

Blackstone Ranch Institute Innovation Challenge Grant

Final Report

Improving cold season biogas digester efficiency for global energy solutions

Report by Katey Walter Anthony¹ and Thomas Culhane²

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PARTICIPANTS

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Dr. Peter Anthony: Senior personnel (UAF); Assisted in experimental design and implementation of small-scale, cold-temperature biogas research in Alaska and Botswana

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Capitalizing on interdisciplinary synergies, these Explorers used an innovative way to harness the power of the Arctic's cold-tolerant methane-producing microbes by introducing them to affordable equatorial-derived biogas digesters to simultaneously battle global climate change, slow deforestation in tropical forests, and meet the energy needs of households and communities worldwide that experience cold seasons.

COLLABOTATORS (alphabetical by region)

Alaska, USA - Clay Koplín (Cordova Electric Cooperative) and Adam Low (Cordova High School science teacher); Cordova High School chemistry class (students); Laurel McFadden (UAF technician); Casey Pape (UAF technician). Collaborated with PIs K. Walter Anthony and TH Culhane through a parallel Denali Commission Grant on small-scale biogas digester experimentation with temperature and microbes in Cordova, Alaska.

Botswana - Dereck and Beverly Joubert, (Great Plains Conservation & National Geographic Explorers in Residence); Pete Unwin (Selinda Reserve); Katherine Mackinnon and Marijn Letschert (Zarafa Camp); Dave Pahl and Gobusamang Mokopi (Selinda camp). The Jouberts hosted K. Walter Anthony and P. Anthony for cold-temperature improvements to biogas digesters at the Selinda and Zarafa camps in the Okavango River Delta.

Brazil - Luis Felipe Vasconcellos (Architecture for Humanity, lead architect); Theresa Williamson (Catalytic Communities NGO, director).

California, USA - Alvaro Silva (Solar South Central NGO community leader); Mike Bonifer (Game Changers Director); Frank DiMassa (DiMassa Utility Consulting, Sonoma).

China - Dr. Jianan Wang (Puxin Biogas technologies, Shenzhen, CEO).

Egypt - Mustafa Hussein (ICE Cairo -- Innovation, Collaboration, Entrepreneurship); Kareem Ibrahim and Naveen Akl (Architects, Aga Khan Trust for Culture); Dr. Laila Iskander (Roh El Shabab NGO founder, current Minister of the Environment); Hanna Fathy (Roh El Shabab NGO community leader).

Germany - Sybille Culhane, Solar CITIES e.V.; Imbrahm Biogas, Essen, Germany; Dr. Martin Denecke, University of Essen, Engineering Professor and Biogas researcher. Dr. Sven Volkmouth, M.D. (director, Chance for Growth NGO).

Hungary -- Esther Kovach (Director of Gypsy Development NGO Vedegylet <http://www.vedegylet.hu>), Mester Attila (Engineer for Vedegylet).

Israel and Palestine - Yair Teller, Oshik Ofrazi (Ecogas Israel Home Biogas CSO and CEO); Mike Kaplan and Alex Cicelsky (Kibbutz Lotan Green Apprenticeship Program Directors); David Lehrer (Arava Institute for Environmental Studies Director).

Iraq - Taha Majeed (Iraqi Ministry of Science and Technology - Engineer), Karin Mayer (Chief Humanitarian Officer, United Nations Assistance Mission in Iraq, UNAMI); Jacqueline Babcock (Director General UNAMI); Frank Finver (US Embassy Iraq, Chief Cultural Affairs Officer).

Kenya - Dominic Wanjahia Kahumbu (Simply Logic Flexi-Biogas, CEO); David Redmond, Henry Okayao and Adam Masava (Mukuru Slum Art Center Teachers and Students); Kakenya Ntaiya and Salenta Ntaiya (Kakenya's Dream School, Enoosaen), Dereck Joubert and Dorian Hoy (Ol Donyo Was Nature Reserve).

Kurdistan - Jennie Lee (US Embassy Erbil, Public Affairs Officer).

Minnesota, USA - Zach Spangenberg, (middle school student and farmer from South Africa, experience with biogas production in dairy farming in Minnesota); Assisted K. Walter Anthony in biogas research in South Africa and conducted an internship supervised by K. Walter Anthony and middle school science fair project studying winter-time methane production beneath an ice-covered lake in Minnesota.

New York, USA - Dean Joan Toglia, Dean Mary Kelley, Associate Provost Saul Fisher, Facilities Director Tom Simmonds (Mercy College, Health and Natural Sciences and Social and Behavioral Sciences); Gail Richardson Ph.D. (Executive Director, Solar Cities Solutions), Andrew Faust (Permaculture Design Institute), Diana Juettner Ph.D and Tom Madden (Greenburgh Town Council); Anne Jaffe Holmes (Greenburgh Nature Center).

Nigeria -- Former President Oluwasegun Obasanjo (flew us to his country and had us stay with him in his home in Abeokuta and provided drivers to take us to build and train people in biogas digester construction at his home, at the Bell's High School, at a University and at a Hospital and introduced us on stage in presentations at churches and schools).

Philippines - Bernard Pierquin (Director, Alouette Foundation, Pasay City and Palawan Island, Philippines), Sven Volkmouth M.D. and Christian Kories M.D (Chance for Growth e.V., Germany, which supports the Alouette Foundation).

South Africa - Dr. Sonette Marx (North West University), Piet Lodder (AgriEden), Yvette and Zach Spengenberg (farmers), Duwig Everson (Earthship, S.A.). Consultation about potential for widespread biogas technology in South Africa.

Tanzania - Grace Gobbo, National Geographic Emerging Explorer and Ethnobotanist, Joram Samoan (assistant to Grace Gobbo, volunteer with Jane Goodall Institute).

Turkey - Melisa Eyiakkan (Fox Television, National Geographic Channel, PR and Communications Director), Kursad Fendoglu (Director of IT at Onkosel Biyoteknoloji); Mohammed Ansarin (Koc University Dept of Engineering); Yaşat Hacıbaloglu (Marmara University Dept of Engineering).

