HIGH SOLIDS LEACHBEAD ANAEROBIC DIGESTION FOR THE REDUCTION AND STABILIZATION OF ORGANIC WASTE GENERATED FROM AN EXPLORATORY SPACE MISSION

By

PATRICK EDWARD HALEY

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSIT OF FLORIDA IN PARTIAL FULFILMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING

UNIVERSITY OF FLORIDA

2005

To my sweet wife, forever encouraging and supportive.

ACKNOWLEDGMENTS

I thank the following individuals for their help in the daily research, data collection, and friendship: Amy Dedrick, Sandy Chicowitz, Becky Reide, and Melissa Baum-Haley. I would also like to thank my graduate committee members (Dr. Art Texiera, Dr. Timothy Townsend, and Dr. Roger Nordstedt) for guidance, patience, and encouragement. I would like to give a very special thank-you to Dr. David Chynoweth for his work in being a mentor, guide, and friend on this endeavor. Lastly, I would like to thank Dr. John Owens for his overall guidance, encouragement, and friendship. This research was supported by a grant from the NASA/UF Environmental Systems Commercial Space Technology Center.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure page

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering

HIGH SOLIDS LEACHBEAD ANAEROBIC DIGESTION FOR THE REDUCTION AND STABILIZATION OF ORGANIC WASTE GENERATED FROM AN EXPLORATORY SPACE MISSION

By

Patrick Edward Haley

December 2005

Chair: Arthur Teixeira
Major Department: Agricultural and Biological Engineering

The National Aeronautical and Space Administration (NASA) solidified its goal of a long-duration human space exploration as a reality in the near future. Long-duration space missions will require a crew to go beyond Earth's orbit for an extended number of years, including planetary missions to Mars' surface. In a confined environment away from Earth's surface, regeneration of natural resources including air, water, and nutrients is essential for the crew to survive. NASA is currently funding research for a variety of solid waste resource recovery technologies that may provide useful alternatives to the current method of waste storage. One of the biological technologies being tested is a type of anaerobic digestion named high-solids leachbed anaerobic digestion. This technology combines leachate recycle with solid phase fermentation for the treatment of wastes. This process is able to inoculate new batches quickly, remove volatile organic acids that cause inhibition, and concentrate nutrients and buffer. This high solids sequential batch

anaerobic composting process enables anaerobic bacteria to convert organic wastes into methane, carbon dioxide, and compost over a period of 3 weeks.

The ability of different biological materials was tested to degrade into methane gas. This number related directly for the potential of that material to reduce in mass during the process. Based on the final methane yields of the feedstocks tested, the highest conversion was observed for inedible biomass from peanut, rice and radish and the lowest for inedible biomass from wheat, lettuce, and tomato. A laboratory digester was designed, constructed, and modified to test the effectiveness of the process. The reduction in organic matter was 70% and 77%, respectively for the first two runs. Run 3 was conducted with a blend of feedstocks, which included rice residue, shredded paper, and dog food at particle sizes representative of that anticipated in a mission-scale system. These feedstocks simulate the types of materials (crop residue, paper, and feces) expected during a space mission. Performance of this run exceeded that of the previous runs, with a final reduction in organic matter of 85%.

From this information a prototype digester was designed and constructed with; startup and two shakedown runs were conducted using a feedstock blend consisting of rice residue, paper, and dog food. Runs 2 had a final organic biomass reduction of 77%. Run 3 had a final organic biomass reduction of 85%. Research presented here supports the use of high-solids leachbed anaerobic digestion for bioregenerative reduction and stabilization of the organic components of solid wastes during extended planetary space missions.

CHAPTER 1
INTRODUCTION

The National Aeronautical and Space Administration (NASA) solidified its goal of a long-duration human space exploration as a reality in the near future. Long-duration space missions will require a crew to go beyond Earth's orbit for an extended number of years, including planetary missions to Mars' surface. Because of the inability to return to Earth quickly, human exploration missions of long duration will require the recovery of critical life support resources. In a confined environment away from Earth's surface, regeneration of natural resources including air, water, and nutrients are essential for the crew to survive. Careful attention must be paid to how astronauts handle air, water, and solid waste to maximize the resource recovery effort. NASA is currently funding research for a variety of solid waste resource recovery technologies that may provide useful alternatives to the current method of waste storage. These technologies include both physicochemical and biological treatment options. One of the biological technologies being tested is a type of anaerobic digestion named high-solids leachbed anaerobic digestion.

High-solids leachbed anaerobic digestion is a multiple step process involving a consortium of anaerobic microorganisms. The process is capable of reducing the waste volume and weight, stabilizing, and recovering inorganic nutrients, compost, carbon dioxide, and methane gas from biodegradable waste fractions. This process has the advantages of not requiring oxygen for degradation of solid waste, the ability to be

wetted and compacted, and potential integration into the wastewater and air treatment processes.

Under a recent contract with the NASA supported University of Florida Environmental Systems Commercial Space Technology Center (UF/ESCSTC) entitled "Anaerobic Composting Systems for Space Missions" the feasibility of high-solids leachbed anaerobic digestion as a waste treatment option was tested. Previous work using the sequential batch anaerobic composting system (SEBAC) as a biological waste treatment option has shown effectiveness in terrestrial environments. The purpose of this thesis project was to develop and evaluate high-solids leachbed anaerobic digestion for management and resource recovery from solid wastes associated with an exploratory mission to Mars' surface. This developmental information can then be used to design, construct, and operate a prototype high-solids leachbed anaerobic digestion system capable of operating under altered gravity conditions envisioned for the space mission.

The goal of this thesis project was to test high-solids flooded leachbed anaerobic digestion as a possible solution for management and resource recovery of solid wastes generated during an extended exploratory space mission. The specific objectives of the study were defined. Perform biodegradability assays on feedstocks appropriate for long duration space missions. Modify an existing lab-scale high-solids flooded leachbed anaerobic digestion system and perform feasibility trials on feedstock samples. Assist in the design and oversee the construction of a prototype high solids leachbed anaerobic digestion system for solid waste reduction and resource recovery from typical solid wastes generated during a long duration mission. Perform trial runs on the prototype reactor system including initial start-up, troubleshooting, and normal operation.

CHAPTER 2
LITERATURE REVIEW

The following chapter contains background information helpful to the understanding of the processes in science utilized for this research.

Advanced Life Support for Space Missions

As NASA scientists advance the study of space exploration, long duration missions involving the establishment of permanent lunar surface bases or exploration of Mars' surface will become a reality. No matter whether the mission is short term, such as a trip to the international space station or long term, setting up a colony on Mars surface, astronauts will continue to need food, water, and air free of harmful pathogens or contaminants. Because of the great expense and time requirements to send cargo ships to Mars surface, it may not be economical or practical to resupply basic life support elements from Earth (Advanced Life Support Project Plan, 2002). Therefore, it is necessary for NASA and the space community to develop systems that produce food, purify the water supply, regenerate oxygen, and remove undesirable components from the air (Advanced Life Support Project Plan, 2002). The only limiting factor is that without the resupply missions, astronauts are sent with a defined number of life support resources. In order for the astronauts to survive, these resources must be regenerated continuously in a safe, healthy, and reliable manner. The regeneration of these valuable resources without the need for external resupply is referred to as "closing the loop."

Advanced Life Support is the approach taken for keeping the environment suitable for astronauts to maintain a healthy life while under the constraints of a space exploration

mission. Research on human life support began in the 1950's with oxygen regeneration using algae. In the late 1970's, NASA's interest in life support systems became more focused in order to support long-term space missions. Since that time, the Advanced Life Support Program at NASA has researched growing plants for food and oxygen regeneration, and the use of physico-chemical and biological methods to process waste into usable resources (Advanced Life Support Project Plan, 2002). For long-duration space missions, both inside and outside of low Earth orbit, life support systems will require not only a high degree of closure of the oxygen and water regeneration loops, but they must also begin to close the food loop. Closure is driven by high costs associated with the launch and storage of consumables. For lunar or planetary bases, greater autonomy of the life support system will also reduce the dependency on resupply missions, thereby increasing safety and reducing cost (Advanced Life Support Requirements Document 2002).

Currently, there are two primary objectives of the Advanced Life Support Project, with corresponding supporting objectives (NASA, 2002), are to (Advanced Life Support Requirements Document, 2002). The first is to provide Advanced Life Support technologies that significantly reduce life cycle costs, improve operational performance, promote self-sufficiency, and minimize expenditure of resources for long-duration missions (Advanced Life Support Requirements Document, 2002). To meet this objective scientists are focusing all efforts to the following points. Fully closing the air and water loops in a manner that eliminates expendables. Developing and integrating resource recycling/processing and contaminant control systems that will increase the level of self-sufficiency. Optimize the food closure loop, with associated air and water revitalization,

based on the growth of crop plants or other photosynthetic organisms. Provide efficient, reliable active thermal control including heat acquisition, transport, and rejection. Develop technology with fully regenerative integrated systems that provide air, water, food, and resource recovery from wastes.

The second primary objective of the Advanced Life Support Project is to resolve issues of microgravity performance through space flight research and evaluation. To meet this objective NASA scientists are focusing efforts on the following. Develop predictive models of liquid and liquid/gas behavior and interactions in microgravity environments that can be used as a basis for design of new life support hardware for microgravity applications. Achieving equivalent productivity, control and predictability of bioregenerative life support components in microgravity as on Earth and characterize performance of bioregenerative systems at Lunar and Martian gravity (i.e., 1/6g and 1/3g, respectively). Demonstrate microgravity performance of gravity-sensitive life support hardware components and subsystems (e.g., membrane behavior, microbe performance, crop nutrient delivery systems).

By contrast with past and current spacecraft life-support systems, advanced life support systems will include food production, and will utilize biological processes in addition to physicochemical processes for mission success (Advanced Life Support Requirements Document, 2002). An example of an advanced life support system would be a tightly controlled and closed loop system in which the growth of crop plants would contribute to the life support functions. The natural function of plants would provide food and contribute to water purification, air revitalization and even the processing of waste

materials. All systems would have to operate under the restrictions of minimizing volume, mass, energy, and labor (Advanced Life Support Project Plan, 2002).

The selection of an effective system for advanced life support equipment will depend on the space mission destination. Therefore, it is important that time be taken to explain the different scenarios of proposed space missions to Mars. These reference missions were developed from the data in the drat Reference Mission's document (Verostko, 2001). This document breaks the types of missions down into five scenarios. Mission duration will be a determining factor in resource recovery requirements.

Mars Mission Scenarios

Human missions to the surface of Mars may vary widely in their protocols and constraints depending on the primary mission objectives. In some situations, careful preservation of the Martian surface may be vital to mission success, while in other cases the rules of exploration may be more lenient. Such protocols affect how the life support system provides commodities to the crew. Such protocols are unique to each mission and will likely not be specified until an actual flight program is formulated. Generally, however, from the perspective of life support, the Martian surface environment differs significantly from other locales. Thermally, the Martian surface is again fairly benign and rejection of heat loads from the crew cabin should not be problematic (Ewert et al., 1999). Dust storms may provide a unique challenge, but at present they are not expected to invalidate traditional radiant heat rejection approaches. The radiation environment is currently unknown. It is likely more severe than on Earth, but the crew may not be as vulnerable on the Martian surface as in interplanetary space (Mendell et al., 1999). Mars also provides a gravitational field that is roughly three eighths as strong as that of Earth. While some physical and chemical processes exhibit significant differences under such

low gravity, other processes are relatively unaffected. Finally, the Martian surface may offer resources in its atmosphere and surface soil that are completely unavailable in interplanetary space depending on the landing site and mission protocols (Advanced Life Support System Integration, Modeling, Analysis Reference Document, 2001).

For the independent exploration mission, the Mars Dual Lander architecture employs three vehicles: a Mars Transit Vehicle, a Surface Habitat Lander, and a Mars Descent/Ascent Lander (Drake, 1999). This approach proposes employing a common descent stage for both the Surface Habitat Lander and the Mars Descent/Ascent Lander. Therefore, the Surface Habitat Lander and the Mars Descent/Ascent Lander are referred to as the Dual Landers. A single Mars Transit Vehicle is used for the outbound and return trips. The Surface Habitat Lander, which contains an inflatable structure to provide an expanded habitable volume once on the Martian surface, provides the crew's habitat quarters. The Surface Habitat Lander is piloted robotically during the trip from Earth to the Martian surface. A second lander, the Mars Descent/Ascent vehicle, transports the six crewmembers from Martian orbit to the surface at the beginning of the surface mission phase, and returns the crew to the orbiting Mars Transit Vehicle at the conclusion of the surface phase. Since surface site selection is independent of any previous or following missions, multiple trips to Mars will allow explorers to visit any site, targeting exploration opportunities to satisfy demands for scientific information. This overall mission design also permits multiple visits to the same site where redundancy or common use of previous vehicles in whole or in part can reduce the overall cost of multiple missions (Advanced Life Support Baseline Values and Assumptions, 2002).

The Mars Transit Vehicle launches initially into low Earth orbit. After outfitting, the Mars Transit Vehicle boosts to high Earth orbit to await transfer of the crew. Similarly, the Surface Habitat and Mars Descent/Ascent Landers initially launch into low Earth orbit before boosting to a high Earth orbit. In both cases, the Mars Transit Vehicle and the Dual Landers use energy efficient electrical propulsion and lengthy transfer orbits to reach high Earth orbit. All three vehicles are serviced for the voyage to Mars and the crew is delivered to the Mars Transit Vehicle by a taxi flight just before departure. The voyage to Mars will nominally take 180 days for the crew. The Dual Landers, because they transfer to Mars under robotic control, follow a somewhat slower yet more energy efficient transfer orbit than the Mars Transfer Vehicle, so they depart from Earth ahead of the crew so as to arrive at Mars just before the crew. The Mars Transit Vehicle and the Dual Landers all enter into a low Mars orbit through aerocapture and then rendezvous (Advanced Life Support Baseline Values and Assumptions, 2002).

Once they arrive in low Martian orbit, the crew transfers to the Mars Descent/Ascent Vehicle and descend to the Martian surface. At this time, the Surface Habitat Lander is already in place on the Martian surface. The Surface Habitat Lander deploys automatically, checks and verifies its functionality, and adopts a protected mode prior to crew arrival. Upon arrival, the crew has 30 days for acclimation and an in-depth habitat checkout. The crew need not commit to landing until the Surface Habitat Lander is operational. During the surface mission, nominally 600 days, the Mars Transit Vehicle awaits in stand-by mode untended in low Mars orbit, while the Mars Descent/Ascent Lander waits in stand-by mode on the Martian surface. After a second rendezvous in Mars orbit following the surface mission, the crew transfers to the Mars Transit Vehicle

and returns to Earth. The return interplanetary voyage nominally requires 180 days (Advanced Life Support Baseline Values and Assumptions, 2002).

The concentrated exploration mission assumes a stay on Mars surface for approximately 600 days per mission. This mission promotes the build up of infrastructure and utilizes one growth chamber to grow food in situ (Maxwell and Drysdale, 2001). This mission will last approximately 600 days on Mar's surface. Instead of relying solely on a salad crops for a regenerative food source, astronauts will have one growth chamber for food. This chamber would be responsible for growing the primary diet crops of the astronauts.

