on the order of 1,000 mg/L of ammonium as nitrogen, and the urine freeze-thaw treatment system, which will also have an ammonium-rich brine discharge. In the ALS there can be no sink of nitrogen. Nitrogen in the system, in any one phase, must continuously move from phase to phase at a rate that continues to sustain all of the biological organisms required for the sustenance of the colony. Therefore, ammonia that has been scrubbed from the off-gas from Grey water treatment and STAR, will have to be converted to a form that can be used in other processes, predominantly to a source that can be utilized by different plant systems in the ALS.

A common theme in the study of the nitrogen cycle on earth has been that while the physiology, biochemistry, and chemistry of nitrogen fluxes between organisms, water, soil, and air are relatively well understood, this knowledge has not translated into a thorough understanding of how these processes are regulated in the environment (Robertson, 1986). The balance of nitrogen in a large closed system will not be as complicated as field experiments on earth, but

Figure 7. Nitrification and Denitrification

FUTURE NEEDS

The two objectives of this research project were to: effectively treat ammonia rich wastewaters from various process streams and convert it to a form that is amenable to uptake by plants; and to quantify the dynamics, transformations, and mass balance of nitrogen throughout the ALS. The sources of ammonia will include the off-gas from the STAR operation, on the order of 1,000 mg/L of ammonium as nitrogen, and the urine freeze-thaw treatment system, which will also have an ammonium-rich brine discharge. In the ALS there can be no sink of nitrogen. Nitrogen in the system, in any one phase, must continuously move from phase to phase at a rate that continues to sustain all of the biological organisms required for the sustenance of the colony. Therefore, ammonia that has been scrubbed from the off-gas from Grey water treatment and STAR, will have to be converted to a form that can be used in other processes, predominantly to a source that can be utilized by different plant systems in the ALS.

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elucidated the biochemical pathways and physiology of nitrogen reactions, multiple physical, chemical and biological factors will contribute to a complicated ecological system. The variability in reaction rates based on these factors will largely determine how the balance in the closed environment will be maintained. The complexity of this system will lead to high spatial and temporal variability of the production of gases and the use of nutrients in the environment.

Due to the shortening of the NSCORT Center and the reductions in the original funding committed, only one of the objectives was successfully completed. While most other Principal Investigators received funding for four years, this Principal Investigator received the equivalent of 2.5 years of funding (\$250,000) of the originally projected \$400,000 over four years. Based on the amount of funding that was appropriated, completing one of two originally proposed objectives matches the funding allotted.

In the future, the connection between physical removal followed by zeolite bioregeneration needs to be studied thoroughly. There is a need to define the proper amount of treatment of the high ammonia concentration that will result from the oxidation of proteinaceous material regardless of the degradation method (anaerobic digestion, composting, or thermophilic aerobic digestion).

TRAINEES

MS Students: Ressa Chee Wah and Hugh-Berk Sinclair
Undergraduate Students: Wendell Khunjar and Kurt Smith

RESEARCH COLLABORATION

- Banks co-chaired the 2004 ICES session on "Biological Treatment for Water Recycling" with Jay Garland from KSC. Due to the large number of papers submitted to this session, two periods, morning and afternoon, were devoted to this topic.
- Kennedy Space Center – Jay Garland is a member of Sybil Sharvelle's PhD committee. Sybil has traveled to KSC several times for research interaction.
- Johnson Space Center – Banks has communicated with researchers at JSC and Texas Tech. to provide updates on NSCORT progress with BREATHe.
- Banks attended the NASA Biological Water Treatment Workshop held in Houston, TX.
- Banks visited the University of Florida's NASA Commercialization Center.
- Monthly BREATHe meetings are conducted with Al Heber's and K. Banks' research groups.
- Monthly Water Group Telecons are conducted with PIs and students from Purdue and Howard.
- Sharvelle presented a BREATHe experimental plan at the NSCORT Systems Group Retreat.

- Sharvelle is collaborating with Bruce Applegate, an NSCORT food area researcher to identify surfactant degraders.
- Banks hosted Kim Jones' student in her laboratory to develop methods for an experimental project to determine the effect of biofouling on reverse osmosis efficiency.