Slovakia -- Mgr. Ján Grenčík (programový koordinátor Dobrej noviny Catholic Mission)

Washington DC, USA - Carsten Binsner, Mohammed Nouristani, Vivianne Forrester (Washington Math Science Technology School Science Teachers and Curriculum Coordinator).

PROJECT SUMMARY

Energy is a high cost, imported commodity to most communities. Biogas digester systems, which take organic material into an air-tight tank, where microbes break down the material under anaerobic conditions and release methane-rich biogas, may offer an alternative energy solution. Biogas can be burned as a fuel for cooking, heating, generating electricity and powering lights; and the liquid effluent can be used as organic compost. While small-scale biogas digesters are being used by thousands of households in India, Egypt, Costa Rica, and other warm-climate countries, seasonal limitation to biogas production is experienced in colder climates due to the shut-down of mesophilic (warm loving) microbial communities in winter. This project set out to improve the efficiency of biogas digesters under cold climate regimes by inoculating digesters with active-methane-producing psychrophiles (cold-tolerant microbes) readily available in Alaskan thermokarst (thawing permafrost) lake mud and the natural mud in ecosystems of other regions characterized by seasonally cold temperatures. Psychrophilic methanogens, despite a temperature optimum of 25°C, still actively produce methane year-round at temperatures as low as 0°C in Alaska, unlike conventional microbes.

The objectives of this project were to:

- Improve the efficiency of existing small-scale methane biogas digesters, including by using cold-adapted microbes to increase cold-season biogas production
- Produce a renewable and alternative fuel
- Reduce the release of harmful greenhouse gasses
- Implement dwelling-size and community-scale applications to evaluate their acceptance and sustainability for widespread application in the United States, Germany, Egypt, and other locations
- Test the technology to help fight deforestation in Africa by using biogas to replace firewood

This project was carried out in three phases. Phase I and II were accomplished through collaboration with a Denali Emerging Energy Technology Grant obtained by PI K. Walter Anthony; results were previously reported to the Denali Commission Alaska. In Phase I, we used an experimental approach to compare biogas production rates from psychrophilic (lake mud) vs. mesophilic (manure) microbial consortia in six small, 1000-L household scale digesters under two relatively cold temperature regimes (15°C and 25°C) in Cordova, Alaska. Phase II research focused on the utilization (the capture, compression, analysis and usage) of biogas produced during the project and assessment of this technology for widespread application in cold-climate boreal and arctic communities. Phase III involved implementing knowledge gained from experiments in Alaska in other regions of the world where utilization of cold-adapted microbes could improve biogas efficiency during cold seasons.

In Phase I, we found that digesters containing psychrophiles were more robust to temperature and pH fluctuations. Among our experimental digesters, tanks containing psychrophile-rich lake mud produced more biogas (275 ± 82 L gas d⁻¹, mean \pm standard deviation) than tanks inoculated with only mesophile-rich manure (173 ± 82 L gas d⁻¹); however, digester temperature appeared to be the overarching control over biogas production among all tanks. Extrapolating the linear relationship between biogas production and mean digester temperature observed among our study tanks [Production (L gas d⁻¹) = 34.35*Temperature (°C) - 432] to the temperatures typically used for biogas production in warmer climates (35-40°C), it is possible that our digesters would have produced 770-940 L gas d⁻¹, a rate similar to that reported for warm climate digesters. Without knowing the temperature response from the microbial communities in our specific digesters, it is not possible to extrapolate these results with a high level of certainty; however, we can conclude that psychrophile-rich lake mud is a viable source of microbial inoculums for producing biogas at cold temperatures, albeit at only 28-56% of rates typical of warmer temperature regimes. Other benefits of the psychrophile-rich lake mud digesters included reduction of foul odor and a source of nutrient-rich, liquid organic fertilizer for growing plants.

Combining the observed biogas production rates with the long-term mean methane concentration of biogas collected from the digesters (~67% CH₄ by volume), biogas had an equivalent BTU rating of 3,950-6,270 BTU per digester per day (mean) and 12,750 BTU per digester per day (maximum).

In Phase II of the project, we designed and implemented a new gas collection system suitable for small-scale applications. The system, based on a telescoping holding tank principle, is simple and easy to assemble in areas where elaborate mechanized storage and gas delivery systems are not available. The gas was collected from the primary digesters using the telescoping

storage system and delivered for use in a variety of applications to demonstrate biogas utility as a source of combustion fuel. The most notable demonstration projects included the use of biogas as a cooking fuel with a cast iron single-burner stove, powering of a 4-cycle lawn mower engine, production of electricity using a converted gas-powered generator and use of digester effluent as liquid fertilizer in a student greenhouse project.

A Benefit-Cost Analysis and Sensitivity Analysis to assess the economic feasibility of the project showed that small scale biogas digesters are not cost-effective at the current prices of displaced fuels and electricity in Alaska. While replication of the small, household-scale biogas digester technology is unlikely in Alaska due to the heat and energy requirements of maintaining digesters above freezing in winter, the time required for building and maintenance, and the relatively low energy yield; this technology could be economically viable in regions with different economies.

In Phase III we implemented knowledge gained in Phases I and II to help improve small-scale biogas digester efficiency in various other regions of the world where seasonally cold temperatures challenge biogas production. This phase of the project involved strong collaboration among the project participants and collaborators in the United States and other countries (see Collaborators). This phase provided the opportunity for collaboration among various National Geographic, Blackstone Ranch, and other national and international partners to establish a foundation for climate friendly household and community-scale energy independence. We observed in Phase III that the benefits of biogas technology are global. The collection and utilization of methane, one of the strongest greenhouse gases, prevents its release into the atmosphere. Waste streams often present a liability to communities by filling landfills and posing environmental hazards; however, biogas technology offers other uses for waste streams. The overall impacts of biogas technology include protection of the environment and the potential for reduced energy costs, even when implemented at small scales in some regions.

Keywords: Biogas, anaerobic digester, reactor, psychrophiles, mesophiles, methane, methanogens, Alaska, cold-climate, thermokarst lakes.