Table 2-1. Estimates of daily solid waste streams for a 6-person crew during a 600-day exploratory mission

Waste Component	Dry Wt., Kg	Ash, % dw*	Organic Matter, kg	Moisture, %	Percent of total
Dry human waste	0.72	5	0.68	85	9.4
Inedible plant biomass	5.45	5	5.2	75	51.4
Trash	0.56	5	0.53	10	5.3
Packaging materials	2.02	5		10	19.0
Paper	1.16	5	1.1	10	10.9
Tape	0.25				2.4
Filters	0.33				3.1
Remaing miscellaneuos	0.07				0.7
Total	10.6		7.5		100

(Verostko et al., 2001)

Solid Waste Management Options for Space Missions

NASA has determined that long-duration human space missions will require the recovery of critical life support resources. Resupply missions for long-term exploratory or planetary missions may not be cost effective and may jeopardize the well being of the

crew. Therefore, NASA is exploring different waste treatment options for reducing wastes and conserving valuable resources. Table 2-1 illustrates the waste stream of a six person crew during a 600 day mission on Mars surface. The two main categories of technologies NASA is exploring include physicochemical and biological treatment options

Physiochemical Treatment Options

Physicochemical processes can rapidly convert waste to products without the use of biological organisms. These processes can also produce useful products including CO_2, water, inorganic nutrients, activated carbon, fuels, organic chemicals, solvents, and paper. Some of the physiochemical options of waste treatment include incineration, electrochemical oxidation, pyrolysis, and gasification (Verostko et al., 2001).

Incineration is the analytical procedure of heating a substance with free access to air until only its ash remains. Incineration is capable of completely converting all the waste to carbon dioxide, water, and inorganic ash. This process handles all organic waste and most of the inorganic waste expect metal and glass (Fisher et al., 1998). Incineration is proven to provide high conversion of waste in many commercial applications in a short amount of time. Incineration at high temperatures also destroys many of the toxics and pathogens in biological and other potentially hazardous human wastes. Resistance to incineration has focoused on the hazardous emissions, such as dioxins (polychlorinated dibenzodioxins) and furans (polychlorinated dibenzofurans), which can be produced by the incomplete combustion of compounds containing chlorine, including many common plastics. In order to prevent toxic emissions such as metals, inorganic acid gases and particulate matter, systems are equipped with air pollution control devices. Such devices include scrubbers, fabric filters (bag houses) and electromagnetic precipitators (Diemer et

al., 1996). In a manned space mission the drawbacks of incineration include having to clean up gas contaminants in a closed environment, requirements for the process to operate at high temperatures in order to effectively destroy biological pathogens, and high oxygen consumption required to complete waste reduction (Verostko et al., 2001).

Electrochemical oxidation oxidizes liquid organic material at low temperatures with electrochemical cells (Tennakoon et al. 1995). Waste is first reduced to a slurry form with a particle size of less than 100 microns in diameter. The waste is then oxidized, in a heterogeneous reaction, when it comes into contact with a positive electrode made of platinum or lead dioxide (Rajeshwar and Ibanez, 1997). Organic wastes are broken down at the interface between the electrode surface and the electrolytic solution with or without the addition of redox mediators. A corresponding reduction reaction takes place at the negative electrode where usually hydrogen is formed. The technology is capable of being scaled down easily and is commercially proven to work (Tatapudi and Fenton, 1995). The low temperature, ambient pressure process produces gaseous emissions that require reduced clean-up and does not generate NOx, SOx, or CO gas. The problems with the process involve the preprocessing of the waste, which requires particles to be 100 microns in size (Kaba et al. 1989).

Pyrolysis breaks down wastes by heating them to high temperatures without oxygen addition. Pyrolysis typically produces char, hydrocarbon liquids, and hydrocarbon gas. The process produces many useful products from all waste except glass and metals (Verostko et al., 2001). Unfortunately, the process is very complex, produces CO gas, and has to operate at high temperatures.

Gasification is a process that converts any carbon-containing material into a synthetic gas. This synthetic gas "syngas" produces CO and hydrogen with smaller amounts of CO_2, NO_x, SO_2, and CH_4 that can be used as a fuel to generate electricity (Verostko et al., 2001). Unfortunately, the process is very complex, has to operate at a high temperature, and has a low technology readiness level.

Biological Treatment Options

Biological treatment is a common approach to handling biodegradable wastes such as residues from plant and animal systems. Both aerobic and anaerobic treatment processes have been used in the treatment of sewage sludge, industrial effluents, and municipal solid waste. These processes handle highly variable biodegradable waste streams, requiring minimal preprocessing. Considerations for these technologies include temperature, moisture content, oxygen dependence, volatile solids, carbon, nitrogen, pH, and particle size.

Composting is the accelerated biological decomposition of organic materials in a predominantly aerobic environment (Haug, 1993). The process involves the breakdown of organic materials to stable, unusable organic substrates by bacteria, fungi, and other microorganisms. The organisms involved consume oxygen and release heat, water, and CO_2. After decomposition the remaining compost can be used as a soil conditioner, organic fertilizer, or a food base for microorganisms for disease control (Hoitink and Keener, 1993). Aerobic composting is able to operate in a batch or continuous mode at near ambient temperature and pressure. Although it effectively destroys human and plant pathogens, the process requires a large reactor volume and produces a large amount of residue and gases including VOCs, NH_3, NO_x, and CH_4 (Verostko et al., 2001).

The Continuously Stirred Tank Reactor uses a biological suspension of aerobic heterotrophic microorganisms (bacteria, fungi, and microfauna such as ciliates, amoebae, and flagellates, rotifers, nematodes) to degrade soluble and particulate organic materials (Edeen et al., 1995). This technology has already been proven to work in advanced life support systems at various scales. The process is easily controlled and operates at a low temperature and power requirements. Possible problems associated with the technology include incomplete carbon degradation, requiring a large reactor volume, and solid/liquid separation at post-harvest (Verostko et al., 2001).

High solids anaerobic digestion (HSLAD). The biological treatment option, which is the concern of this research project, is a technique of high solids leachbed anaerobic digestion developed at the University of Florida. This technology combines leachate recycle with solid phase fermentation for the treatment of wastes. This process is able to inoculate new batches quickly, remove volatile organic acids that cause inhibition, and concentrate nutrients and buffer. This high solids sequential batch anaerobic composting process enables a consortium of anaerobic bacteria to convert organic wastes into methane, carbon dioxide, and compost over a period of 3 weeks. The process does not require mixing or oxygen and has been shown to remain stable without feedstock addition. Furthermore, the process can be operated at low pressure, which can reduce the need for massive high-pressure vessels.

The advantages of HSLAD include dry biodegradable waste added to the system with minimal pretreatment while producing methane and compost and conserves nutrients. This treatment option does not require oxygen, has low energy requirements, operates at low temperatures and pressures, sanitizes waste, and produces minimal

microbial biomass. Additionally, it is a proven technology with simple design and ease of operation. The disadvantages of HSLAD are include the long resistance time and that it is limited to feed batch operation with design modification. Also, the conversion is limited based on type of feedstock and the effluent solids may require storage or further treatment if not used as compost.

Sequential batch anaerobic composting technology (SEBAC). SEBAC is a patented technology that was developed at the University of Florida under the guidance of Dr. David Chynoweth. This method of anaerobic digestion has proven effective in terrestrial applications. SEBAC is an anaerobic sequential batch digestion leach bed designed to overcome inoculation, mixing and instability problems common of anaerobic reactor designs. A liquid recycle method is used to provide water, nutrients and bacteria to the fresh feedstock. Fermentation products such as volatile acids formed during start-up are removed via the liquid handling system to a mature bioreactor where they are converted to methane. In doing so, the instability is eliminated as is the need for mixing feed and effluent. This process has achieved bioconversion of biodegradable organics in less than 30 days.

The SEBAC process is a net producer of energy and soil conditioner. In the process anaerobic digestion occurs sequentially in three reactors. Initially, biodegradable waste is loaded into the reactor. This reactor is termed a new reactor and its recycling of leachate comes from the mature reactor. The mature reactor has a well-established consortium of anaerobic bacteria including methanogens. These mature organisms are capable of reducing the volatile organic acids (VOAs) produced by the hydrolysis of waste in the new reactor. The VOAs are transferred from the new reactor to the mature

reactor via the recycling leachate. Furthermore, the mature reactor transfers some of its established organisms into the bed of the new reactor, again via the leachate recycle. After the new reactor has started up successfully, usually in seven days, the new reactor becomes an activated reactor and the flow of leachate is recycled onto itself. This activated stage also occurs for seven days. The reactor becomes a mature reactor after the activated stage is completed and the anaerobic digestion process is ready to start-up another new reactor. The end products of the process include a usable biogas and a soil conditioner rich with nutrients. The biogas contains approximately 60% methane and can be used for heating or power generation. The soil conditioner contains stabile organic material and can be used as potting soil or a soil additive for improved plant growth.

Anaerobic Digestion. Anaerobic digestion, or biomethanogenesis, is a controlled process of microbial degradation that occurs in the absence of oxygen. The process involves a consortium of anaerobic bacteria that convert organic matter into methane, carbon dioxide, inorganic nutrients, and humus. Anaerobic digestion utilizes a consortium of microorganisms, including protozoa, fungi, and bacteria to decompose organic matter using carbon dioxide as the methyl group of acetate as electron acceptors in the absence of oxygen. The microorganisms perform the overall process in a sequential manner that ultimately produces methane and carbon dioxide as terminal products (Chynoweth, 1995). Methane is formed from two primary substrates, acetate and formate (Chynoweth and Pullammanappallil, 1996). In the absence of methanogens, microorganisms that produce methane, to utilize the volatile acids, hydrogen and free electrons build-up. This build-up retards the overall degradative process by the accumulation of volatile organic acids causing a decrease in pH which inhibits growth

and stops fermentation. The overall role of anaerobic digestion in the biosphere is to complete the degradation process by removal of inhibitory fermentation products (Chynoweth and Pullammanappallil, 1996).

Anaerobic digestion is the overall anaerobic biological process that involves several general pathways the decompose lignocellulose and other organic complexes and compounds to methane and carbon dioxide. Several species of microorganisms are involved in the overall reactions, which include depolymerization, intermediate reactions, and methanogenesis (Zinder, 1993).

The first step for the anaerobic digestion of organic wastes is the depolymerization of polymeric (macromolecular) solid substrates into smaller molecules. Often this step is referred to as hydrolysis, but hydrolysis is only one of the man routes of depolymerization (Chynoweth and Pullammanappallil, 1996). Depolymerization is mediated by extracellular enzymes; the most common are either hydrolases or lysases. Depending on the bond catalyzed these hydrolyases can be esterases (enzymes that hydrolyze ester bonds), glycosidases (enzymes that hydrolzye glycosidic bonds) or peptases (enzymes that hydrolyze peptide bonds). The products of depolymerization are soluble smaller molecules. The degradable polymeric substances found in solid wastes include lignocellulosics, proteins, lipids, and starch.

Organisms that convert fermentation products, such as volatile organic acids (propionate, butyrate, lactate) generally exhibit obligate proton-reducing metabolism producing dihydrogen as a fermentation product. This reaction is dependent on hydrogen removal by methanogenic or other hydrogen-using bacteria. This mechanism is commonly referred to as inter-species hydrogen transfer (Zinder, 1993). The reactions

that produce dihydrogen as a fermentation product are referred to as the intermediate reactions, and are dependent on methanogens to remove the inhibitory excess hydrogen produced.

Methanogenic bacteria are such a unique group of organisms that they have been placed into a new evolutionary domain (separate from eukaryotic plants and animals and prokaryotic bacteria) referred to as archaea (Woese et al., 1990) formerly known as archaebacteria (Woese, 1987). Methanogenesis is the process performed by methanogenic bacteria in which a substrate is reduced to methane gas. Methanogenic substrates include acetate, methanol, dihydrogen/carbon dioxide, formate, carbon monoxide, methylamines, methyl mercapants, and reduced metals (Chynoweth and Pullammanappallil, 1996). Methane production from acetate, formate, and dihydrogen/carbon dioxide are the most important reactions in nature allowing for the degradation of organics without inhibition from acid build-up.

The methanogenic consortium of bacteria may play a role in the metabolism of halogenated compounds by affecting the critical dehalogenation step (Zinder, 1993). These compounds are of major significance in solid waste and the residual leachate streams (Pohland et al., 1993; Suidan et al., 1993; Christensen, 1992). The principle mechanism of anaerobic dehalogenation is reductive dehalogenation which is equivalent to the addition of dihydrogen across the carbon-hydrogen bond (Chynoweth and Pullammanappallil, 1996). This reaction is favorable and could serve as a source of energy for growth (Zinder, 1993).

CHAPTER 3
MATERIALS AND METHODS

The scope of work for this thesis project was divided into five phases. Determination of the biodegradability of feedstocks appropriate for long duration space missions through Biochemical Methane Potential (BMP) assays. Development and implementation of design modifications to an existing lab-scale high-solids leachbed anaerobic digestion system. Development and execution of experiments to evaluate the performance of the high-solids leachbed anaerobic digestion system on selected blends of feedstock. Development and implementation of the design and construction of a prototype high-solids leachbed anaerobic digestion system for solid waste reduction and resource recovery from typical solid wastes generated during a long duration space mission. Finally, development and execution of experiments to evaluate the performance of the prototype reactor system including initial start-up, troubleshooting, and normal operation.

Phase 1: Biodegradability Determination

The biochemical methane potential (BMP) assay was developed to determine the ultimate biodegradability through the methane yield of an organic material during its anaerobic decomposition by a mixed microbial flora of methanogens in a defined medium (Chynoweth and Owens, 2000). This assay provided a simple means to monitor relative biodegradability of substrates. The defined medium, in which the substrate was placed, has all the components ideal for anaerobic digestion to occur, including a broad spectrum of anaerobic bacteria, excess inoculum, excess nutrients, substrate

concentration below inhibitory levels, excess buffering capacity, moderate temperature, and strict anaerobic conditions (Chynoweth et. al., 2002). Because this test was performed under ideal anaerobic conditions, the result of this test will predict the maximum degradation that can occur during the anaerobic digestion of the feedstock.

Selection of Feedstocks

Feedstocks for the BMP testing were selected based on recent publications in the NASA community (Drysdale et al., 2001; Wheeler, 2001). These articles identified crops that astronauts would be capable of growing in an altered gravitational environment (gravity either greater than or less than that of Earth's surface). The crops that the astronauts would be consuming are predicted to be grown in a hydroponics system. Therefore, it was to our benefit to select samples also grown in a hydroponics system. The samples tested were not the actual fruit of the crop (i.e. the whole potato) but the processing wastes that the astronauts would generate in eating the crop. For example, the wastes tested would be the portion of the plant that was not consumed by the astronaut. The following feedstocks were selected for BMP assay and subsequent reactor runs:

- Space vehicle: Tomato, Carrot, Cabbage, Spinach, Chard, Lettuce, Radish, Onion
- Planetary: Wheat, White Potato, Sweet Potato, Rice, Peanuts
- Paper: High grade office paper
- Human feces: Simulated with dog food

Description of Feedstock Categories

Space vehicle crops would be grown in transit or on a planetary surface. These crops are the salad crops and have a less complex root structure than the other categories of crops. This root structure easily lends these crops to be grown in a hydroponics system.

The planetary crops are the crops that would be grown on a planetary surface, i.e. Mars' surface. These crops have a more complex root structure and require a higher demand of nutrients to grow. Astronauts may grow these crops in a hydroponics system or the traditional terrestrial soil method. Soil growth becomes a viable option for growing planetary crops due to the presence of some form of gravity and a larger working area on a planet's surface.

The remaining categories (paper products and human feces) constitute the other portions of biodegradable waste streams to enter the anaerobic digestion system. Paper products will be used for packaging supplies, writing surfaces, and the towelettes and sanitary wipes used for personal hygiene by the crew. The human feces portion will be generated by the consumption of the edible parts of the crops grown.

Several of the feedstocks were provided to this project from the various NASA centers and researchers affiliated with NASA's biological life support systems as well as a University of Florida researcher. These crops were all hydroponically grown. Remaining crops were obtained through the University of Florida Agronomy Department and local grocery (Table 3-1).

Testing Procedure

Feedstock Preparation

A portion of each sample was dried at 105ºC in a drying oven for 24 hours. The sample was then milled using a Waring commercial blender to reduce the particle size to the millimeter range. After the particle size was reduced, the total solids (TS) of each feedstock was determined by drying for 24 hours at 105ºC. Volatile solids for each feedstock was determined by ashing the dry sample for two hours at 550ºC and determining the ash free weight.