PUBLICATIONS

Glass, C. C. and Ressa, C. (2006). "Enhancement of Ammonium Adsorption Capacity with

Pretreated Natural Zeolites." *In Review with the Journal Habitation, Accepted with Major Revisions.*

Glass, C. C. and Chee Wah, R. (2004). "Nitrogen Recovery during Solid Waste Treatment for Advanced Life Support," *International Conference on Environmental Systems*, Paper #04-01-2514.

PRESENTATIONS

Glass C. C. (2006), "Nitrification and Denitrification of Effluent from Solid Waste Treatment", Presented at the Habitation Conference, Orlando, FL.

Glass, C. C. and Chee Wah, R. (2004), "Nitrogen Recovery during Solid Waste Treatment in Advanced Life Support Systems," Presented at the Habitation Conference, Orlando, FL.

Chee Wah, R. (2003), "Nitrogen Recovery during Solid Waste Treatment in Advanced Life Support Systems," Presented at the NSCORT Summer Symposium, Purdue University, West Lafayette, IN.

Khunjar, W. (2003), "Nitrogen Recovery through Nitrification and Denitrification," Presented at the NSCORT Summer Symposium, Purdue University, West Lafayette, IN.

Sinclair, H. (2004), "Optimization of Zeolite Performance for Ammonia Removal," Presented at the NSCORT Summer Symposium, Purdue University, West Lafayette, IN.

Glass, C. C. (2004). "Nitrogen Recovery during Solid Waste Treatment for Advanced Life Support," Presented at the *International Conference on Environmental Systems*, Colorado Springs, CO.

REFERENCES

1. Jorgensen, S. E.; Libor, O; Graber, K. L.; Barkacs, K. Ammonia removal by use of Clinoptilolite. *Water Research* 10: 213- 224; 1975.
2. Baykal, B.B.; Guven, D. A. Performance of Clinoptilolite alone and in combination with sand filters for the removal of ammonia peaks from domestic wastewater. *Wat. Sci. Tech.* 35(7): 47-54; 1997.
3. Veigh, R.M.; and Weatherley, L. Ammonium ion (NH₄⁺) removal from secondary effluent through ion-exchange: the effect of biological activity and the presence of other cations. *Wat. Sci. Tech.* 40(2): 143-149; 1999.
4. Rozic, M.; Cerjan-Stefanovic, S.; Kurajica, S.; Vancina, V.; and Hodzic, E.; Ammonical nitrogen removal from water by treatment with clays and zeolites. *Wat. Res.* 34(14): 3675-3681; 2000.
5. Jorgensen, T. C.; Weatherley, L. R. Ammonia removal from wastewater by ion exchange in the presence of organic contaminants. *Wat. Res.* 37: 1723-1728; 2003.
6. Langella, A.; Pansini, M.; Cappelletti, P.; Gennaro, B. D.; Gennaro, M. D.; Colella, C.