1. Introduction

1a) Background

Anaerobic digester technology has been in use for hundreds of years for the making of high energy, methane-rich gas, known as biogas. Modern implementation of the technology is wide-spread throughout urban and rural communities in India and China, with emerging efforts in Africa and Europe gaining popularity in recent decades. The technology is based on the biological production of methane by bacterial and archaean microbes, particularly methanogens, which naturally break down organic feedstock to produce methane in anaerobic conditions (without oxygen). This process can be observed in nature in bubbling methane seeps from lakes, peat bogs, and other organic-rich oxygen deficient environments (Walter et al., 2006).

The basic concept behind a biogas digester is to create an ideal environment for a methanogenic microbial community, and then harvest the methane which it produces over time. As the microbe's needs are minimal, a relatively simple technology develops: provided with an organic, water-logged, food substrate, the anaerobic microbes produce methane which bubbles out of the substrate into a collection vessel. This is opposed to aerobic microbes which consume oxygen and produce carbon dioxide as a byproduct of respiration. By collecting the gases vented from a biogas digester, useful work can be performed by diverting and combusting the gas in variety of conventional gas-powered devices.

Temperature is a major restricting factor in biogas technology (House, 1978, Massé et al., 1997, Gerardi, 2003). Traditionally, ungulate manure containing mesophilic (warm-loving) microbes is used as a source of both methanogens and substrate. Each addition of manure to anaerobic digesters simultaneously supplies microbes and organic material, allowing conversion of organic matter to methane-rich biogas. However, the metabolism of mesophiles slows or shuts down at cold temperatures (usually below 20-25°C). This requires that digesters employing mesophilic microbes be stored indoors, heated, or retired in the cold season.

If solutions to this temperature-limitation were achieved, biogas technology could prove an excellent alternative energy source for communities, especially those which face particularly high fuel costs and have a high per capita energy consumption rates due to cold climates (EIA, 2011). It is already known that psychrophilic (cold tolerant) methanogens thrive in cold lake bottom mud across Alaska and Siberia, producing methane year round. These microbes have been shown to produce strong methane seeps in thermokarst (permafrost thaw) lakes even in the middle of winter, at temperatures close to freezing (Walter et al., 2006, 2007). With this in mind, this project set out to test the capacity of psychrophilic microbes collected from Alaskan thermokarst lake sediments and sediments from other natural ecosystems that experience seasonally cold temperatures to improve biogas production in existing small-scale digester technology under cold temperatures.

In Phase I, we used an experimental approach to compare biogas production rates from psychrophilic vs. mesophilic microbial consortia in small, household scale digesters under two relatively cold temperature regimes (15°C and 25°C). Phase II research focused on the utilization (the capture, compression, analysis and usage) of biogas produced during the project. Phase III implemented knowledge gained in Phases I and II through improvements to small-scale biogas digester in other regions of the world where seasonally cold temperatures challenge digester efficiency.

1b) Project Goals and Hypotheses

The objectives of this project were to: improve the efficiency of existing methane biogas digesters operating at cold temperatures by utilizing cold-adapted microbes from thermokarst lake bottoms, produce a renewable and alternative fuel, reduce the release of harmful greenhouse gasses, and implement dwelling-size applications to evaluate their acceptance and sustainability for wide spread application.

In experimental Phase I, we tested the following hypotheses:

- H1: Biogas production will be greater at tepid (25 °C) temperature than at cold (15 °C) temperature.
- H2: At any given cold or tepid temperature, tanks inoculated with cold-tolerant microorganisms (psychrophiles) from thermokarst lakes will produce more biogas than tanks inoculated with warm-loving microorganisms (mesophiles) in manure.
- H3: Despite psychrophiles having an advantage over mesophiles at cold temperatures, biogas production at cold temperatures (15-25 °C) will not be as great as at warm temperatures (35-50°C).

Phase II Objectives:

- O1: Demonstrate the capture, storage and utilization of produced biogas to power household-scale appliances
- O2: Evaluate the technology with respect to the potential for its practical widespread application in communities.

Phase III Objectives:

- O1: Deploy temperature data loggers in small-scale biogas digester systems in other regions of the world to quantify daily and seasonal temperature fluctuations
- O2: Consult with national and international collaborators to help improve efficiency of existing small-scale biogas digesters
- O3: Utilize knowledge gained in Phase I and II, particularly that cold-adapted microbes collected from local natural-ecosystem sediments can be used to sustain biogas production during cold seasons
- O4: Establish a social network as network for climate friendly household and community-scale energy independence through small-scale biogas utilization. See <https://www.facebook.com/groups/methanogens/> and <http://solarcities.blogspot.com>

2. Methods

Phase I

2a. Experimental design. Figure 1 shows the experimental design of the anaerobic digester experiment conducted under the leadership of PI Walter Anthony in Cordova, Alaska in Phase I. Six 1000-L Sorbitol HDPE containers (tanks), obtained from local Cordova fish processing facilities, were converted into single continuous feed anaerobic digestion reactors and inoculated with methanogenic microbial cultures obtained from thermokarst lake sediments in Fairbanks