Table 3-1. Feedstocks received from contacts

Feedstock	Description	Contact Person
Wheat	hydroponically grown	Keith Henderson, JSC
Tomato	field grown	Agronomy Department, UF
Peanut	hydroponically grown	Desmond Mortley, Tuskegee
Potato	hydroponically grown	Neil Yurio, Dynamak, KSC
Sweet Potato	hydroponically grown	Desmond Mortley, Tuskegee
Rice-Italica	temperate Japonica dwarf-med. Italica	Hartwell Allen, UF
Rice-Koshi	temperate Japonica dwarf Koshi	Hartwell Allen, UF
Rice-K204	tropical Japonica dwarf L204	Hartwell Allen, UF
Rice-Labelle	tropical Japonica tall Labelle	Hartwell Allen, UF
Rice-M103	temperate Japonica dwarf M103	Hartwell Allen, UF
Rice-M202	temperate Japonica dwarf M202	Hartwell Allen, UF
Rice-N22	tropical Indica tall N22	Hartwell Allen, UF
Rice-S102	terperate Japonica dwarf S102	Hartwell Allen, UF
Cabbage	whole fruit waste (grocery)	N/A
Carrot	whole fruit waste (grocery)	N/A
Lettuce	whole fruit waste (grocery)	N/A
Onion	whole fruit waste (grocery)	N/A
Radish	whole fruit waste (grocery)	N/A
Red Chard	whole fruit waste (grocery)	N/A
Tomato	whole fruit waste (grocery)	N/A

Media Preparation

The Biochemical Methane Potential procedures employed were developed from the anaerobic Warburg test combined with serum-bottle techniques by Owen et al. (1979). Modifications to these procedures are also outlined in ASTM (1992) and examples of results can be found in Owens and Chynoweth (1993).

The solutions used to make the anaerobic media each possess a specific function for the overall success of creating an ideal anaerobic environment. Stock solution (S-1) containing resazurin, a redox indicator, assures the media is in the reduced state and turns the media pink when oxygen is present (Chynoweth and Owens, 2000). Stock solution (S-2) contains macronutrients that assure nitrogen, phosphorus and potassium are not limiting. Stock solution (S-3) contains micronutrients that assure appropriate trace metals

are available in the final media. Previously, (Owen et al., 1979) the micronutrient solution lacked a source for nickel but studies showing the importance of nickel in methanogen metabolism resulted in its addition to the defined media (Chynoweth and Owens, 2000). Also, the original protocol by Owen et al.(1979) included a stock solution containing vitamins and cofactors which have been eliminated from the protocol since the inoculum seems to provide adequate amounts of these compounds. Sodium sulfide solution, a reducing agent, is included in another stock solution (S-4) and serves to remove any remaining available oxygen in the media after preparation. Sodium bicarbonate, the final chemical added, provides pH buffering to assure acidification of the substrate does not cause an inhibitory pH drop.

Each feedstock was tested in triplicate, where ground samples of feedstocks were anaerobically incubated, in a sealed serum bottle, with the standard media and inoculum until gas production had ceased. This process can take up to 30 days for simple substrates, such as sugars and starches, and up to 120 days for recalcitrant lignocellulosic substrates, such as cypress (Chynoweth and Owens, 2000).

Inoculum

The inoculum for the media solution was derived from a portion of a 10L inoculum digester (Figure 3-1). The 10L digester was a semi-continuous stirred vessel which was fed daily with 22 g of ground dog food (Science diet Large Canine Growth Formula, Hill Pet Nutrition, Inc.) as a feedstock. This feedstock had proven to generate reproducible results in past projects (Chynoweth et al., 2002). The digester was operated at a loading rate of 2.0 g VS per L per day and had a hydraulic retention time of 20 days. At steady state, the digester gas methane content was 57%, the methane yield was 0.33L per g VS

added, and the methane production rate was 0.53 L CH4/L reactor/day. The digester had a stable pH of approximately 7.3 and a low volatile fatty acid concentration of 155mg/L, well below inhibitory levels.

Figure 3-1. 10L inoculum digester

Control Bottles

To account for biogas production from residual degradable matter in the inoculum, triplicate sludge controls containing only media and inoculum are incubated and sampled simultaneously to allow subtraction of gas not attributed to the substrate. In addition, triplicate positive controls containing cellulose were also incubated and sampled simultaneously to assure that inoculum, media, and sampling procedures were not affecting the results (Chynoweth and Owens, 2000).

Figure 3-2. Sample bottle with media, substrate, and inoculum

Sampling

Sampling of the individual serum bottles containing the media and substrates took place over the course of the assay. When sampling the serum bottles, the excess gas produced was removed to equilibrate the bottles to atmospheric pressure. The sampled volume of gas was recorded and analyzed to determine the CH_4 and CO_2 content. Gas production was measured via a graduated syringe and methane content was determined by thermal conductivity gas chromatography. Sampling continued periodically until no further gas production could be detected (typically thirty days).

Calculations

Calculations were performed for each of the serum bottles tested. The calculations determined the volume of methane removed from each bottle for each day of sampling, the amount of methane remaining in the headspace of the bottle after each day of sampling, the total methane of each bottle, the corrected value for methane in the bottle taking into consideration volume and vapor pressure of water, the methane production rate, and the methane yield. The final methane yield was used to determine the biodegradability of a feedstock.

Phase 2: Lab Scale Equipment Modifications

The terrestrial high-solids leachbed anaerobic digestion system was dependent on gravity to move leachate through the packed reactor bed. For space applications, including altered gravitational environments, modifications were needed to overcome the dependency on gravity to recycle leachate through the reactor bed. To overcome this problem the digester system was modified to operate in a flooded mode with no headspace. Flooded operation permits the forced pumping of leachate through the reactor beds without the dependence on gravity. In this form of operation, the leachate was in

contact with the reactor bed at all times. Because the headspace of the vessel was removed for flooded operation, an external vessel with headspace for gas separation from the leachate and leachate storage was added to the system. Therefore, the leachate was pulled from the external vessel and moved through the reactor system with an external pump and transported back to the external vessel, with headspace, for gas separation.

To test the flooded operation, two reactors were required to operate in the flooded mode without headspace, and one external vessel was required for gas separation. Figure 3-3 shows a schematic of the laboratory system after modifications were made to overcome initial operational problems. The two reactors were fabricated from clear PVC pipe, 102-mm id (4-in), with an overall height of 72.9 cm; the total working volume was 5.9 L. A PVC cap was secured to the bottom of each reactor and was drilled and tapped in the center for a 3.2 mm (1/8)-in NPT fitting. The top lid of each reactor was made of a 12.7 mm thick clear Lexan blank-flange, which was drilled to accept the bolts from a glued 102 mm (4-in) PVC flange fitting attached to the pipe. The clear Lexan top was also drilled and tapped (3.2 mm NPT) for a sampling port and a biogas/leachate outlet. The top flange was connected to the base of the reactor with a Neoprene connector with stainless steel hose clamps. A steel frame supported the reactors by the top flange along with chain clamps attached to the frame. A 4-L glass aspirator bottle served as a common leachate reservoir and biogas/leachate separator (Chynoweth et. al., 2002).

The PVC reactors and glass reservoir were wrapped with 2.4 m (8-ft) of 416-watt flexible electric heating tape (Thermolyne Corporation), which was powered by a Thermolyne 45500 input control to maintain leachate temperature at 34-37^{o}C. Flexible plastic tubing was connected to 12.7 mm (½-in) barbed/NPT couplings threaded into the

top and bottom of the reactors. Leachate was pumped at around 128 mL/min using a peristaltic pump (Cole-Parmer Model 7553-30 pump with two 7018 pump heads). Schedule-80 12.7 mm (½-in) PVC ball valves allowed isolation of the reactors from the influent leachate lines. Leachate was drawn from the bottom of the reservoir into the bottom of both reactors via the peristaltic pump (Chynoweth et al., 2002).

After passing up through the solid waste beds and reactors, the leachate and biogas flowed out of the top of the reactors and into the top of the reservoir through a No. 10 black rubber stopper. Separated biogas flowed out of the top of the reservoir, through natural rubber tubing, through a check valve, to a wet tip gas meter (submerged inverted tipping bucket triggered by 110 mL of gas), which controlled the gas pressure in the reservoir at around 10 cm H_2O. Sampling points for biogas and leachate were placed using 12.7 mm (½-in) barbed T's and septums. An additional barbed-T with septum on the reactor inlet lines allowed measurement of hydraulic pressure using a Model 05-2 pressure transducer (Setra Systems, Inc.) (Chynoweth et al., 2002).

Schematic of modified laboratory high-solids anaerobic digestion system for flooded operation. (1) - 4L external vessel leachate reservoir. (2) – Timer controlled peristaltic pumps set at 128mL/min flow. (3) – 5.9L PVC reactors heated by electrical tape and containing solid wastes in a wire mesh basket. (4) – Leachate and biogas outlet tubing. (5) – Biogas line. (6) – Tipping bucket biogas meter.

Phase 3: Lab Scale Feasibility

Initially, the laboratory reactor system was started by placing 540 g of milled wheat stems (wet basis) in a screen basket in one reactor, along with 540 mL of inoculum from the 10-L inoculum digester used for BMP assays, 23.5 g $NaHCO_3$, and 4960 mL of de-

chlorinated tap water. The second reactor contained only de-chlorinated tap water (~5.9 L). Initially, each reactor had a designated leachate reservoir made from 500-mL sidearm

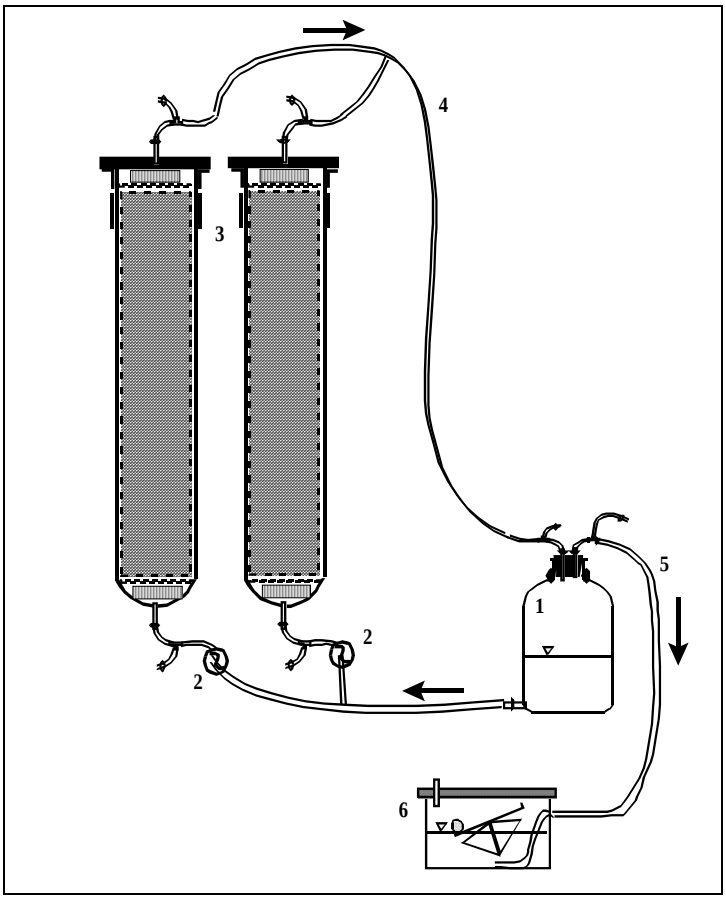

Figure 3-3. Schematic of modified anaerobic digestion system

Erlenmeyer flasks. The flasks were connected to each of the reactor outlet tubes and contained an additional 100 mL of tap water in each. Also, two individually-controlled peristaltic pumps recirculated leachate continuously from each reservoir into the bottom of the other reactor.

The pH of the leachate was monitored and an attempt was made to keep it above 6.5 by the addition of $NaHCO_3$ and/or additional inoculum. On days 5, 7, and 11, 27.6 g

of $NaHCO_3$ were added. On day 4, 500-mL of leachate was replaced with fresh inoculum from the 10L inoculum digester and on days 11, 19 and 20, 200-mL of leachate were also replaced with inoculum. On day 32, another 500 mL of leachate were replaced by inoculum. Performance data from this initial start-up was erratic until equilibrium was reached. When the data became more predictable, normal operation of the reactor system could begin.

After the initial start-up of the first reactor, the second digester was capable of start-up without additional inoculum or $NaHCO_3$. When a run was completed the pumping system was shut-off and the ball valves at the bottom of each reactor were closed. The tubing from the top of the reactor to the leachate reservoir was clamped off and detached. Also, the tubing was disconnected from the ball valve at the bottom of the reactor and the leachate was drained out of the reactor into a storage container. The lid of the reactor was taken off and the basket removed. Remaining biomass was removed from the basket, weighed and frozen to await analysis of VS and TS. The basket was then rinsed with deionized water and placed back into the empty reactor.

Approximately 500 g of shredded feedstock were placed into the wire mesh basket and compacted using a 5.1 cm **(**OD) solid plastic tamper. The wheat straw for the initial runs was received pre-shredded to a particle size of less than 1cm. Rice straw (obtained as whole grass) was shredded using a garden shredder to a particle size of 3.1-7.6 cm (Black and Decker model 8051). Office paper was shredded using a paper shredder to a 2 cm particle size (Fellows model PS-70). Dog food was placed into the reactor in its unaltered pellet state of 1.3 cm (Science Diet Large Canine Growth formulated by Hill's Pet Nutrition, Inc). For the third run, portions of each feedstock were placed into the

reactor and then compacted to create a layering effect inside the basket. After the reactor was filled, the screen and spacers were replaced on top of the basket and the previously removed leachate was poured into the reactor onto the contents. Additional de-chlorinated tap water was added to fill the reactor. De-chlorinated tap water was also added to the leachate reservoir to achieve a 3000 mL volume. The top was then sealed and the system tubing was reconnected. Leachate was pumped every other hour for a 20-minute interval at a flow rate of 128mL/min. The reactor system was run until the gas production rate peaked and then dropped below 1 L of gas production per day. At this time, the process of empting and filling the reactor was repeated.

Total solids (TS) and volatile solids (VS) were performed on the remaining biomass by the same method as described in the BMP assay section described above. Leachate pH was determined on a model 805MP pH meter (Fisher Scientific). Methane in the biogas was measured on a gas partitioning gas chromatograph with a thermoconductivity (TC) detector (Fisher Scientific) and compared to an external standard containing N_2:CH_4:CO_2 in a volume ratio 15:55:30 (the detector response is linear in the range used). Methane volumes were converted to dry gas at STP.

Volatile organic acids (VOA) in the leachate were assayed on a gas chromatograph (Shimadzu) with a flame ionization detector (FID). Samples were centrifuged at 10,000 rpm for 10 min and the resulting supernatant was acidified with 1:9 v/v parts sample to 20% H_3PO_4. Two µL of sample were injected on to a 2-m long 3.2 mm id glass column packed with 10% SP1000 and 1% H_3PO_4-coated 100/120 Chromosorb WAW. Carrier gas was N_2 at a flow rate of 60 mL/min. Conditions were: inlet - 180^o C, column - 155^o C, and detector – 200^o C. Quantification was determined on a LC-100 integrator (Perkin

Elmer) using an external standard containing acetate, propionate, butyrate, isobutyrate, valerate and iso-valerate at 100 mg/L each (the detector response was linear in the range employed).