- NH_4^+ , Cu^{2+} , Zn^{2+} , Cd^{2+} and Pb^{2+} exchange for Na^+ in a sedimentary clinoptilolite, North Sardinia, Italy. *Microp. And Mesop. Mat.* 37: 337-343; 2000.
7. Rodriguez-Iznaga, I.; Rodriguez-Fuentes, G.; Benitez-Aguilar, A. The role of carbonate ions in the ion-exchange $\text{Ni}^{2+}=2\text{NH}_4^+$ in natural clinoptilolite. *Microp. and Mesop. Mat.* 41:129-136; 2000.
 8. Rodriguez-Iznaga, I.; Gomez, A.; Rodriguez-Fuentes, G.; Benitez-Aguilar, A; Serrano-Ballan, J. Natural clinoptilolite as an exchanger of Ni^{2+} and NH_4^+ ions under hydrothermal conditions and high ammonia concentration. *Microp. and Mesop. Mat.* 53:71-80; 2002.
 9. Klieve, J.R.; Semmens, M. J. An evaluation of pretreated natural zeolites for ammonium removal. *Wat. Res.*14:161-168; 1979.
 10. Jung, J. Y.; Chung, Y.C.; Shin, H. S.; Son, D. H. Enhanced ammonia nitrogen removal using consistent biological regeneration and ammonium exchange of zeolite in modified SBR process. *Wat. Res.* 38: 347-354; 2004.
 11. Campos, J.L.; Corral, M.; Sanchez, M.; Mendez, R.; Lema, J. M. Nitrification in saline wastewater with high ammonia concentration in an activated sludge unit. *Wat.Res.*36: 2555-2560; 2002.
 12. Lahav, O.; and Green, M. Bioregenerated ion-exchange process: The effect of the biofilm on the ion-exchange capacity and kinetics. *Wat. SA.* 26(1): 51-57; 2000.
 13. Yang, L. Investigation of nitrification by Co-immobilized nitrifying bacteria and zeolite in a batchwise fluidized bed. *Wat. Sci.Tech.* 35(8): 169-175; 1997.
 14. Allen, E.R., Hossner, L.R., Ming, D.W., and Henninger, D.L. Solubility and cation exchange in phosphate rock and saturated clinoptilolite mixtures. *Soil Society of America Journal* 57(5):1368-1374; 1993.
 15. Lahav, O.; Green, M. Ammonium removal using ion exchange and biological regeneration. *Wat. Res.* 32(7): 2019-2028; 1998.
 16. Dyer, A.; Zubair, M. Ion-exchange in chabazite. *Microporous and Mesoporous Materials.* 22:135-150; 1998.
 17. Shim, S. H.; Navrotsky, A.; Gaffney, T. R.; and MacDougall, J. E. Chabazite: energetics of hydration, enthalpy of formation, and effect of cations on stability. *Amer. Mineralogist.* 84:1870-1882; 1999.
 18. APHA, AWWA, WEF, 2005. Standard Methods for the Examination of Water and Wastewater, 21st Edition. Washington D.C.

The PABLO project: Plant-based Anaerobic-aerobic Bioreactor Linked Operation

Ronald Turco, College of Agriculture

Larry Nies, College of Engineering

Megan Heller, College of Agriculture

Statement of Project Goals and Expected Results

This project focuses on the adaptation and use of anaerobic-aerobic technologies for the treatment of three types of biological waste (plant residues, greywater and human waste) for the Mars colony and for use in the production of Earth-based biofuels. The primary goal is the anaerobic conversion of a variety of plant waste to CH_4 . The aerobic portion of the project is for conversion recalcitrant materials to form materials that can be further converted to CH_4 . This is a novel approach that will have applications in Earth-based as well as space. For the Mars portion of the project we are interested the use of dried plant residues and other organic materials grown within the space colony. Consideration is also given to the impact of long-term storage of materials. For the Earth-based biofuels generation, we are interested in wet waste materials (food processing) as well as dried residues. While we are presently perusing methane production from plant waste, the long-term goals is to develop a dual systems, one to handle the combination of plant waste and greywater and one to handle the human waste. While both will result in the formation of CH_4 , the plant waste-grey water system Plant-based Anaerobic-aerobic Bioreactor Linked Operation (PABLO) will also be used to develop an organic plant growth media similar to compost. The human waste treatment system Waste-ABLO (WABLO) uses the same approach but the resulting biosolids are not used in food production. In both cases, anaerobically processed waste streams will provide an energy source based on a renewable source and will result in a reduction in the mass of plant waste present. In the long-term the anaerobic digester will be a source of methane (leading to small scale electricity generation), produce water, treat waste materials while conserving O_2 and act as a heat sink as optimal digester operation is achieved with an elevated temperature. Advanced biological treatment may be able to convert CH_4 to methanol that can be used directly in fuel cells. The PABLO solid waste materials will be an ideal bedding material for the production of mushrooms and any other plant types that are difficult to grow in liquid systems. In order to maintain a high quality food, at no time do we propose using biosolids from WABLO in food production. These anaerobic digester systems will provide a robust treatment technology that will allow a rapid and consistent conversation of waste to energy and in the case of PABLO needed secondary plant growth materials.

Biomass Waste Conversion with Energy Reclamation

A significant fraction of waste material (plant residue, greywater and human waste) generated during space missions and on the earth, contains recoverable energy. The specific objective of the project is to optimize an approach that will demonstrate a Plant-based Anaerobic-aerobic Bioreactor Linked Operation (PABLO) that efficiently converts plant residuals and greywater into fuel grade methane (CH_4), electricity, and biosolids that will be suitable for plant and fungal culture. This effort will optimize the potential for CH_4 production by aerobically treating anaerobically recalcitrant waste materials - biosolids before they are used in as a plant growth material. This step will breakdown the resistant materials, freeing soluble carbon and stabilizing the materials. In a second part of the project we will modified the PABLO system to a system concerned with converting human waste in to CH_4 and biosolids. The Waste-ABLO (WABLO) approach is for the

conversion of human waste into CH₄ and biosolid residuals that are condensed but not used in the production of food.