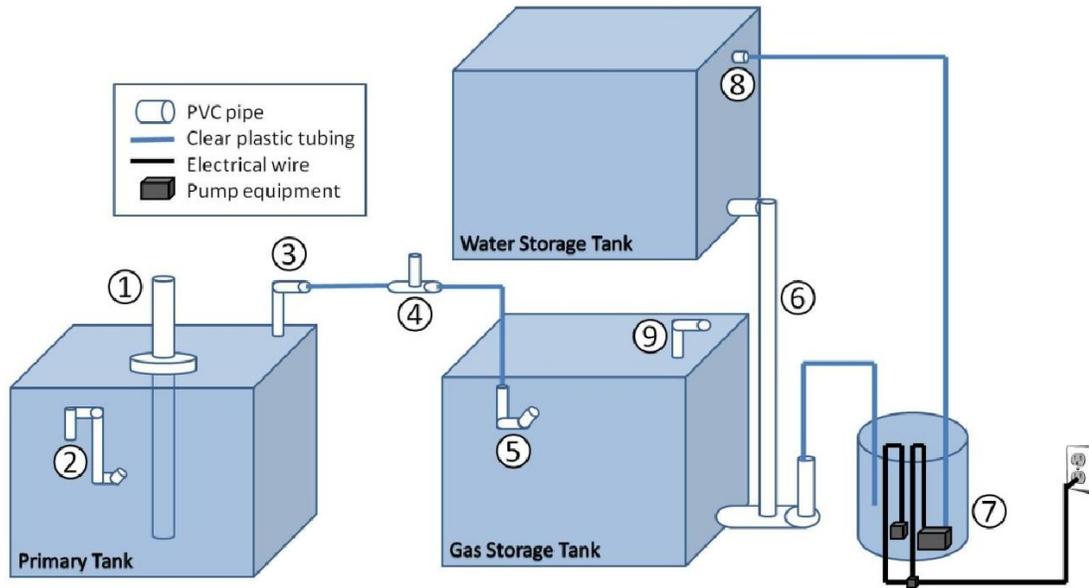


Figure 2. Schematic showing the 3-tank digester and water pressure system. 1) Feeding tube 2) Effluent pipe 3) Primary gas outlet 4) Flame tester 5) Gas inlet 6) Water transport 7) Pump bucket 8) Water inlet 9) Final gas outlet. After experiencing considerable drawbacks of the water storage tanks and gas pressurization system, we removed components 5-9 and either exhausted biogas outside or collected and pressurized biogas in a secondary, telescoping holding tank that required no external power source.

Hobo temperature data loggers (HOBO water temp pro v2 U22-001) were secured to the feeding inlet tube in each tank. Tanks 1, 3, 4 and 6 had multiple loggers installed at the top, middle and bottom of the tank in order to observe potential temperature stratification. Both rooms within the Conex were monitored by Onset pendant loggers (HOBO UA-002-64). Cordova local area temperature data was obtained from online sources (www.wunderground.com).

On February 19, 2010, the reaction vessels were sealed to facilitate microbial O_2 consumption in the tanks for the establishment of anaerobic conditions. Initial physical and chemical data on starting conditions were recorded.

2b. Tank chemistry measurements.

We measured pH, dissolved oxygen (DO) and oxidation reduction potential (ORP) initially three times per week, and later weekly, in 100-mL samples collected from each of the six digesters. pH measurement were initially quantified by visual assessment using Macherey-Nagel litmus paper (used until April 16, 2010) and with a more precise electrode (Oakton PC510) from April 17, 2010 through June 6, 2011. ORP measurements were performed with an Xplorer GLX Pasco PS-2002 Multi-Datalogger from January 21st to April 9, 2010, before more accurate instrumentation was available (Oakton PC510 ORP meter). Dissolved oxygen measurements were recorded with an Xplorer GLX Pasco PS-2002 Multi-Datalogger until March 24, 2010, and later with a Hanna HI9142 DO meter.

2c. Feeding digesters

Once it was established through chemistry measurements that the tanks were mostly anaerobic and through positive flame tests that biogas production had begun (within 2 days to 2 weeks, depending on the tank), we began feeding tanks to provide substrate to fuel methanogenesis. In accordance with conventional warm-temperature, small-scale biogas system protocols (Samuchit Enviro-Tech Pvt. Ltd.), students from Cordova High School's chemistry class fed each tank a 2-kg organic slurry consisting of 1-kg wet food weight plus 1-kg water. Food scraps from the school lunch hall were collected daily and processed in large batches by way of an industrial sink disposal (Appendix 1). The processed food scraps were then divided into measured 1-kg portions, labeled and frozen in a large storage freezer kept in the school's science classroom. Each day, individual portions were removed from the freezer, thawed, and fed to digesters through a 2" PVC (schedule 40) pipe that extended 2 feet above and 3 feet down into the reactor vessel, into the water liquor. At the time of feeding, reactor gas valves were closed off and equivalent volume of effluent was removed via a 1 inch ball-valve located mid-level in the side of each tank. After each feeding treatment was performed, the students reopened the reactor gas valves and capped the feed inlet tube. Effluent was disposed of through the local storm water sewer system, located near the project site.

2d. Gas flow measurements

Gas flow was measured in real-time from February 18 – December 11, 2010 using mass flow meters installed in-line with the gas outlet valve on each reactor vessel (Sierra Top-Track 820 Series). For better quality measurements, later gas flow data were obtained using the same flow meters, but on different, labor-intensive sampling intervals. As of December 2010, all monitoring of biogas production was performed by closing off tank gas outlet valves for 6-8 hours to allow the reactors to build positive pressure. As the tanks began to distend, pressure was relieved by partially opening the valve and allowing biogas to flow past the mass flow meters at a higher rate, which was in the range of the flow meter calibration.

2e. Gas composition analysis

We sampled biogas from the outflow pipes of each digester over the course of the two-year study. Samples were collected into 60-ml glass serum vials, sealed with butyl rubber stoppers, and stored under refrigeration in the dark until analysis in the laboratory following the method described in detail by Walter et al. (2008). We measured the concentration of methane (CH₄), carbon dioxide (CO₂), oxygen (O₂) and nitrogen (N₂) in samples using a Shimadzu 2014 gas chromatograph equipped with an FID and TCD at the Water and Environmental Research Center (WERC) at University of Alaska Fairbanks (UAF).

2f. Effluent nutrient analysis

Samples of reactor effluent were periodically collected from each digester over the course of the experiment. Samples were stored in 20-mL scintillation vials, sealed with paraffin tape, and frozen on-site until being sent to the UAF WERC lab for analysis. Nutrient fractions were

analyzed on a high pressure liquid chromatograph (Dionex LC 20) equipped with auto feed sampler on April 18, 2010. Samples were run [unfiltered] with a five to one dilution ratio (1:5).

2g. Odor. Qualitative observations of odor from digester effluent samples were recorded.

Phase II

2h. Biogas collection and storage

Initially, a gas storage system was constructed outside the project Conex and used to store biogas via a water-pressure and pump system. The system was built by PI T.H. Culhane to demonstrate to the project how biogas is stored and utilized in his projects outside Alaska. In September 2010 this system, which was not appropriate for Alaskan environments due to freezing of water inside pipes and tanks, was disassembled, allowing biogas to vent from digesters to the outside atmosphere. In June 2011, a telescoping 500-gallon (approx. 2000-L) HDPE tank was installed on-site to collect and distribute biogas produced inside the project Conex container (modified from a 500 gal and 1000 gal tank, Greer Tank and Welding, Inc., Fairbanks, AK). The collection vessel consolidated and stored gas produced from active tanks 1, 4, 5 and 6 using ½” reinforced vinyl and ¼” air tubing. Standardized ¼” gas ball-valve and female flaring were used to make further connections down line of the storage vessel.