Phase 4: Full Scale Prototype Reactor Design

For space applications, a five-reactor system was envisioned, including one for feed collection and compaction, three for anaerobic digestion, and one for post-treatment processing (Figure 3-4). The system was designed so that feed would be collected, coarsely shredded, mixed with station wastewater to give the desired <35% solids, and compacted to a density of 300 kg_{dw}/m^3. The actual testing performed on the reactor system, for this thesis, was only for the anaerobic digestion phase at much lower bulk densities. This collection pre-treatment step would require 5 days and be conducted in the same reactor used for the entire treatment process. The anaerobic digestion steps would proceed for 15 days. Biogas from anaerobic composting would be treated to recover carbon dioxide and remove hydrogen sulfide and other contaminants. The methane could be used for energy or discarded. The final compost would be dewatered, treated 1-2 days with air to oxidize reduced residues, and heated for 1 hour at 70^oC to insure inactivation of pathogens. Pathogens would also be inactivated during the anaerobic process and aerobic post-treatment step (Bendixen, 1994; Engeli, 1993). The final compost and associated nutrient-rich water would be used as a solid substrate and source of nutrients for plant growth.

Initial Reactor Volume Calculations

The expected amount of waste entering the anaerobic digestion system would be that generated by a 6 person crew. For a typical 15-day anaerobic digestion cycle (5 days for each anaerobic stage), each reactor would contain 5-days worth of solid waste.

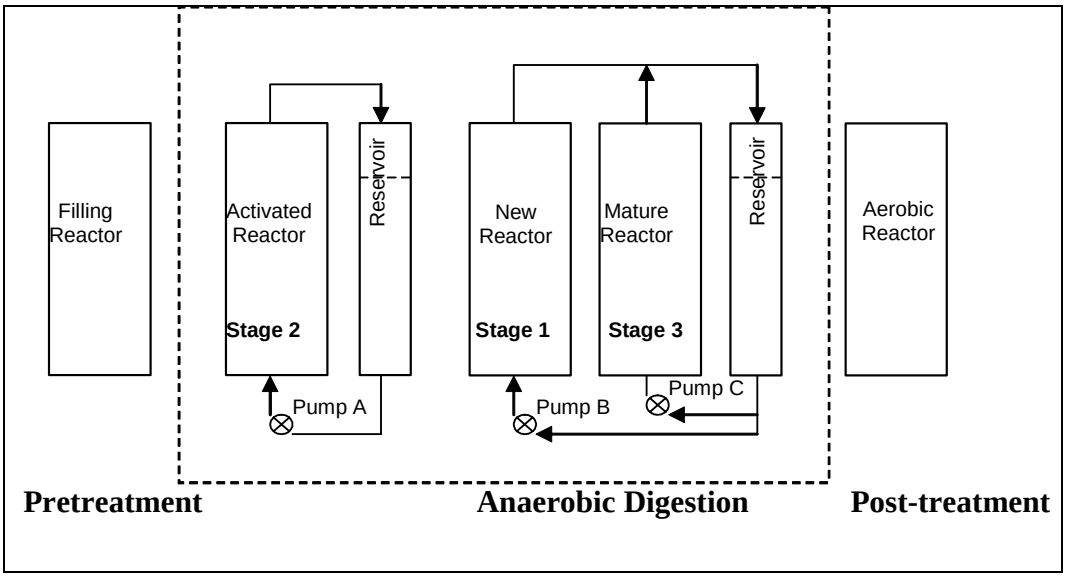

Figure 3-4. High-solids leachbed anaerobic digestion system for space missions

Therefore, the amount of ash free waste in each reactor is (Xu et al 2002):

$$7.5\ kg\ waste/day \times 5\ days = 37.5\ kg\ waste \quad [3\text{-}1]$$

After compaction, the density of the biodegradable waste reached 300 kg (ash free dw)/m^3. Reactor volume (V) needed for wastes is (Xu et al., 2002):

$$V = \frac{37.5\,kg}{300\,kg/m^3} = 0.125\,\mathrm{m}^3 \quad [3\text{-}2]$$

Assuming the reactor is a rectangular tank, with a height to side ratio of 2 and it is necessary to add an additional 25% to the height for leachate distribution and collection, the practical dimension of the reactor can be calculated as follows (Xu et al., 2002):

$$V = L^2 \times H \quad [3\text{-}3]$$

$$H = H'/1.25 \quad [3\text{-}4]$$

$$H'/L = 2 \quad [3\text{-}5]$$

If the sides of the reactors are L= 0.43 m, the height of the reactors is H' = 0.86 m, the waste height is H = 0.69 m, then the practical reactor volume is $V_P = 0.16\ m^3$ (Xu et al., 2002).

Initial Water Reservoir Volume Calculations

As shown in Figure 3-4, two leachate reservoirs were used in the system, which mainly provided the necessary leachate to initially saturate the waste to the optimal moisture content of 70% and then operate in the flooded mode. The reservoirs also serve as gas separators and allow the solid waste beds to be saturated at all times, replacing the leachate lost due to evaporation and the removal of entrapped biogas bubbles in solid leach-bed.

After the dry waste is compacted to 300 kg ash free dry wt/m^3, some water and leachate must be added to achieve a wet density of approximately 1000 kg/m^3. For one reactor, the total amount of water required will be the sum of required water and the head space water:

$$0.125\,m^3 \times (1000-300)\,kg/m^3 + (0.16-0.125) = 0.123\,kg = 0.123\,m^3 H_2O \quad [3\text{-}6]$$

There are two reservoirs in the HSLAD system and it is assumed that 25% volume of each reservoir is always filled with leachate. So the total amount of water needed is:

$$0.123m^3 \times 3 + 2 \times 0.25V_{reservoir} = 2V_{reservoir} \quad [3\text{-}7]$$

The volume of reservoir is 0.25 m^3. Assuming the reservoir has the same height as the reactor, 0.86m, the side length of the reservoir is 0.54 m (Xu et al., 2002).

Initial Pump Design Calculations

A pump was needed to circulate the leachate from the reservoir to the reactor. As calculated above, for one reactor, the required leachate volume was 0.0875 m^3. Based on

the operational experience, it was assumed that the total leachate recirculation flow rate was 8 times the required leachate volume per day, (0.0875 m^3). However, the pumps operated only 30 minutes every 2 hours. So the average leachate circulation flow rate was:

$$Q = 8 \times 0.0875 \frac{m^3}{day} \div (\frac{24}{2} \times 30) \frac{\min}{day} \quad [3\text{-}8]$$
$$= 1.9 \times 10^{-3}\ m^3 / \min$$

According to Darcy's Law, the hydraulic head of leachate (h) was found to be 14.8 m and was calculated from the follow equations:

$$q = K \times i = K \times \frac{h + H}{H} \quad [3\text{-}9]$$

$$q = \frac{Q}{A} = \frac{Q}{L^2} \quad [3\text{-}10]$$

The hydraulic head of water and can be converted to pressure:

$$P = \gamma_{water} \cdot g \cdot h = 145\ kPa \quad [3\text{-}11]$$

So, 145 kPa (21 psia) pressure should be provided by pump. And the energy required by the pump can be calculated as follows:

$$E_T = P \times Q = 101.5\ \text{KJ} \quad [3\text{-}12]$$

and the results of pump design are listed in table 3-2 (Xu et al., 2002). The prototype system design discussed here is described in more detail in Xu et al., 2002.

Constructed Prototype Reactor System

The actual prototype reactor system built was a further modification of the design described in (Xu et al., 2002). The built system still possessed five reactors, three for anaerobic digestion and two for pre- and post- treatment, but the material, shape, and overall design layout were altered from the envisioned space reactor system. These

Table 3-2. Design parameters of HSLAD for space mission (6-person crew)

	Height (m)	Side length (m)	Volume (m^3)	Pressure (kPa)	Pump Energy (kJ)
Reactor	0.86	0.43	0.16		
Water Reservoir	0.86	0.54	0.25		
Pump A				145	101.5
Pump B				145	101.5
Pump C				145	101.5

modifications for the reactor system were made to meet project budget constraints; the actual space system would not be under such constraints and thus could be fabricated with parts and materials to minimize the size and weight of the system.

The prototype reactor system was comprised of five cylindrical loading vessels (Figure 3-5). Each vessel was constructed of schedule 80 PVC with a 17.5" ID (20"OD) and was 47.5" in height; the total volume of the cylinder was 6.61 ft^3 (0.187m^3). Each bioreactor cylinder was fitted with a top and bottom lid. The lids are constructed of 20" OD, 1" thick PVC and have two pieces of 17.5"OD (0.125" thick) perforated steel screen (1/8" holes) suspended at a distance of 3.25" and 5.5" from four steel bolts in the lid itself. The screens functioned as a barrier to prevent biomass particles from clogging the leachate recycle lines (Figure 3-6). The total working volume which solid waste can be placed was thus reduced to 4.94ft^3 (0.14m^3), from the 1foot loss in height due to the perforated steel screens. The lids were attached to the body of the vessel using DE-STA-CO #331 quick release clamps. Where, each lid required 5 (5 additional clamps added after start-up for a total of 10) evenly spaced clamps around the perimeter. Both the top

and the bottom lids were tapped and a ½" PVC valve was attached for drainage of leachate or escape of gas.

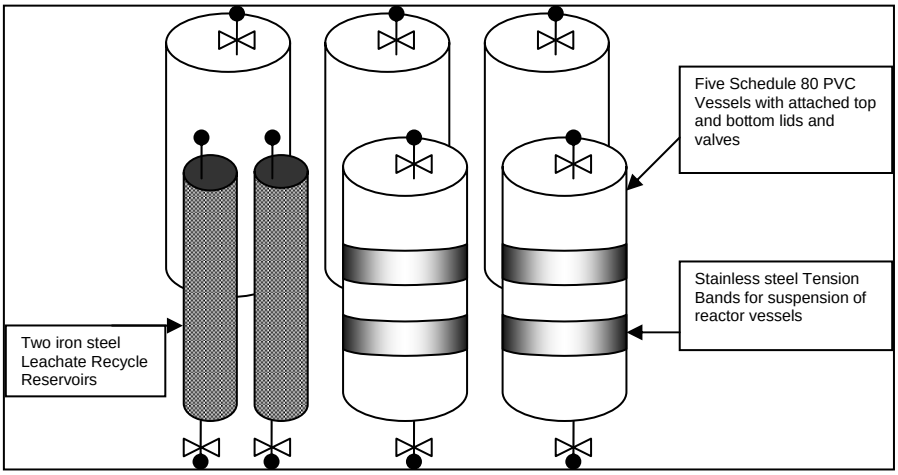

Figure 3-5. Prototype system schematic

Each of the five vessels was suspended from the ground via two stainless steel tension bands attached to a steel frame platform. Two additional iron steel 8" ID x 48" cylinders were mounted to the steel frame of the system and function as the leachate recycle vessels. The leachate recycle vessels were sealed at the bottom and fitted with an electric water heater with a built-in thermostat (Tempco TSPO2081) for heating of the leachate. The leachate recycle vessels were fitted with a 3/4" PVC removable top with a 3/8" brass fitting to allow gas to escape and be counted at the gas collection device (wet tip gas meter). The leachate reservoir lids were attached to the vessel using four DE-STA-CO #331 quick release clamps.

Each of the five reactor vessels was tapped with three ½" iron ports with a 90º elbow on the bottom side (2" from the bottom) and two ½" iron ports with a 90º elbow on the top side (2" from the top) to allow for the flow of leachate through the vessel and into the leachate reservoir. Two of the three ports on the bottom allow for the upflow

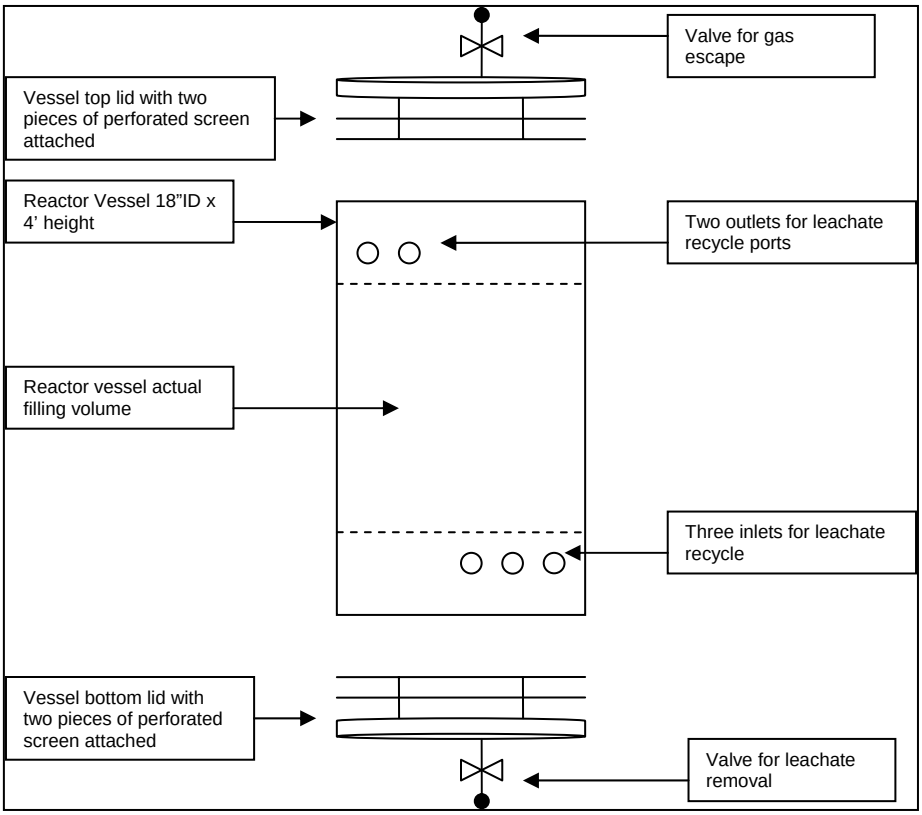

Figure 3-6. Schematic of a single reactor vessel

movement of leachate through the bed of the reactor and out one of the two ports on the top of the reactor system. The two bottom ports that allow flow into the reactor were each connected to a pumping line (Figure 3-7). The pumping lines allowed for the flow of leachate to go into any combination of the five reactors. Two of the bottom ports pumping lines were directly attached to a Monyo ½" inlet ½" outlet positive displacement pump. Each pump was fed from a designated leachate reservoir. Therefore, each positive displacement pump pulled leachate from its own reservoir and was attached to a manifold line to which each reactor was connected. Each top port was connected to a manifold leading back to one of the two leachate reservoirs. The remaining port on the bottom side of the reactor was for draining one reactor and filling

another with its leachate. The selection of the reactor(s) which will receive flow was determined by manually turning PVC valves on each of the port lines.

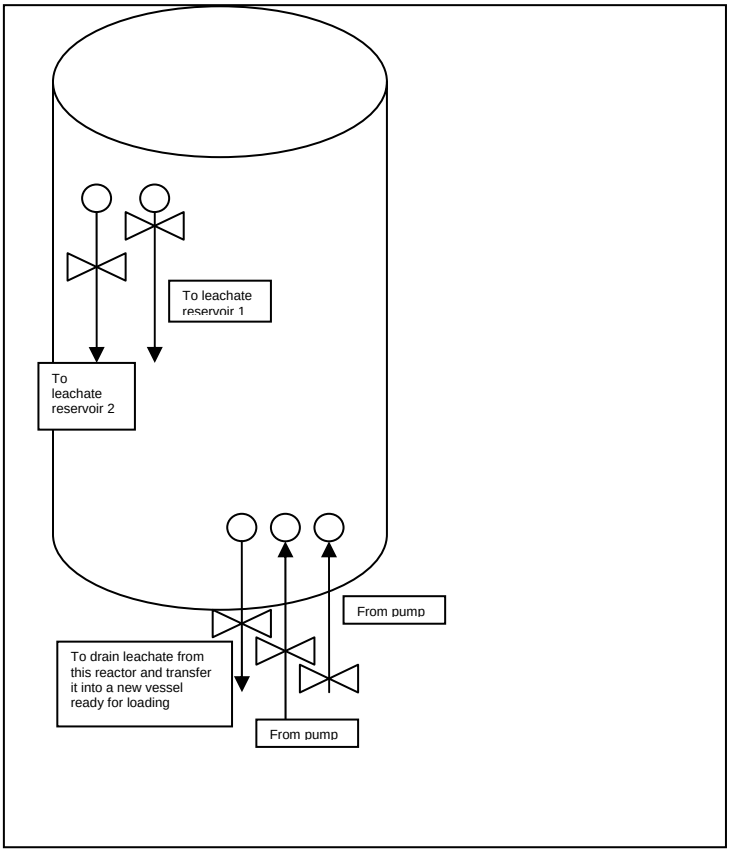

Figure 3-7. Leachate flow schematic

Phase 5: Prototype Reactor Testing

The prototype reactors were loaded at 25 times the loading rate of the lab scale reactor system. The reactors were loaded with a blend of rice straw, dog food, and paper that was proportional to the expected waste generated during a planetary Mars mission for a crew of six. During each loading 4790g of shredded paper, 5610g of shredded rice straw, and 920g of pelletizied dog food were weighed out into empty Rubbermaid trash bins and then loaded into the reactor system. One start-up and two shake down runs were conducted in this final phase of the project.