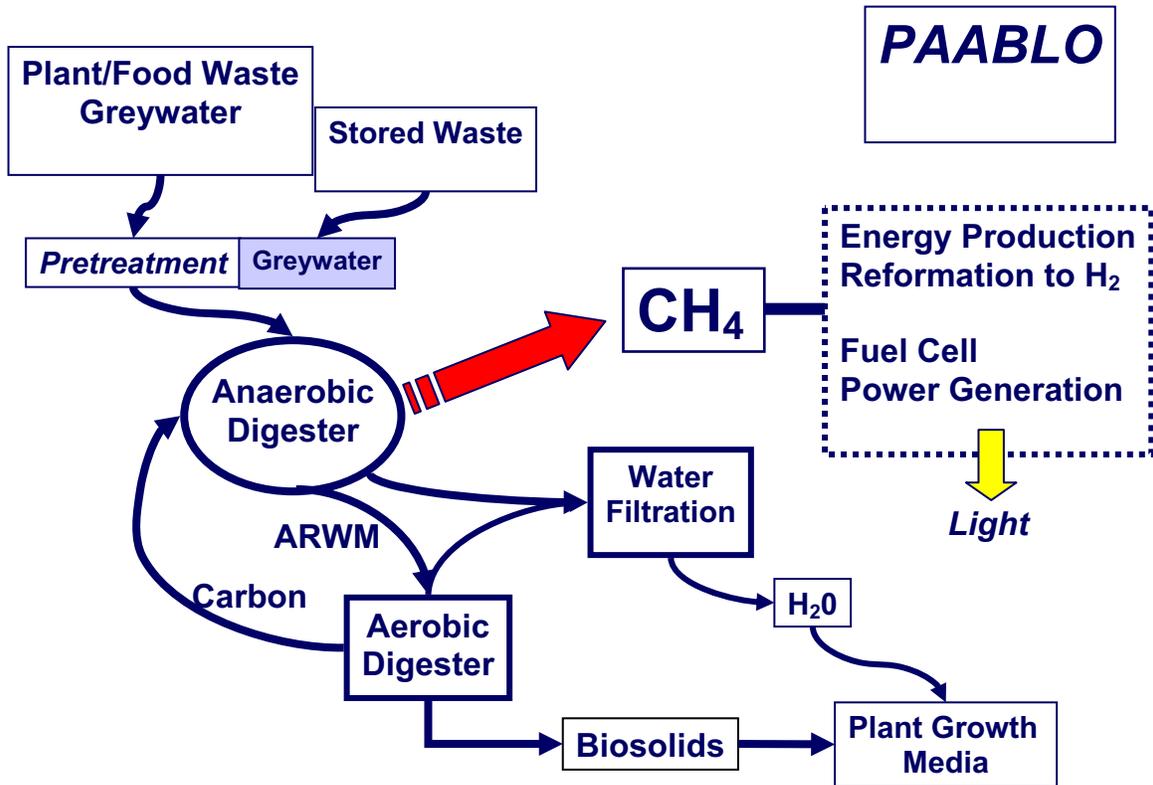


Figure 1. Conceptual design of the Plant-based Anaerobic-aerobic Bioreactor Linked Operation PABLO system; ARWM: anaerobically recalcitrant waste materials.

In both the space based and Earth-based systems the starting point will be waste materials. The major difference is in the space-based system we will be dealing primarily with dried residues that will be rewetted with greywater. In the earth-based system, the residues will be wet or dry. Outputs from the system will include: CH₄, CO₂ and solids. In this system, the residuals will be treated with an aerobic process to and returned to the anaerobic system. The residuals that settle in the system will be removed and land applied (earth) or used in confined growth systems (Mars).

The project is divided into three tasks:

Task 1. The objective is use a anaerobic-aerobic bioreactor system to optimize production of methane from plant-based waste materials and for the recovery of high-quality biosolids.