The larger 1000 gal containment vessel was filled with approximately 500 gal of water to serve as an air seal for the top gas-holding tank. Pressurization of the gas was performed by placement of a water-filled 1000-L HDPE tank above the floating tank (Fig. 3).

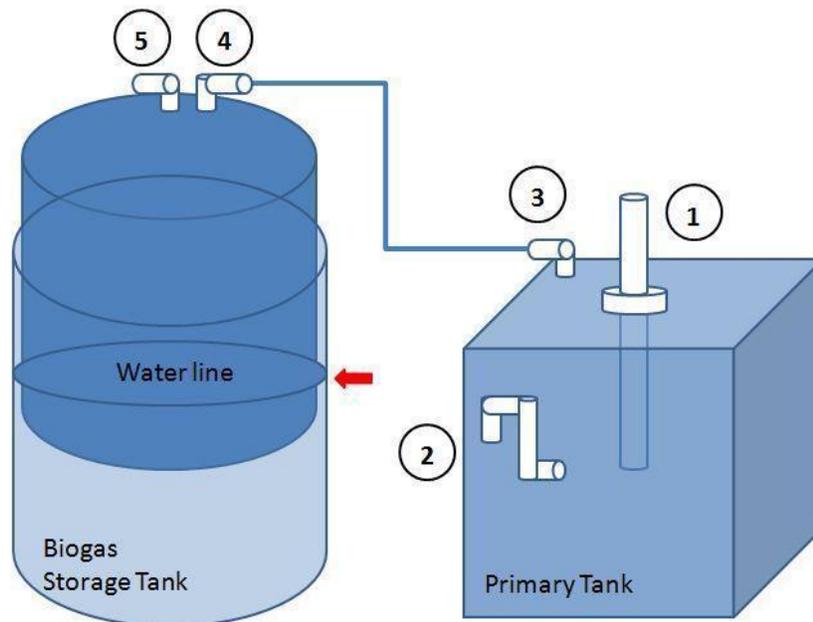


Figure 3. Schematic of a successful telescoping gas collection and re-distribution system. 1) Feeding tube 2) Effluent pipe 3) Primary gas outlet 4) Storage collector inlet 5) Gas outlet valve. The biogas storage container was filled approximately half way full in order to create an air seal

for the collector vessel above. The top floating collection vessel was open at the bottom. Additional weight was placed on top of the floating tank to increase biogas line pressure.

2i. End use testing

Biogas combustion demonstrations were performed using a converted single-burner cast iron stove with 3/8" natural gas conversion kit (SGB-01 NGKIT). Power generation demonstrations were performed using an 1850-W generator with 4-cycle Subaru engine (Husky) with a tri-fuel carburetor conversion kit installed. All fittings were adapted with 1/4" male compression to female swivel flares for ease of operation.

Additional student science projects and demonstrations were performed with biogas stored in car tire inner tubes. Air hose lines were connected to 1/4" Schrader valves which were used to fill the tubes. The tubes were then transported to a proper testing site in order to distribute the contained biogas.

3. Results

Phase I results

3a. Temperature control in the Conex

Temperature fluctuations inside the project Conex closely mimicked changes in ambient outside temperature at the Cordova study site (Fig. 4). The average temperature \pm standard deviation recorded in Cordova for the study period (January 15, 2010 – June 15, 2011) was 3.6°C. Though experimental room temperatures drifted from design conditions of 15°C and 25°C throughout the course of the project, the average temperatures remained elevated above ambient air temperature and were within close proximity of initial targets. Average \pm standard deviation of the recorded 'cold' and 'tepid' room temperatures in the Conex were 15.4 \pm 7.1°C and 25.6 \pm 5.1 °C respectively.

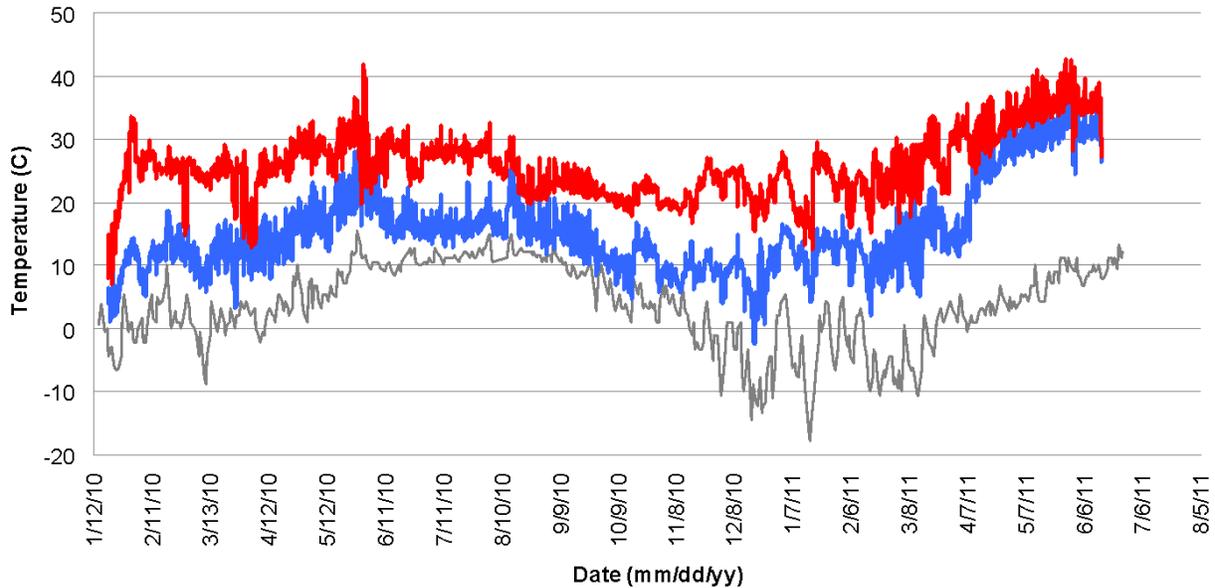


Figure 4. Ambient Cordova mean daily air temperature (grey) and mean hourly room temperature in the Conex ‘cold’ (blue) and ‘tepid’ (red) rooms during the study period, January 15, 2010 – June 15, 2011.