During the initial loading process of the anaerobic reactor system, de-chlorinated water was added to fill to the top screen of the bottom lid. The biomass (rice straw, paper, and dog food) was added to the vessel intermittently along with 15 gallons of digested dairy manure from the University of Florida Dairy Research Unit anaerobic digestion system, 10 gallons of horse manure compost previously run through the terrestrial Sequential Batch Anaerobic Composting system to act as a buffering system to the process, and 15 gallons of additional de-chlorinated water to fill the reactor to just below the leachate recycle outlet. The biomass was compacted using a wooden 2"x4" three times during the filling process. The final compaction observed was 19" below the vessel top, to a calculated density of 128.6 kg/m^3. The leachate reservoir was supplemented with 5 gallons of SEBAC leachate and 5 gallons of dechlorinated water. Pump rate was controlled by a Dayton DC speed controller attached to each of the Moyno pumps and efforts were made to keep the flow rate of leachate between 2 and 3 LPM.

The pH of the leachate was monitored and an attempt to keep it above 6.5 was made by the addition of $NaHCO_3$, SEBAC leachate, and decholrinated water. 2500.0g of $NaHCO_3$ was added into the leachate reservoir for entry into the vessel on days one and two of the process. The leachate reservoir was emptied and its volume was replaced with dechlorinated water and SEBAC leachate on days 1, 2, 3, 4, and 6. Leaking of leachate was a chronic problem experienced during the trial runs. 5 additional clamps were added to the top and bottom of the reactors after run 1 began having leaking problems. Thus, run 2 and 3 had 10 clamps on each lid, top and bottom. Run two continued to leak and was terminated earlier than anticipated. Before run three began, all taps through the PVC

side walls and the reactor lids were sealed with silicon putty and new o-rings were installed. Furthermore, gas collection of the system was unreliable because of temperature change where gas was being collected and negative pressures that caused the fluid in the gas collector to be removed.

After the initial start-up of the first reactor, the remaining reactors in the system were capable of start-up without additional inoculum or $NaHCO_3$. When a reactor run was completed, the pumping system to the reactor was shut off and the ball valves at the top and bottom of the vessel were all shut. The top ball valve that allowed for gas escape from inside the reactor was shut and the gas line tubing, leading to the gas counter, was clamped and removed from the reactor. First, the leachate in the vessel was drained into a Rubbermaid trash bin and stored to await addition into an empty reactor scheduled to be loaded. The reactor top lid was unclamped and removed to observe the residual biomass. The reactor bottom lid was unclamped and allowed to drop onto a 5-gallon bucket for support. The residual biomass was removed by hand and stored into a Rubbermaid rectangular storage vessel to await further analysis. The reactor was then rinsed with tap water and the lids and o-ring were wiped clean with a cloth, and fresh vacuum grease was placed on all seals. The lids were replaced to await filling of the reactor.

When a reactor was ready for filling the top lid was removed and approximately 4790g of shredded paper, 5610g of shredded rice straw, and 920g of dog food were placed into the reactor vessel. Rice straw (obtained as whole grass) was shredded to a particle size of 4 – 8 cm using a yard chipper/shredder (Yard Machines (MTD) 5.5HP). Office paper was shredded using a cross-cut paper shredder to a particle size of 1-2 cm

(Fellowes model PS8OC-2). Dog food was placed into the reactor in its unaltered pellet form of 1.3 cm (Science Diet Large Canine Growth formulated by Hill's Pet Nutrition, Inc.). Leachate was added to the biomass throughout the filling process in 5 gallon aliquots. Biomass was placed into the reactor to create a layering effect inside the vessel. The biomass was compacted with wooden 2"x4" three times during the filling process and a final height of the compacted biomass was taken for a density calculation. The reactor was then filled with leachate to within 6 inches from the top of the vessel and the lid was replaced and clamped shut. The gas line was attached to the new reactor and its top valve was opened. The valves of the reactor were arranged to recycle leachate between itself (new reactor) and the mature reactor. The pump was started to maintain a flow rate between 2-3 LPM. The shared leachate reservoir was opened and the level of leachate was observed until flow was established through the inlet of the reservoir (indicating the new rector was completely flooded). The leachate reservoir level was brought to approximately 5 inches below the inlet to the vessel with de-chlorinated tap water. The leachate vessel was then sealed and the system was operated in a continuous mode through subsequent stages until the next unloading.

The remainder of the reactor was filled with de-chlorinated tap water. The new reactor would share its leachate reservoir with the mature reactor to ensure mixing of leachate between the new and mature reactors. This would allow for the volatile fatty acids produced by the new reactor to be reduced by the mature reactor and the quick inoculation of the new reactor by providing viable methanogens from the mature reactor.

Analysis of total solids (TS) and volatile solids (VS) were performed as described earlier. Leachate pH was determined on a model 805MP pH meter (Fisher Scientific).

Methane in the biogas was measured on a gas partitioning gas chromatograph with a thermoconductivity (TC) detector (Fisher Scientific) and compared to an external standard containing N_2:CH_4:CO_2 in a volume ratio 15:55:30 (the detector response is linear in the range used). Methane volumes were converted to dry gas at STP.

Volatile organic acids (VOA) in the leachate were assayed on a gas chromatograph (Shimadzu) with a flame ionization detector (FID). Samples were centrifuged at 10,000 rpm for 10 min and the resulting supernatant was acidified with 1:9 v/v parts sample to 20% H_3PO_4. Two µL of sample were injected on to a 2-m long 3.2 mm id glass column packed with 10% SP1000 and 1% H_3PO_4-coated 100/120 Chromosorb WAW. Carrier gas was N_2 at a flow rate of 60 mL/min. Conditions were: inlet - 180^o C, column - 155^o C, and detector – 200^o C. Quantification was determined on a LC-100 integrator (Perkin Elmer) using an external standard containing acetate, propionate, butyrate, isobutyrate, valerate and iso-valerate at 100 mg/L each (the detector response is linear in the range employed).

CHAPTER 4
RESULTS AND DISCUSSION

This chapter contains the results from the biochemical methane potential assays lab scale reactor and prototype reactor.

Biodegradability Assays

Biochemical methane potential assays were performed on solid waste components representative of those to be generated during a long-duration space mission to determine the conversion efficiency and ultimate methane yield. These data, shown in Table 4-1, with sample plots in shown in Figure 4-1, indicate that conversion was complete in about 10 days which is significantly shorther than the 21 days projected at the start of the research project (Chynoweth et al., 2002). Based on the final methane yields of the feedstocks tested, the highest conversion was observed for inedible biomass from peanut, rice and radish and the lowest for inedible biomass from wheat, lettuce, and tomato. These data along with those conducted on paper types in a study by Owens and Chynoweth (1993) provided a reasonable spectrum of the biodegradability of the feed types expected during space missions. For interpreting these data, it is important to realize that the ultimate methane yield is influenced by the biodegradability and the hydrogen-to-carbon ratio of the feedstock. Carbohydrates, the major component of plant residues, have a theoretical methane yield of 0.36 L/g VS. This was the reasoning behind using cellulose as a positive control for the trial runs. Using this value, it was possible to estimate the conversion efficiencies of tested materials, which ranged from 50 – 83% (Chynoweth et al., 2002). In general, conversion of peanut and rice residues exceeded

75% and was higher than that of other residues tested. Some plant components (e.g. lignin) are not biodegradable under anaerobic conditions (Chynoweth and Pullammanappallil, 1996).

Kinetic rate constants (Table 4-1) obtained from the semi-logarithmic plots of the BMP data (standard BMP plots in Figure 4-1) varied by about 2-fold. These data can provide an estimate of the potential influence on the kinetics of conversion for a blend of feedstocks and ultimately an estimate of the reactor size and operating conditions. In general peanut and rice residues exhibited more rapid conversion kinetics that other residues and paper types.

Laboratory Scale Feasibility Testing

The laboratory digester design, construction, and modification were completed and one startup and two shakedown runs (Runs 1 and 2) were conducted using wheat stem residues. Run 3 was completed with a blend of feedstocks consisting of rice residue, paper, and dog food. Chronic mechanical problems related to leachate pumping and gas collection required frequent redesign of the system during start-up and Run 1, but these problems were not encountered in Runs 2 and 3 (Chynoweth et al., 2002). A reliable design was finally developed which performed well without leaking, clogging, and pump failure. Data from the three post-startup runs are shown in Figures 4-2 – 4-5 and Tables 4-2 and 4-3.

Runs 1 and 2, which were conducted on only wheat stem residues, exhibited comparable performance. The calculated methane yields for these two runs were 93% and 96%, respectively, of the ultimate yields observed in the BMP assay and the reduction in organic matter (volatile solids reduction) was 70% and 77%, respectively. Both runs had

Table 4-1. Biochemical methane potential data

Feedstock	CH_4 Yield, L/g VS added	Standard Deviation	conversion, % of cellulose	k, d^{-1}	Standard Deviation
This Study (inedible portion)					
cellulose control	0.36				
wheat stems	0.27	0.0150	75	0.109	0.0036
wheat roots	0.18	0.0150	50	0.112	0.0032
Tomato	0.23	0.0007	64	0.095	0.0047
Peanut	0.30	0.0097	83	0.224	0.0164
sweet potato	0.24	0.0024	67	0.175	0.0089
Potato	0.28	0.0228	78	0.212	0.0095
This Study					
rice-Italica	0.30	0.0042	83	0.224	0.0196
rice-Koshi	0.28	0.0006	78	0.171	0.0059
rice-L204	0.29	0.0010	81	0.201	0.0125
rice-Labelle	0.27	0.0030	75	0.173	0.0066
rice-M103	0.30	0.0053	83	0.220	0.0170
rice-M202	0.30	0.0010	83	0.208	0.0093
rice-N22	0.29	0.0219	81	0.189	0.0057
rice-S102	0.28	0.0007	78	0.205	0.0051
This Study (salad crop waste)					
Cabbage	0.23	0.0199	72		
Carrot	0.22	0.0124	70		
Lettuce	0.17	0.0101	54		
Onion	0.24	0.0132	76		
Radish	0.28	0.0004	89		
red chard	0.19	0.0044	59		
Spinach	0.26	0.0078	81		
Tomato	0.14	0.0054	42		
Owens and Chynoweth (1993)					
office paper	0.37			0.140	
food board	0.34			0.120	
wax paper	0.34			0.083	
magazine paper	0.20			0.112	
News paper	0.10			0.069	

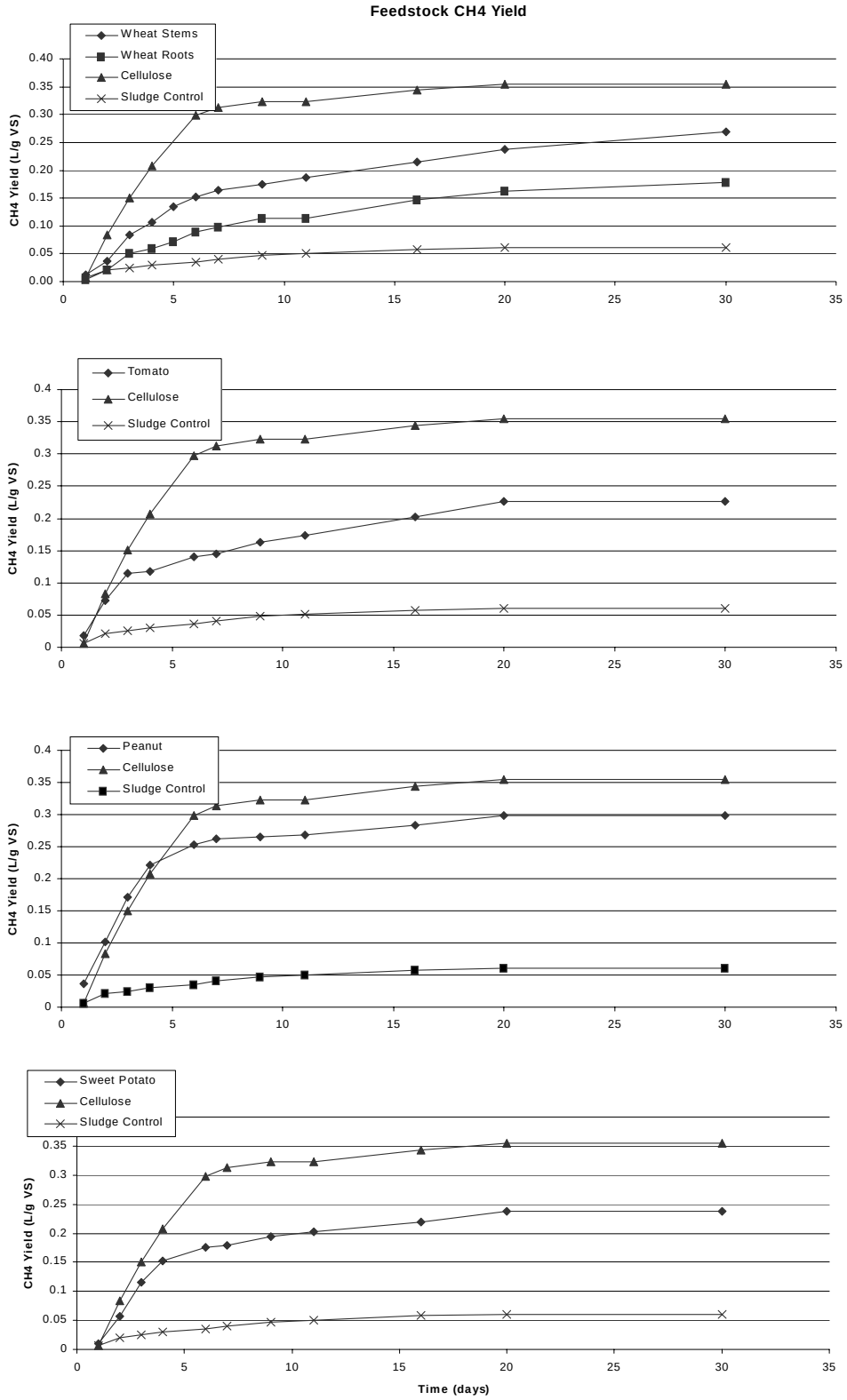

Figure 4-1. Sample BMP plots

final biogas methane contents of ~60%; the balance (~40%) was carbon dioxide. Conversion was more or less complete after 25 days (Figure 4-2, Table 4-3). The volatile organic acids (VOA) concentration in the recirculating leachate increased during the first 6 days of these runs, but then decreased by the end of the runs to <100 mg/L. VOA levels of <500 mg/L are indicative of stable performance (Chynoweth and Pullammanappallil, 1996). The principal volatile acids formed were acetic and propionic (Figure 4-4). The pH dropped slightly in both runs, corresponding to the transient accumulation of volatile acids, but then increased as the VFAs were converted to methane. During the first few days, VFAs are conveyed by leachate recirculation through the leachate reservoir and then into the neighboring active reactor. This removes the VFAs from the site of formation and facilitates their conversion to methane and carbon dioxide.