Task 2. Methods for the optimization of the PABLO biosolids for use in fungal and plant cultivation will be investigated. This will require an evaluation of the makeup the aerobic

reactor's microbial population to maximize the formation of soluble carbon for use in the anaerobic portion of PABLO.

Task 3. The objective is use a bioreactor system to optimize production of methane from human waste materials and to provide a means of drying and storing the material.

Progress to date:

Work has been concentrated on establishing testing protocols for different waster materials. We are using a simple (Figure 2) digester system to evaluate gas production. This has allowed us to begin to evaluate plant materials in single entries or combination applications.

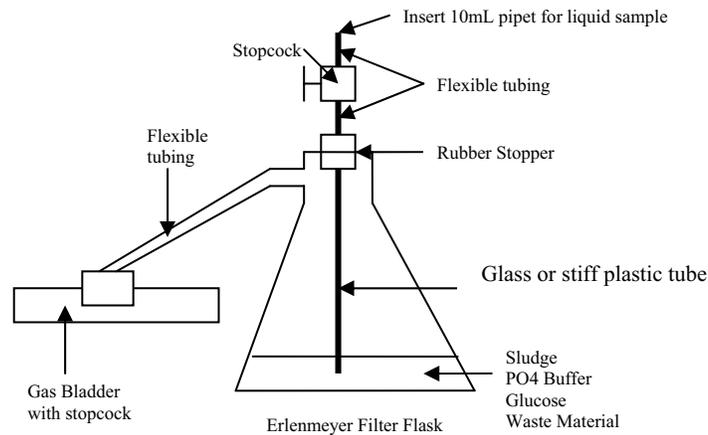


Figure 2. Initial design of the bench scale Anaerobic Bioreactor.

Our data suggests (Figure 3) that a variety of plant materials are capable of being used to produce CH_4 . Of note is the finding that some materials produce a lot less gas than others and this should factor into the discussion making process that goes into meal selection for space flight. For example, carrots are surpassed by vines from sweet potato and a combination of tomato and spinach materials. We are now concentrated on addressing gas production from plant residual materials as these will be in abundance at the space-base but we are also considering plant/fruit waste as this will be available on earth.

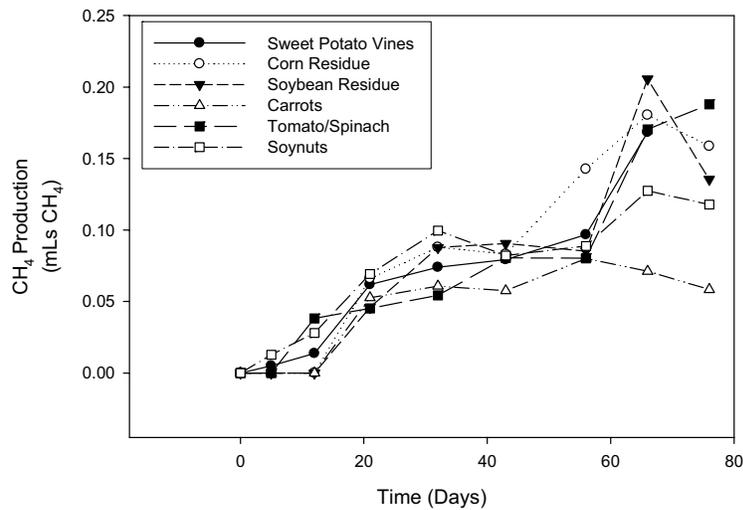


Figure 3. Methane production from a variety of waste materials assessed using our bench scale reactor.

Ongoing work is assessing combinations of fruit and vine waste residues so that we can provide input towards meal planning and cropping sequences. That is, given a choice of two foods stuffs to grow, our input will provide information as to the one that will provide the best level of energy production as a waste material. We are also looking at reactor design. The contribution has important impacts to the space program as well as to Earth applications. For example, which combinations of materials will provide the most significant level of gas production? This has been largely overlooked as a contributor to the success of bioenergy programs. We are also looking at biological approaches to converting CH₄ to methanol. The advantage is that methanol can be easily stored and can be used directly in fuel cells. While this will have applications in space, our major program is aimed at earth applications.