The average temperature of digester slurry, recorded from temperature loggers located at the bottom of each tank, varied by as much as 3.3 °C among tanks within each of the two rooms (Fig. 5). The average temperature \pm standard deviation in each tank was: tank 1 ($15.9^{\circ} \pm 6.7$ C), tank 2 (16.1 ± 7.1 °C), tank 3 (14.8 ± 6.0 °C), tank 4 (22.5 ± 4.3 °C), tank 5 (22.8 ± 4.3 °C), and tank 6 (19.5 ± 4.4 °C). When available, data from loggers placed in the tops of tanks showed higher temperatures than loggers placed at the bottom of tanks (Fig. 6).

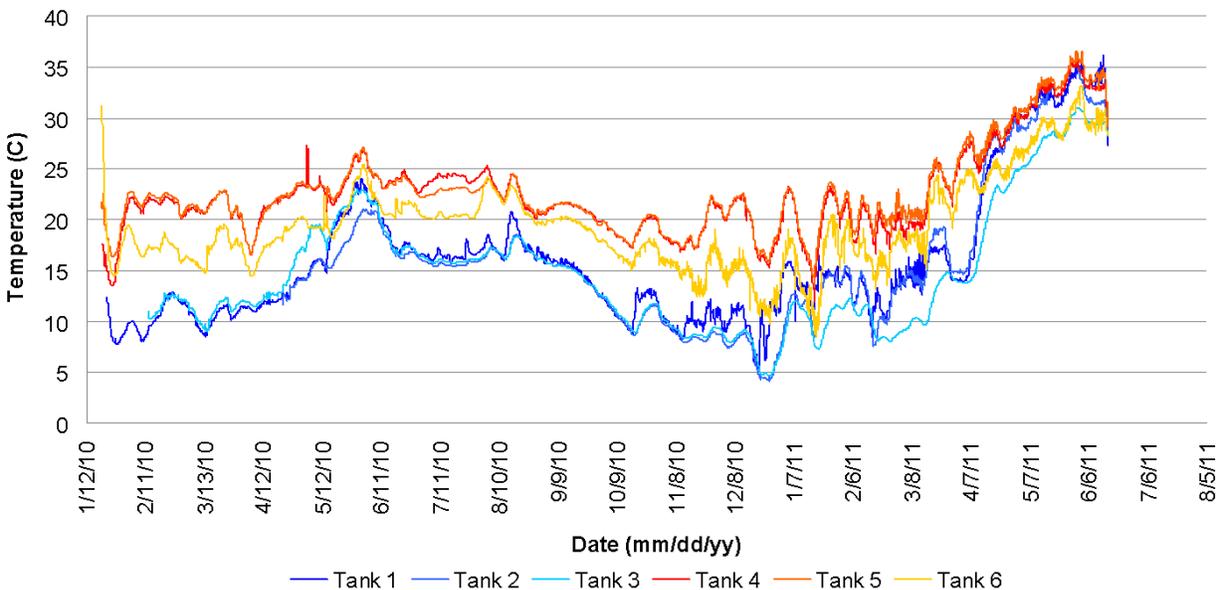


Figure 5. Mean hourly temperature of the data loggers in the bottom of the digesters. Tanks 1-3 were located in the cold room, while tanks 4-6 were located in the tepid room. Digester temperatures tended to track room temperatures, which followed the trend of outdoor air temperatures (Fig. 4).

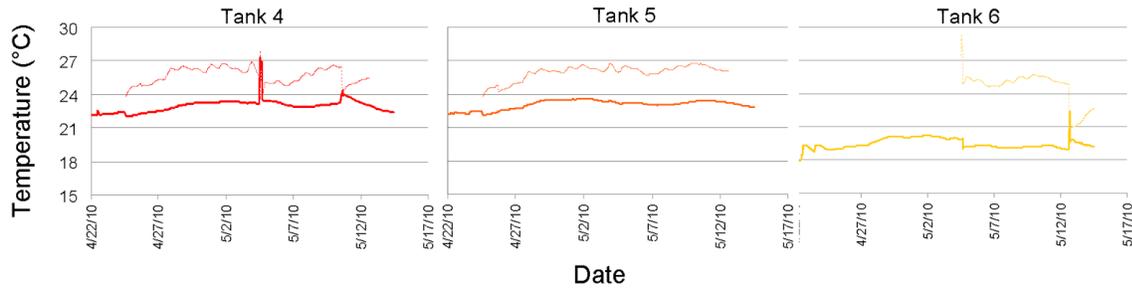


Figure 6. Temperature at the top (dashed lines) and bottom (solid lines) of three digesters. The temperature differences within individual tanks indicate thermal stratification in digesters.

3b. Digester chemistry

Measurements of pH, oxidation-reduction potential (ORP) and dissolved oxygen (DO) were conducted to monitor conditions inside digesters over the course of the experiment, and to alert researchers to potential conditions which could inhibit methanogenesis, such as low pH or high DO or ORP.

We observed that the pH of digester slurries drifted significantly from neutral pH towards acidic pH during the initial part of Phase I. On March 22, 2010, digester feeding regimens were halted and chemical remediation treatments commenced using calcium carbonate (CaCO_3), calcium oxide (lime, CaO) and sodium hydroxide (NaOH) in order to restore digester pH to more neutral conditions. On June 6, 2010, chemical remediation treatments were stopped and the feeding schedule recommenced. By September, 2010, all tanks had recovered to a near neutral pH, except tank 3, which remained acidic. The final pH values, recorded June 11, 2011, were: tank 1 (7.71), tank 2 (7.49), tank 3 (4.82), tank 4 (7.52), tank 5 (7.49), and tank 6 (7.64) (Fig. 10).