Run 3 was conducted with a blend of feedstocks, which included rice residue, shredded paper, and dog food at particle sizes representative of that anticipated in a mission-scale system. These feedstocks simulate the types of materials (crop residue, paper, and feces) expected during a space mission. Performance of this run exceeded that of the previous runs, which used only wheat residues (at a much finer particle size) in terms of methane yield, organic matter (VS) reduction, and kinetics. The methane yield was 0.30 L/g VS added and the VS reduction was 85%. Data in Figure 4-3 and Table 4-3 indicated that the conversion was more rapid and was more or less complete in 15 days compared to 25 days for wheat. As a consequence of faster kinetics, the accumulation of a higher concentration of VFAs was observed, but again the VFAs decreased to low

levels by the end of the run. The principal volatile acids formed were again acetic and propionic acid (Figure 4-4).

Mass balances were conducted for volatile solids, methane, and carbon dioxide for all three runs (Figure 4-5). Sampling errors probably accounted for the loss between initial and final mass calculations. A mass balance for water was conducted for Run 3 only (Table 4-2). The mass balance for volatile solids and biogas resulted in recoveries of 87% to 99%, respectively, where some losses can be attributed to CO_2 and residual VOA, which were dissolved in the leachate and therefore not included in the mass balance calculations. For Run 3, 382g (VS) of feed blend produced 82 g CH_4, 202 g CO_2, and 57.4 g effluent solids, representing an 89% recovery. The mass balance for water in Run 3 gave a recovery of >99% (Table 4-2). The waste blend contained 29.6 g of H_2O when it was placed in the reactor, while the digested residue contained 548 g when it was removed from the reactor. The difference is an estimate of the amount of process water consumed (which can come from other process wastewater), since the leachate drained from the reactor at the end of this run was used in the following run.

Table 4-2. Water balance for Run 3

	Units	**Run 3**
Weight of waste, initial	g	436.6
TS rice	%	91.9
TS paper	%	95.4
TS dog food	%	92.4
Water in rice	g	19.5
Water in paper	g	7.33
Water in dog food	g	2.8
Water in waste, initial	mL	29.6
Weight of full reactor	g	9389.4
Weight of reactor w/o waste	g	3709.0
Water added	mL	5680.4
Water in digested biomass, final	mL	547.9
Water drained from reactor, final	mL	5136.4
Total water in	mL	5710.0
Total water out	mL	5684.3

The process water consumption measured was 518 g H_2O required for 383 g VS of waste processed. In previous work with this system (Chynoweth et al., 1992), the kinetics of degradation improved over the first 3-5 runs, as the population of organisms increased and adapted to the feedstock material (Chynoweth et al., 1991), so these results are promising.

Table 4-3. Data for runs 1, 2, and 3.

	Units	**Run 1**	**Run 2**	**Run 3**
		Milled wheat stems	Milled wheat stems	Rice, paper, dog food
Input solids				
Size	cm	<1	<1	5-7, 2, 1
Initial feedstock weight	g	500	500	241, 159, 38
Total weight	g	500	500	437
TS	%	92.6	92.6	91.9, 95.4, 92.4
VS	% of TS	91.7	91.7	95.1, 92.7, 94.8
TS	g	463	463	407
VS	g	424	424	382
Reactor volume	L	5.91	5.91	5.91
Basket volume	L	4.94	4.94	4.94
Bulk density	g TS / L	93.7	93.7	82.4
Output solids				
Wet weight	g	1350	1130	630
TS	%	10.1	9.3	13.0
VS	% VS	88.7	82.1	70.1
Weight VS out	g VS	121	86.3	57.4
Conversion Data				
TS reduction	%	70.5	77.3	80.2
VS reduction	%	71.4	79.7	85.0
Volume reduction	%	na	na	86.4
Methane yield	dry L @ STP / g VS	0.26	0.25	0.30
Weight of CH4 produced	g VS	79	76	82
Percent of CH4 yield measured by BMP assay	%	96.3	93.0	na
Carbon dioxide yield	dry L @ STP / g VS	0.27	0.25	0.27
Weight of CO2 produced	g VS	222	208	202
Final biogas CH4	% CH4	59.0	60.4	59.4
Final biogas CO2	% CO2	41.8	34.9	32
Max. CH4 production rate	L CH4 / L reactors / d	0.54	0.51	1.02
Max. VOA in leachate	Mg / L	3580	4270	7860
Final VOA in leachate	Mg / L	24	91.9	13.7
Min. pH	pH units	7.11	7.13	6.79
Final pH	pH units	7.47	7.77	7.8
Temperature	^oC	35	35	35