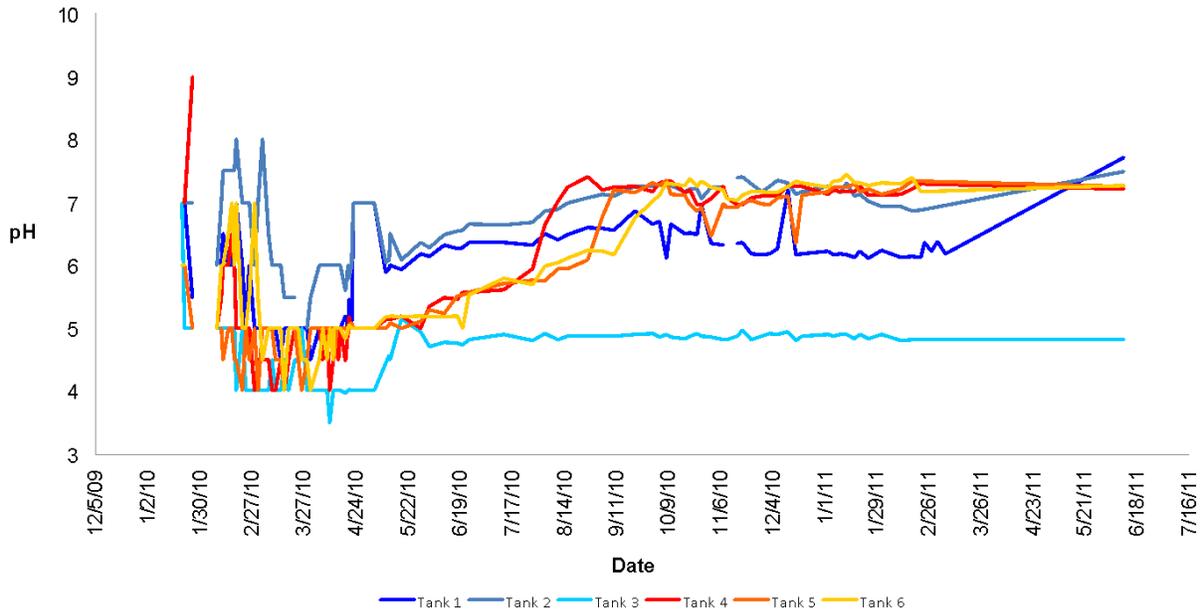


Figure 7. pH of digester slurries in six anaerobic digesters from January 2010 until June 15, 2011.

The oxidation-reduction potential (ORP) of reactor effluent, recorded throughout the experiment, was appropriately low at the onset of the study. ORP increased after feeding commenced, in parallel to the decrease in pH. After pH stabilization, ORP decreased in all of the digesters except Tank 3 (Fig. 8).

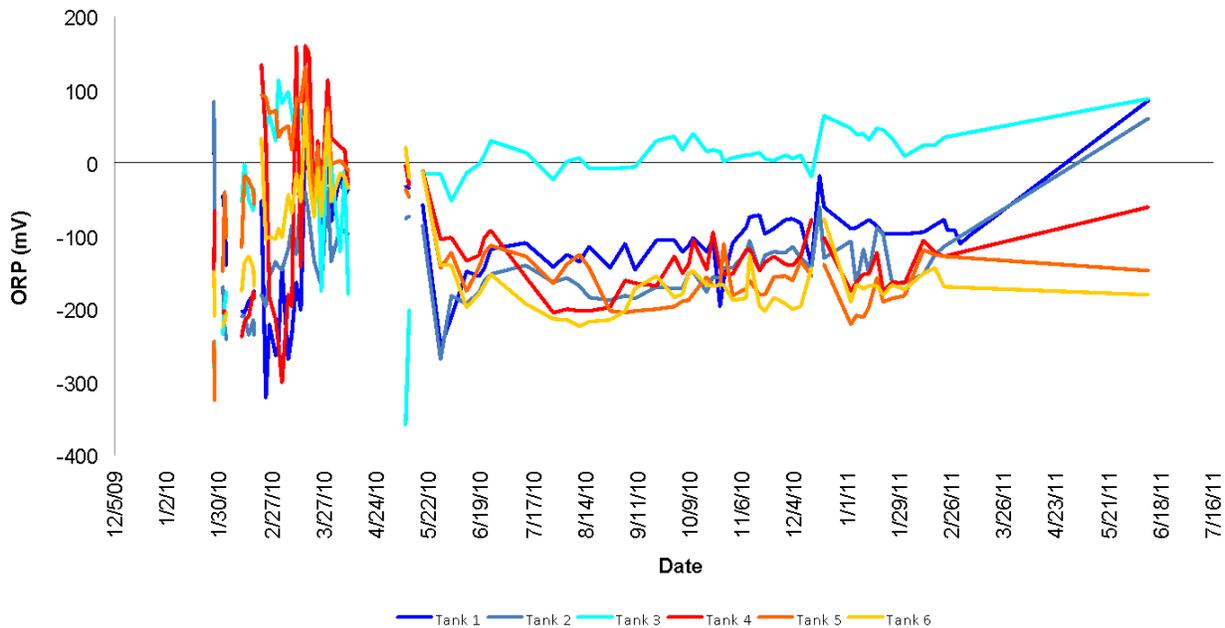


Figure 8. Oxidation reduction potential (ORP) in anaerobic digester slurries.

Measured dissolved oxygen (DO) levels were low, but rarely zero, during the course of the project. The Hanna instrument used to measure DO was reported to be improperly calibrated on several occasions during the fall of 2010, resulting in slightly elevated levels of DO being

recorded (data not shown). After servicing in December 2010, DO measurements returned to values observed earlier in the project (Fig. 9).