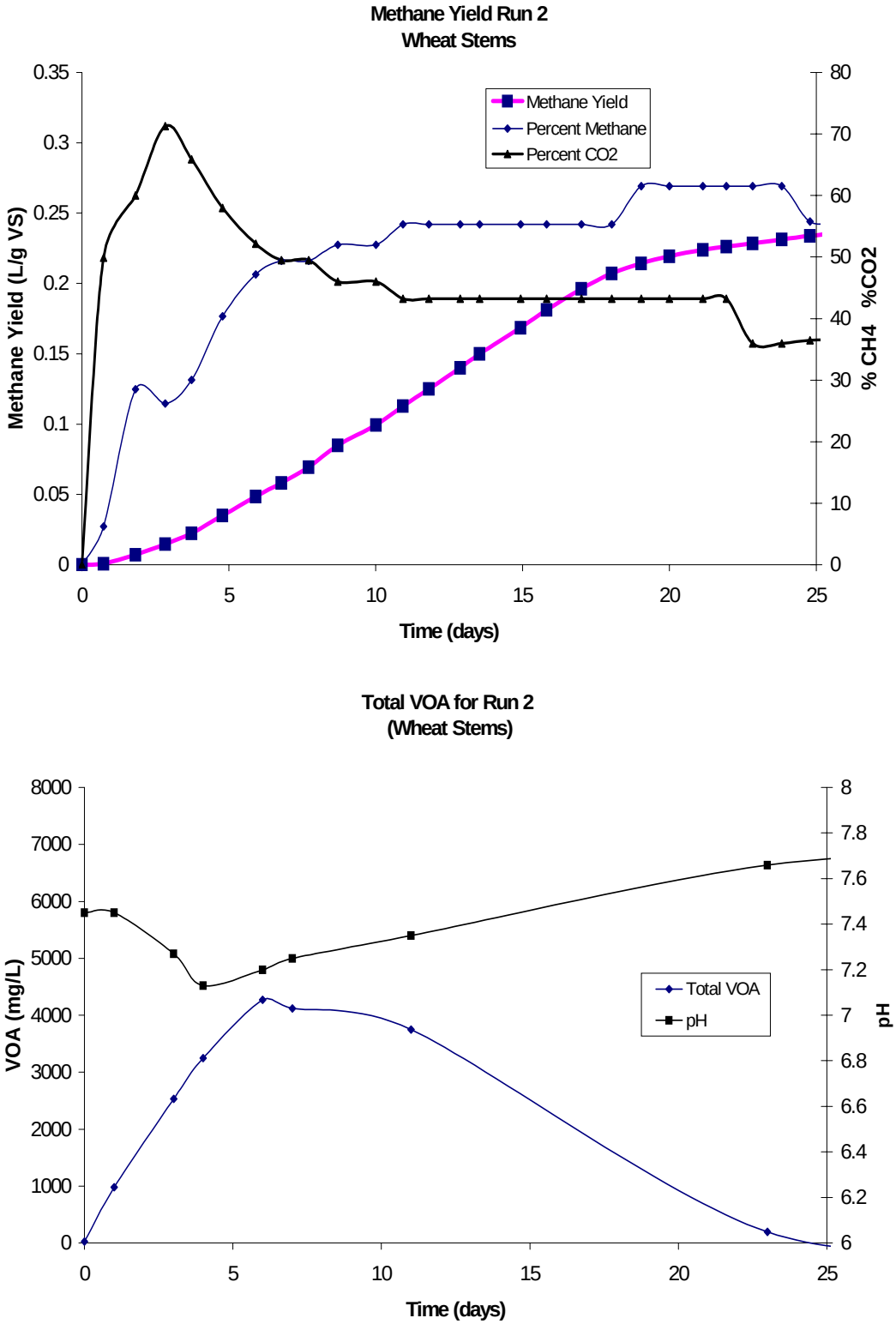

Figure 4-2. Data from run 2 on wheat stems

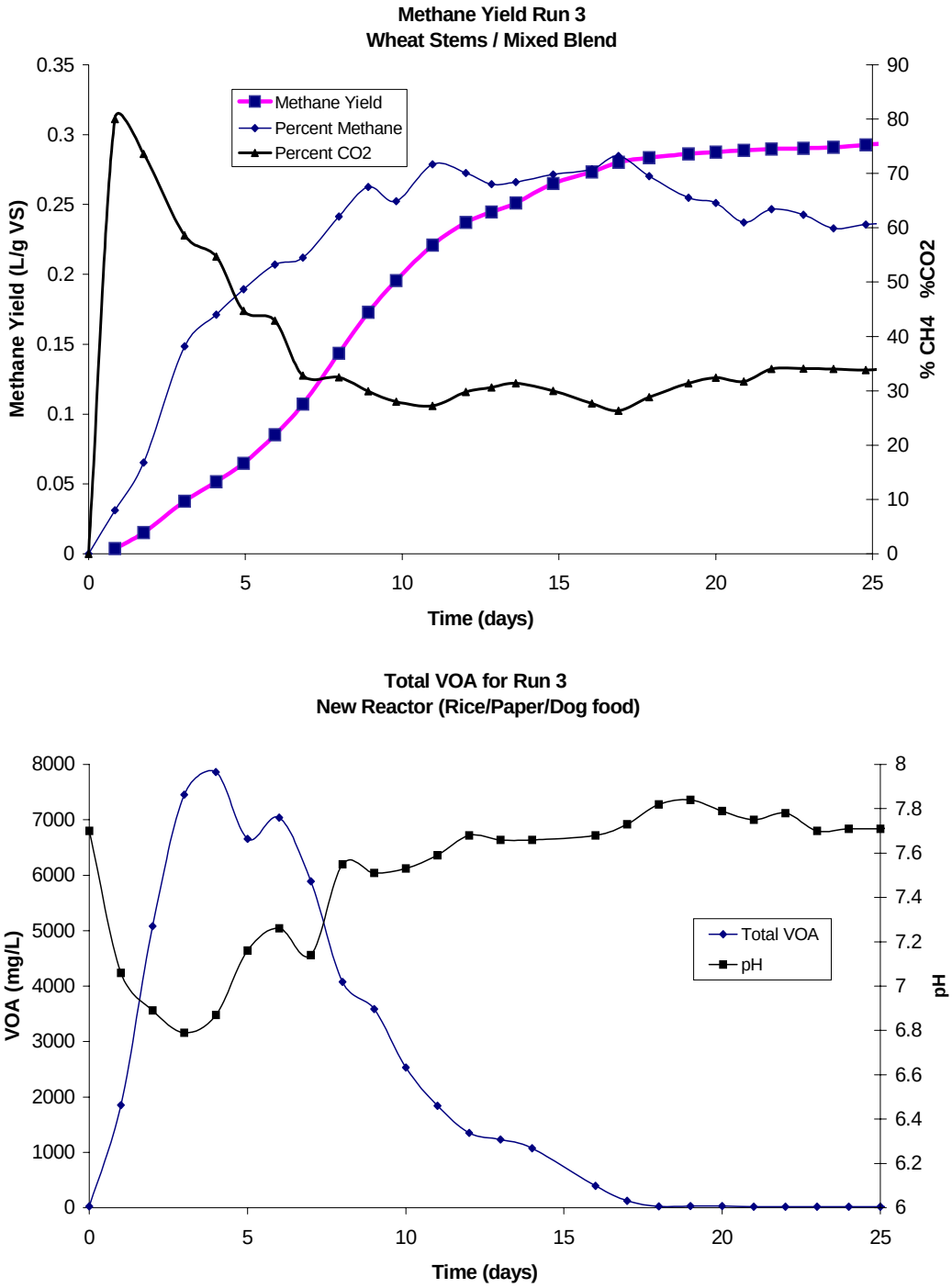

Figure 4-3. Data from run 3 on the waste blend

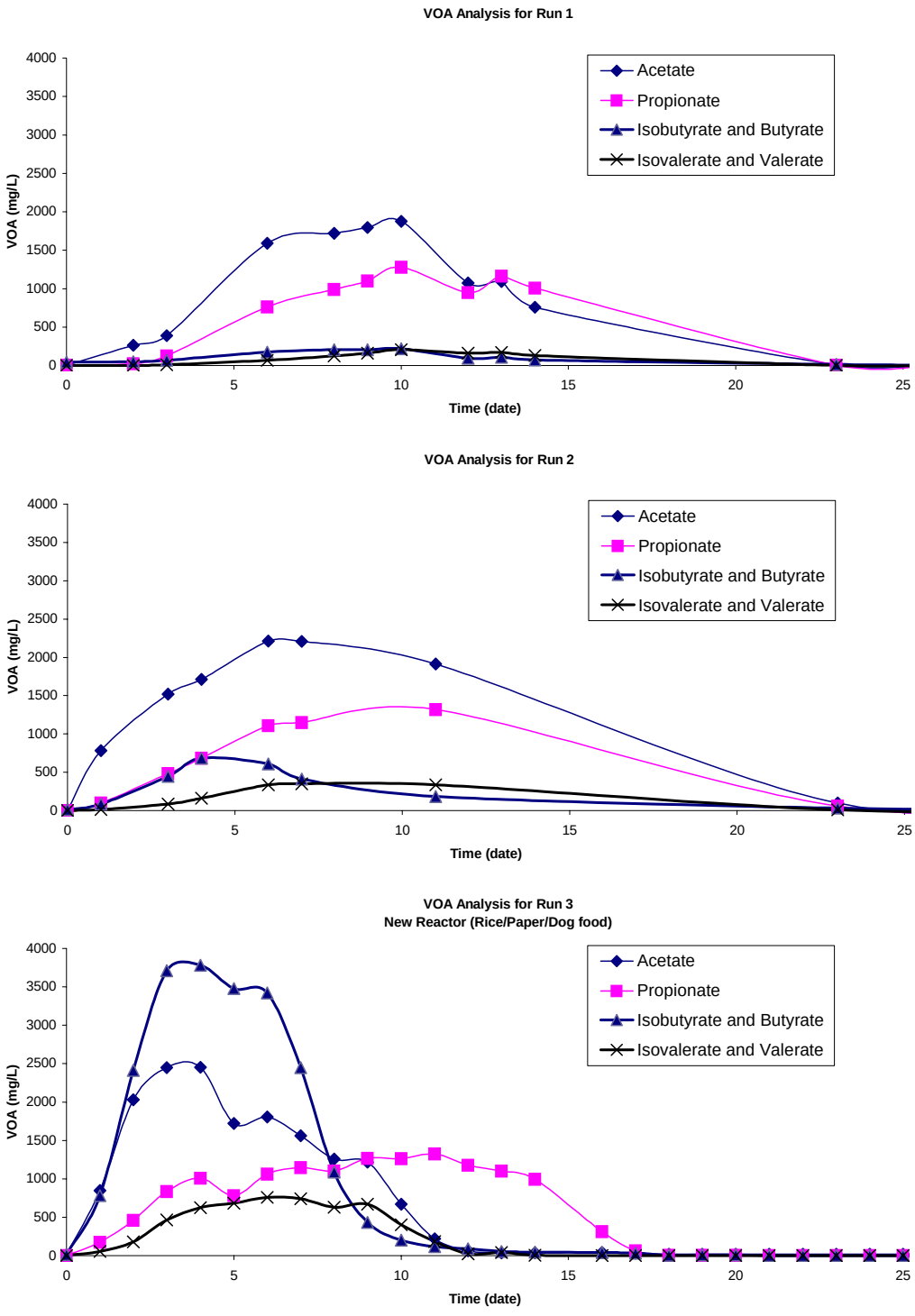

Figure 4-4. Volatile acid data for runs 1, 2, and 3

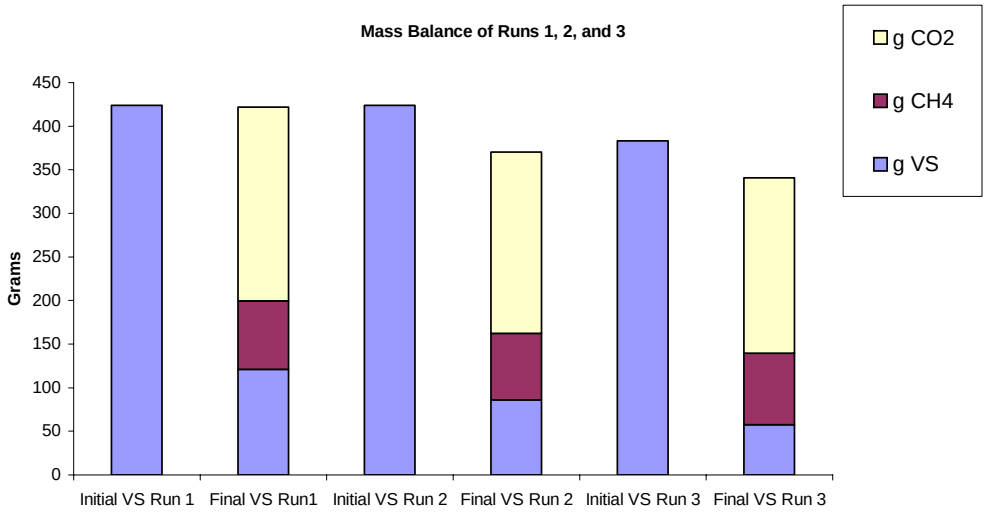

Figure 4-5. Mass balances for runs 1, 2, and 3

Prototype Reactor Testing

The prototype digester design and construction were completed and one startup and two shakedown runs were conducted using a feedstock blend consisting of rice residue, paper, and dog food. Chronic mechanical problems related to leachate leakage and gas collection required frequent redesign of the system during all three runs. To prevent leaking observed in run 1, the number of clamps securing the top and bottom lids were increased from 5 to 10 for runs 2 and 3. Furthermore, the o-rings for the top and bottom lids were increased in thickness for runs 2 and 3. To prevent leaking in the tapped areas for connecting the clamps, all taps through the PVC were sealed with silicon putty for the third run.

Gas collection was also a point of error in data collection. The amount of gas produced was recorded on a wet-tip gas counter, which was exposed to the atmosphere. Because the prototype reactor system was outside, temperature variations throughout the day and night affected the volume of gas recorded by the meter. Furthermore, their were

problems with the meter puling a vacuum, dumping its liquid into the reactor system and allowing any gas produced to escape without being accounted. Modifications to the design of the system still need to be performed for the system to operate free of any mechanical problems. Data from the three runs are shown in Figures 4-6 – 4-8 and Table 4-4.

Table 4-4. Results from prototype reactor runs 1, 2, and 3

	Units	Run 1	Run 2	Run 3
Input solids				
Type		Rice, Paper, Dog food	Rice, Paper, Dog food	Rice, Paper, Dog food
Size	Cm	5-7, 2, 1	5-7, 2, 1	5-7, 2, 1
Initial feedstock weight	G	5611, 4000, 741	5611, 4000, 741	5611, 4000, 741
Total weight	G	10352	11327	11398
TS	%	91.9, 95.4, 92.4	91.9, 95.4, 92.4	91.9, 95.4, 92.4
VS	% of TS	95.1, 92.7, 94.8	95.1, 92.7, 94.8	95.1, 92.7, 94.8
TS	G	9648	10557	10623
VS	G	9752	10670	10737
Reactor volume	L	187	187	187
Basket volume	L	140	140	140
Bulk density	g TS/L	68.9	75.4	75.9
Output solids				
Wet weight	G	28122	18824	15875
TS	%	19.4	14.5	12.4
VS	%VS	77.2	92.0	83.0
Weight VS out	g VS	4211	2511	1633
Conversion data				
TS reduction	%	43.5	74.1	81.4
VS reduction	%	56.8	76.5	84.8
Residence Time	Days	45	20	13
Calculated CH4 Yield (from %VS reduction)	dry L@STP/g VS	0.16	0.28	0.31
Methane yield	dry L@STP/g VS	0.06 (0.12)*	0.091 (0.14)*	0.10 (0.18)*
Carbon Dioxide Yield	dry L@STP/g VS	0.13*	0.15*	0.14*
Final biogas Methane	% CH4	58.2	56.7	60.6
Final biogas CO2	%CO2	41.1	43.9	38.8
Maximum CH4 production rate	L CH4/L reactors/d	0.35 (0.44)*	0.70	0.92
Maximum VOA in leachate	mg/L	20124	12649	10172
Final VOA in leachate	mg/L	175	277	1324
Minimum pH	pH units	6.91	6.58	6.75
Final pH	pH units	7.64	7.24	7.84
Temperature	^{o}C	35	35	35

* Calculation performed using estimation of volume of gas produced

Run 1 received the blend of feedstocks (rice residue, paper, and dog food) along with previously digested residual compost from horse waste (primarily bedding for stalls). This extra compost was added to act as an additional buffering agent during start up of the first reactor. Because of frequent mechanical problems including gas collection, two different estimates were made to calculate the methane yield for all three runs. The first estimate back calculated the methane yield using the % VS reduction and determining methane yield by using 0.36 L/gVS as the theoretical 100% reduction of biomass. The second method relied upon estimates of the gas produced each day. These estimates were determined by using values from days in which the gas counter performed properly and assuming these recorded values applied to surrounding days when the gas counter performed poorly, recording a false value. The methane yields plotted in figures 4-6a – 4-8a were calculated from gas estimates and are lower than the methane yield when calculated by the % VS reduction. The calculation for methane yield from % VS reduction is the better representation of the performance of the anaerobic digestion of biomass in the prototype reactors. The calculated methane yield was 0.16 L/g VS (Calculated from the %VS reduction) added and the VS reduction was 57%. The run had a final biogas methane content of ~60%; the balance (~40%) was carbon dioxide and a small portion of atmospheric air (encountered from leaking and gas collection problems). The run had a retention time of 45 days (figure 4-6a). The volatile organic acids (VOA) concentration in the recirculating leachate increased during the first 10 days of the run, but then decreased by the end of the runs to less than 200 mg/L. VOA levels of less than 500 mg/L are indicative of stable performance (Chynoweth and Pullammanappallil, 1996). The principal volatile acids formed were acetic and propionic

(Figure 4-6b). The pH dropped slightly corresponding to the transient accumulation of volatile acids, but then increased as the VFAs were converted to methane. During the first few days, VFAs are conveyed by leachate recirculation through the leachate reservoir and then into the neighboring active reactor. This removed the VFAs from the site of formation and facilitated their conversion to methane and carbon dioxide.

Runs 2 was conducted with the chosen space mission blend of feedstocks including rice residue, shredded paper, and dog food without the addition of compost for buffering. Performance of this run exceeded that of the previous run but was terminated because of chronic leaking. The methane yield was 0.28 L/g VS (calculated from VS reduction) added and the VS reduction was 77%. Data in Figure 4-7a indicates that the conversion was more rapid and was more or less complete in 20 days compared to 50 days for the start-up run. As a consequence of faster kinetics, the accumulation of a higher concentration of VFAs was observed, but again the VFAs decreased to low levels by the end of the run. The principal volatile acids formed were again acetic and propionic acid (Figure 4-7b).

Run 3 experienced the fewest mechanical problems for the run tested, again its performance was even better than the two previous runs. The methane yield was 0.31 L/g VS (calculated from VS reduction) added and the VS reduction was 85%. Data in Figure 4-8a indicate that the conversion was more rapid and was more or less complete in 13 days compared to 20 days for run 2. The principal volatile acids formed were again acetic and propionic acid (Figure 4-8b). Data for VFAs of run 3 were limited because of the failure of the VFA chromatograph. Despite this failure, the performance of the reactor suggests that it was not inhibited by high VFA levels.

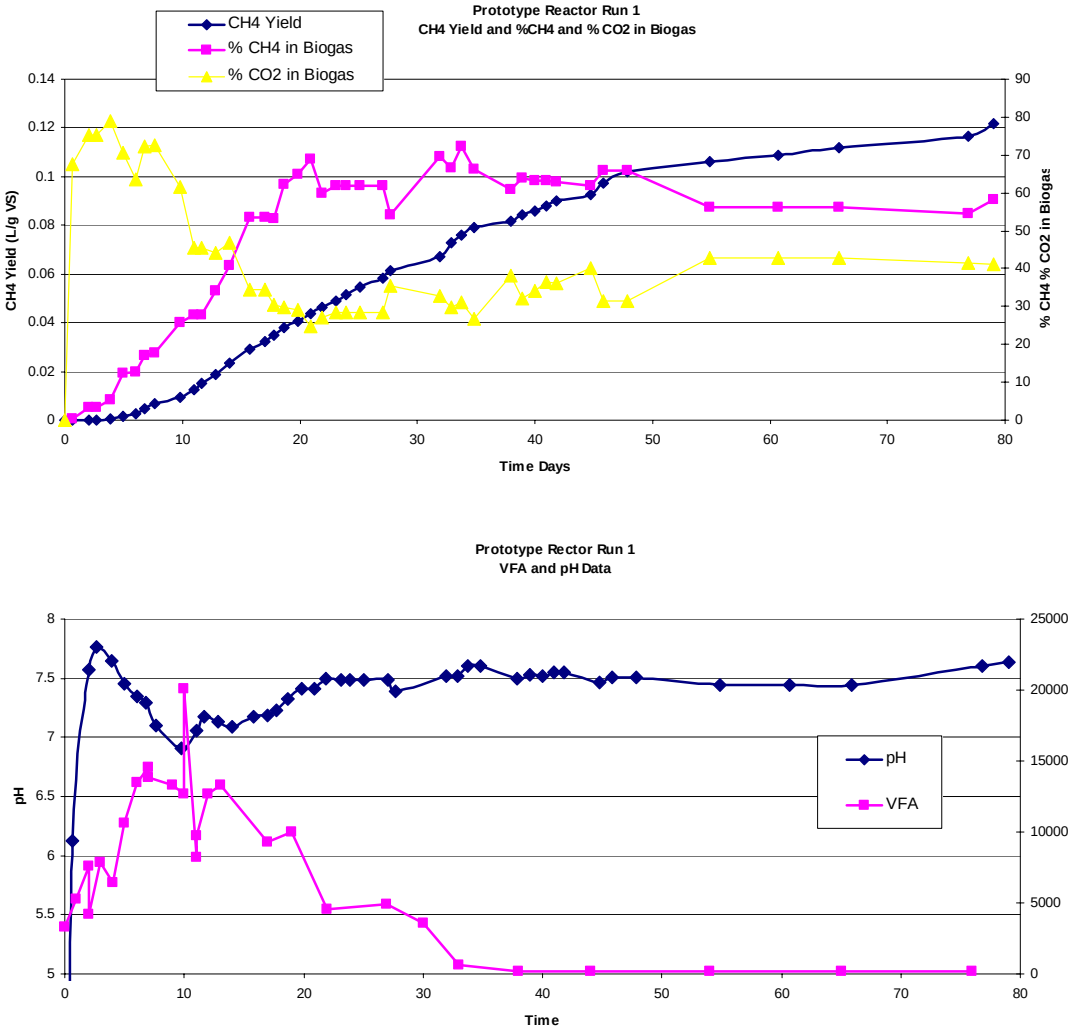

Figure 4-6. Prototype reactor run 1 (a): CH4 yield graph, (b): volatile fatty acids

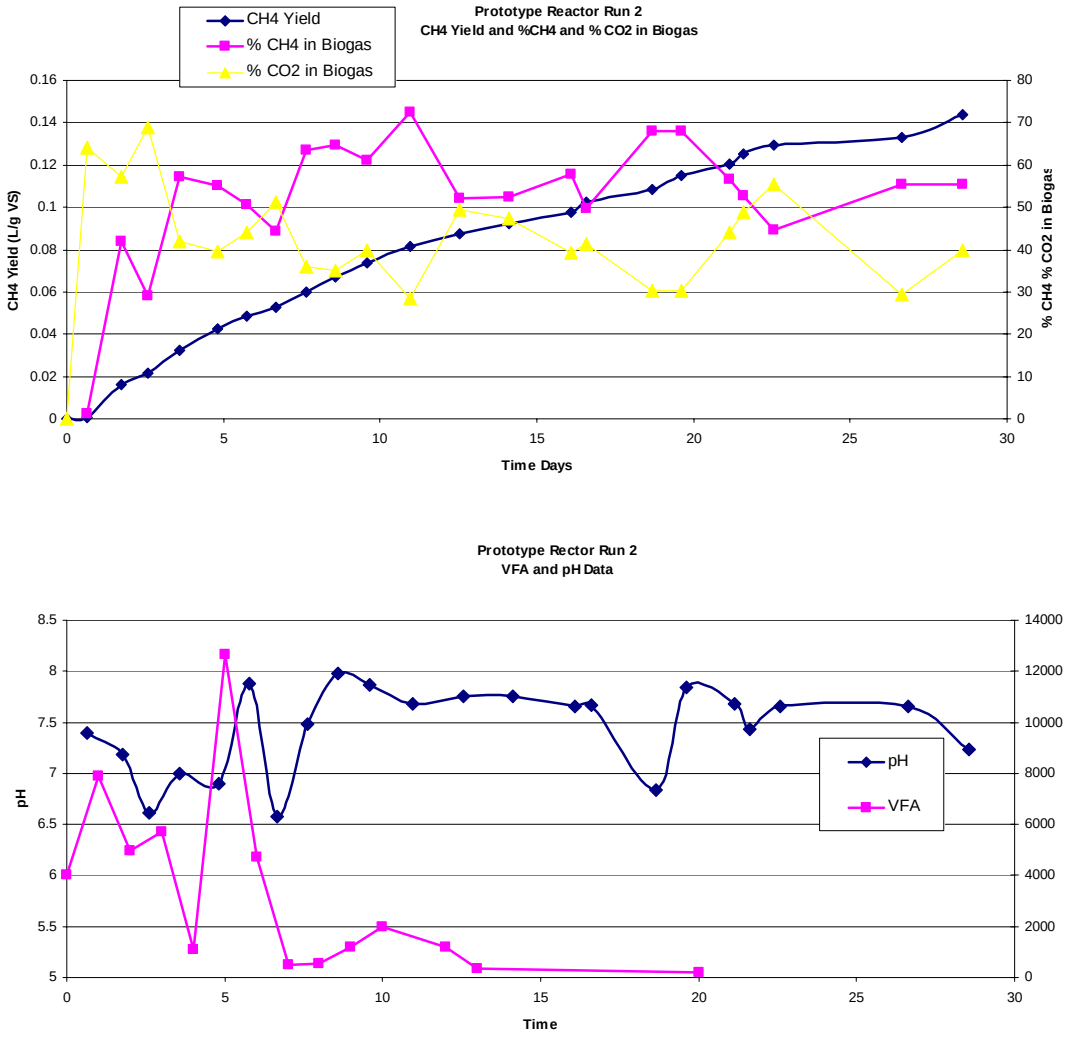

Figure 4-7. Prototype reactor run 2 (a): CH4 yield graph, (b): volatile fatty acids

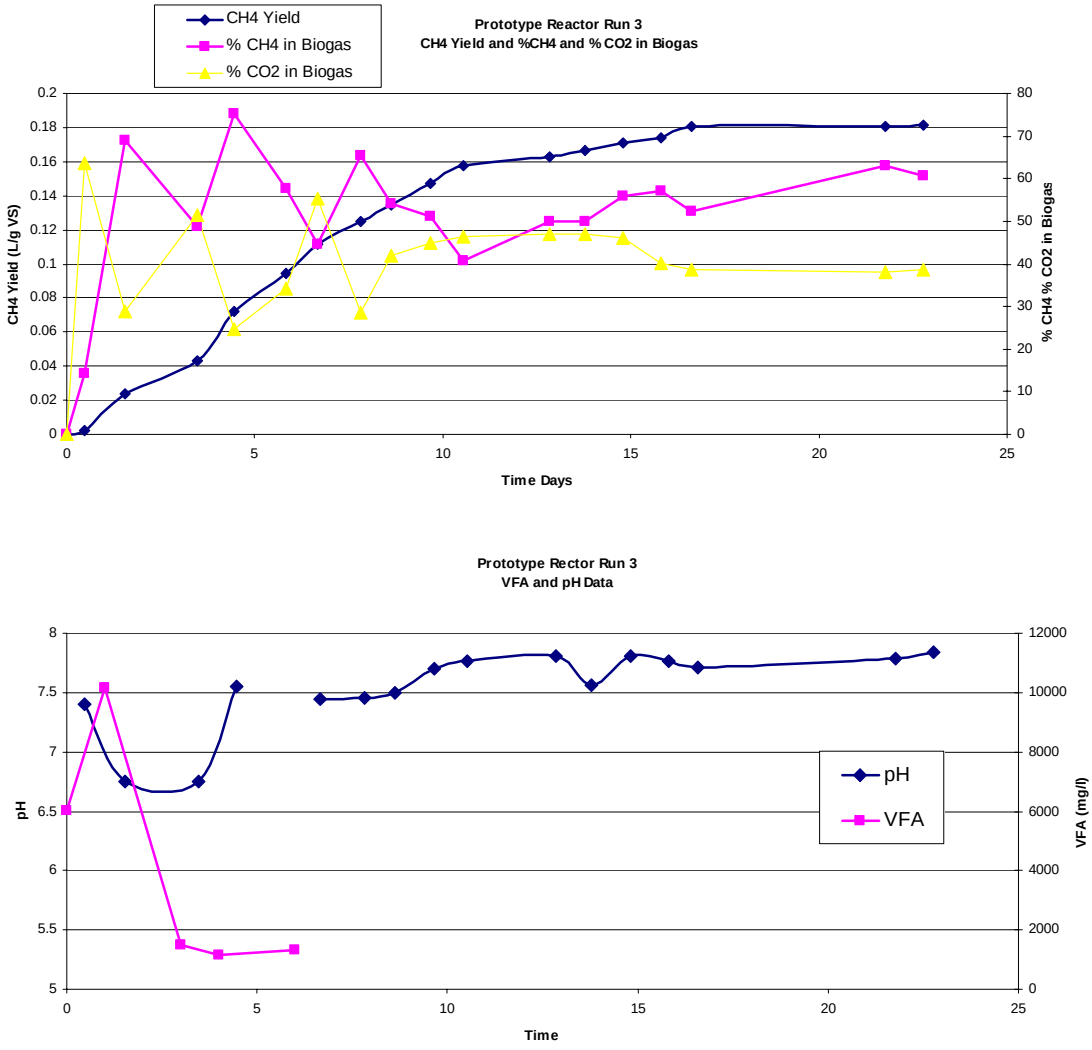

Figure 4-8. Prototype reactor run 3 (a): CH4 yield graph, (b): volatile fatty acids

CHAPTER 5
CONCLUSIONS AND SUGGESTIONS

Research presented here supports the use of high-solids leachbed anaerobic digestion for bioregenerative reduction and stabilization of the organic components of solid wastes during extended planetary space missions. Initial laboratory scale and prototype reactor testing have shown positive results for decreased retention time and increased reduction of biomass in the modified anaerobic digestion system.

Biodegradability Testing

Biochemical methane potential assays indicate variations in the biodegradability of feedstocks envisioned for space missions. Because inedible crop residues represent the largest fraction of solid wastes generated during extended missions, it would be wise to select crops with the highest biodegradability for reduction and conversion in the anaerobic digestion system. With respect to other solid wastes (e.g., packaging, filters, etc.), biodegradability should be given emphasis in materials selection. Rates of biodegradation determined by this method are also relevant as they directly influence the conversion kinetics of feed blends and the reactor volume and weight requirements. The BMP results provide a method for comparing different feedstocks for methane yield and conversion efficiency and kinetics to select feedstocks ideal for aerobic digestion. Actual performance in a digester is dependent upon design and operating conditions such as residence time and temperature.

Laboratory-Scale Feasibility

The flooded, no-headspace reactor design performed well on the laboratory scale. This design can be easily adapted to hypo- and micro-gravity conditions. The flooded design permits forced leachate recycle through leachbeds without dependence upon gravity. It also permits use of pump pressure to move leachate through highly dense beds with limited hydraulic conductivity. The laboratory scale reactor design for anaerobic digestion performed without problems for the three runs following start-up and shake-down trials. This design required an external vessel for gas liquid separation. Under hypogravity conditions, gas would separate from the leachate by gravity. Under microgravity conditions, a gas-liquid vortex separation process (centrifugation) could be employed.

Performance of the laboratory scale modified system has surpassed initial expectations. Conversion efficiencies of 75% and 85% have been obtained at residence times ranging from 15-25 days, for wheat and a blend of rice residue, paper, and dog food. Performance has been stable without requirement for pH control. In the three runs reported, volatile organic acids accumulated to high values, in one case exceeding 8,000 mg/L. Although the process proceeded without detectable inhibition, process kinetics might be improved by increasing leachate recycle rates to reduce VOA accumulation.

Prototype Reactor Testing

The operation of the prototype reactors was plagued with mechanical problems including leakage from both the top and bottom lids and inaccurate gas collection measurements. Despite these apparent set backs, performance data collected from the three trial runs performed in the large scale reactors shows promising results. Conversion efficiencies of 57% and 85% have been obtained at residence times ranging from 13-50

days, for the blend of rice residue, paper, and dog food. After the initial start-up run, performance (not including mechanical problems) was stable without requirement for pH control. In the three runs reported, volatile organic acids accumulated to high values, in one case exceeding 20,000 mg/L. This high level was only experienced during the initial start-up run. Remaining runs acid concentrations were reaching ~ 10,000 mg/L and showed no sign of inhibition.

Recommendations

Mechanical problems with the prototype reactor system need to be addressed to eliminate leachate leakage and gas collection errors. In subsequent runs, performed after the initial three runs, a hard piped gas collection system was installed and actual gas collection recording was taking place in a temperature controlled chamber.

Channeling of leachate through the biomass can cause portions to experience poor to no anaerobic degradation, a process that evenly mixes and evenly compresses the components of the biomass before beginning a trial run may reduce the channeling encountered.

Pressure should be monitored in the pumping lines and the vessels to determine if gas is being entrapped in the biomass and increasing the pressure in the vessels to cause leakage. NASA should consider all packaging materials and crops brought on a long-term mission for biodegradability to make the anaerobic digestion system most feasible for the mission. (i.e., select crops with the highest biodegradability and choose paper for packaging over plastics and synthetic materials.)

Suggestions for Future Work

This work was preliminary and should continue so the following topics of interest can be addressed:

- Nutrient balances for N, P, and K; need to be determined, with identification of their concentrations in feeds and effluent liquid, solid, and gas streams.
- Plant growth potential and phytotoxicity studies should be conducted on digester effluent solid and liquid streams.
- Pretreatment and post-treatment options necessitate evaluation, including feed shredding, feed compaction, effluent dewatering, and aerobic post-treatment of solids.
- Pathogen reduction during the post treatment process should be assessed.
- Further prototype testing to achieve a bulk density of 300kg/m^3 in the reactor should be preformed.

LIST OF REFERENCES

Advanced Life Support Baseline Values and Assumptions Document. NASA Document Number CTSD-ADV-484. 2002.

Advanced Life Support Project Plan. NASA Document Number CTSD-ADV-348RevC. 2002.

Advanced Life Support Requirements Document. NASA Document Number CTSD-ADV-245B. 2002.

Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document. NASA Document Number CTSD-ADV-383. 2001.

Bendixen H. Safeguards Against Pathogens in Danish Biogas Plants. Water Science Technology. IWA Publishing. Colchester, UK. 30:171-180. 1994.

Christensen T, Cossu R, Steggman R. Landfilling of Waste: Lachate. Elsevier Applied Science, Ltd. London, UK. 1992.

Chynoweth D. Environmental Impact of Biomethanogenesis. International Journal of Environmental Monitoring and Assessment. Kluwer Academic Publishers. Berlin: GR. 42: 3-18. 1995.

Chynoweth D, Bosch G, Earle J, Owens J, Legrand R. Sequential Batch Anaerobic Composting of the Organic Fraction of Municicpal Solid Waste. Water Science Technology. IWA Publishing. Colchester, UK. 25(7):327-339. 1992.

Chynoweth D, Bosch G, Earle J, Legrand R, Liu K. A Novel Process for the Anaerobic Digestion of Municipal Solid Waste. Applied Biochemistry and Biotechnology. Portland Press Limited. Portland, OR. 28/29: 421-432. 1991.

Chynoweth D, Haley P, Owens J, Teixeira A, Welt B, Rich E, Townsend T, Choi H. Anaerobic Digestion for Reduction and Stabilization of Organic Solid Wastes During Space Missions: Laboratory Studies. SAE Technical Paper 2002-01-2351. International Conference on Environmental Systems. San Antonio, TX. 2002.

Chynoweth D, Pullammanappallil P. Anaerobic Digestion of Municipal Solid Wastes. In Palmisano A, Barlaz M eds. Microbiology of Slid Waste. CRC Press, Inc. Boca Raton, FL, p. 71-113. 1996.

Diemer R, Ellis T, Silcox G, Lighty J, Pershing D. Incinerators. Kirk-Othmer Encyclopedia of Chemical Technology. 4th Edition, Wiley, John & Sons, Inc. Indianapolis, IN. 14: 86-122. 1996.

Drake B. Reference Point Architecture and Technology Study: Human Exploration of Mars – "1000" Day Class Mission." Internal NASA presentation. Houston, TX. 1999.

Edeen M, Kumagai G, Dittner L, Landau L, Schweickert R, McFadden C. Advances in Development of Bioreactor Technology for a Regenerative Life Support Primary Water Processor. ICES paper # 951740. Warrendale, PA. 1995.

Engeli H, Edelmann W, Fuchs J, Rotterman K, Survival of Plant Pathogens and Weeds During Anaerobic Digestion. Water Science Technology. IWA Publishing. Colchester, UK. 27:69-76. 1993

Ewert K, Curry D, Lin C, Brown R. Thermal Control, Chapter 16, Human Space Flight: Mission Analysis and Design, Larson W, Pranke L. Editors, McGraw-Hill Space Technology Series, New York, NY. 1999.

Fisher J, Pisharody S, Wignarajah K, Lighty J, Burton B, Edeen M, Davis K. Waste Incineration for Resource Recovery in Bioregenerative Life Support Systems. ICES paper # 981758. Warrendale, PA. 1998.

Haug R. Compost Engineering, Principles and Practices. Ann Arbor Publishers, Inc. Ann Arbor, MI. 1993.

Hoitink H, Keener H. Science and Engineering of Composting: Design, Environmental, Microbiological, and Utilization Aspects. Renaissance Publications, Worthington, OH. 1993.

Kaba L, Hitchens J, Bockris. Electrochemical Incineration of Wastes. 19th Intersociety Conference on Environmental Systems, San Diego, CA. #891510, July 1989.

Maxwell S, Drysdale A, Assessment of Waste Processing Technologies for 3 Missions. SAE Technical Paper 2001-01-2356, International Conference on Environmental Systems. Orlando, FL. 2001.

Mendell W, Plescia J, Tribble A. Surface Environments, Chapter 4, Human Spaceflight: Mission Analysis and Design, Larson W, Pranke L. Editors, McGraw-Hill Space Technology Series. New York, NY. 1999.

Miller G, Portier R, Dickey D, Sleeper H. Using Biological Reactors to Remove Trace Hydrocarbon Contaminants From Recycled Water. ICES paper #911504. Warrendale, PA. 1991.

NASA “Increment 3 Cargo Flow Summary 02/07/02,” National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, International Space Station Program Office, Mission Integration and Operations Office, Houston, Texas. Spreadsheet. 2002.

Owen W, Stuckey P, Healey J, Young L, McCarty P. Bioassay for Monitoring Biochemical Methane Potential and Anaerobic Toxicity. Water Resources. IWA Publishing. Colchester, UK. 13: 485-492. 1979.

Owens J, Chynoweth D. Biochemical Methane Potential of MSW Components. Water Science Technology. IWA Publishing. Colchester, UK. 27(2):1-14. 1993

Rajeshwar K, Ibanez J. Environmental Electrochemistry, Fundamentals and Application in Pollution Abatement. Academic Press, San Diego, CA. 1997.

Suidan M, Scrhoeder A, Nath R, Krishnan E, Brenner R. Treatment of CERCLA Leachates by Carbon-Assisted Anaerobic Fluidized Beds. Water Science Technology. IWA Publishing. Colchester, UK. 27:273-282. 1993.

Tatapudi P, Fenton J. Electrolytic Processes for Pollution Treatment and Pollution Prevention. Advances in Electrochemical Science and Engineering, Vol. 4. Weinham, GR. 1995.

Tennakoon C, Hitchens G, Murphy O, Rogers T, Verostiko C. Waste Processing Using Packed Bed Electrolysis Reactor with Thermal Pretreatment at High Pressure. ICES Paper #951742. Warrendale, PA. 1995.

Verostko C, Alazraki M, Joshi J, Fisher J, Solids Waste Processing and Resource Recovery for Long-Duration Missions-A Workshop. SAE Technical Paper 2001-01-2351. International Conference on Environmental Systems. Orlando, FL. 2001.

Wheeler R. Food and Crop Systems Technology Element for Advanced Life Support. Advanced Life Support Teleconference. Gainesville, FL. 2001.

Woese D. Bacterial Evolution. Microbial Reviews. American Society of Microbiology. Washington, D.C. 51: 221-227. 1987.

Xu Q, Townsend T, Chynoweth D, Haley P, Owens J, Rich E, Maxwell S, Choi H, Anaerobic Digestion for the Reduction and Stabilization of Organic Solid Waste During Space Missions: Systems Analysis. SAE Technical Paper, International Conference on Environmental Systems. San Antonio, TX. 2002.

Zinder S. Physiology Ecology of Methanogens. p 128-206. in Ferry J (ed.) Methanogenesis: Ecology, Physiology, Biochemistry, and Genetics. Chapman and Hall. New York, NY. 1993.

BIOGRAPHICAL SKETCH

My name is Patrick E. Haley and I am attending the University of Florida. I am studying in the Department of Agricultural and Biological Engineering, focusing on bioprocess engineering, researching anaerobic degradation of biological wastes. In 2002, I obtained my B.S. from the Department of Agricultural and Biological Engineering at the University of Florida. As a student I was very active in clubs and organizations. I was president of the UF student chapter of the American Society of Agricultural Engineers and active in the UF Alpha Epsilon Agricultural Engineering Honor Society. I also conducted heat transfer demonstrations for undergraduate classes and touring high-school students. I enjoyed my teaching and research experience during my time at the University of Florida.