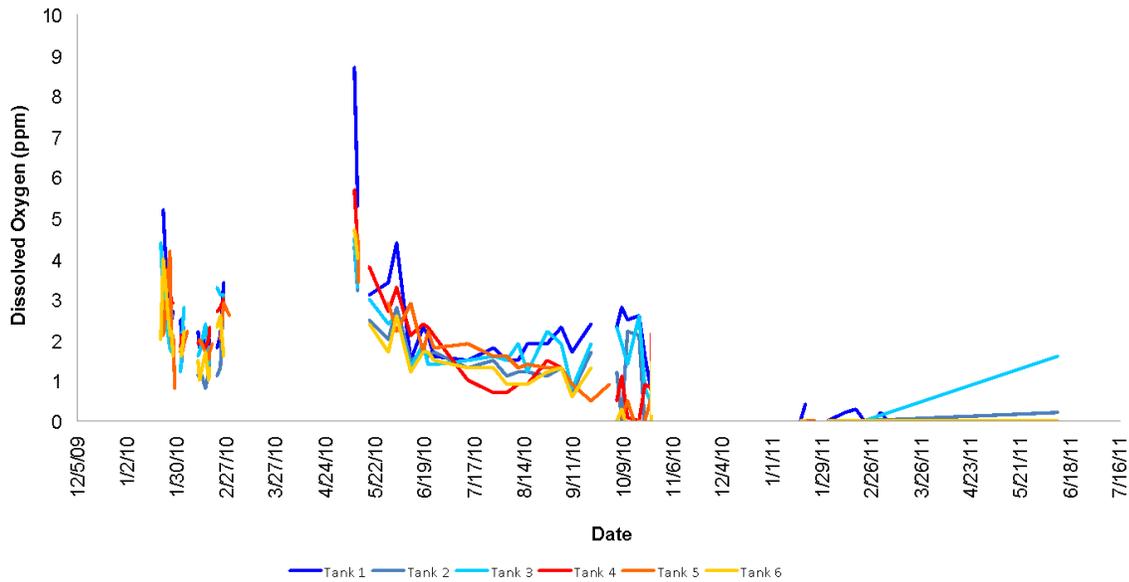


Figure 9. Dissolved oxygen concentration measured in anaerobic digester slurries.

3c. Gas production: Psychrophiles vs. mesophiles at two temperatures

Biogas production was observed throughout the majority of this project. Within two days to two weeks after initial set up, all tanks were producing flammable biogas. The methane content of the gas decreased when tanks acidified in winter 2010 due to over-feeding; however, flammable biogas production was again demonstrated in all tanks except Tanks 2 and 3 by December 2010 (Table 1). Throughout the duration of the project we qualitatively observed that anaerobic digesters in the tepid room produced more biogas than digesters in the cold room.

Table 1. Results of flammability tests

Tank	First positive flame	Last confirmed flame
1	1/31/10	6/6/11
2	NA	NA
3	1/22/10	2/1/10
4	2/1/10	6/6/11
5	1/21/10	6/6/11
6	1/26/10	6/6/11

After improving the method for quantitative measurement of gas flow rates, we found that indeed, biogas production was on average 6 times higher in the psychrophile-only digester in the 25 °C room (Tank 4; 275 ± 90 L gas d⁻¹ expressed as average \pm standard deviation) compared to the psychrophile-only digester in the 15 °C room (Tank 1; 46 ± 23 L gas d⁻¹) (Fig.10).

The psychrophile-only Tank 4 (275 ± 90 L gas d⁻¹) had the highest average biogas production rate among all digesters, and produced roughly 60% more biogas per day than the mesophile-only Tank 6 (173 ± 82 L gas d⁻¹) in the 25 °C room. Tank 5 in the 25 °C room, containing a mixture of psychrophile-rich lake bottom mud and mesophile-rich manure, produced biogas at a similar average rate to Tank 4 (265 ± 80 L gas d⁻¹), and exhibited the highest maximum daily production rate among all digesters (559 L gas d⁻¹) during the period of measurements.

It should be noted that these biogas production rates were approximate estimates on several dates owing to observed spills from the tanks during measurement on three days each for Tanks 4 and 5, and on two days for Tank 6 (Table 2). Due to a lack of sufficient pressure (e.g. low biogas production) in Tanks 2 and 3 we were unable to obtain flow rate measurements in 2011.

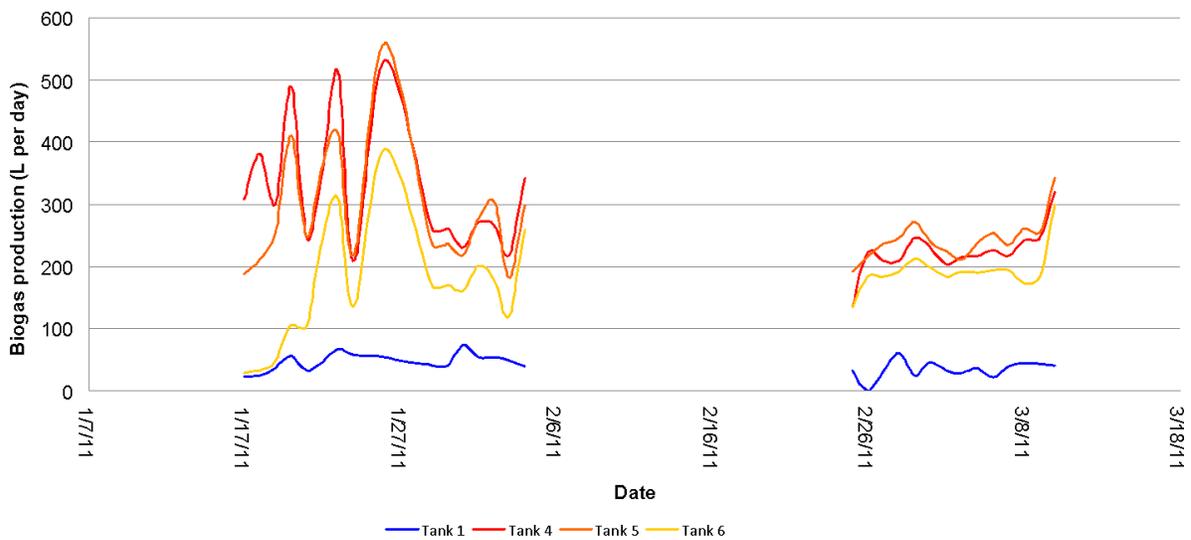


Figure 10. Biogas production, normalized to 1000-L of slurry per digester, observed in Tanks 1, 4, 5 and 6 during winter 2011. Fluctuations in production are an artifact of the sampling method, where tanks were sealed for 6-8 hours to build pressure in between gas flow readings.

Table 2. Daily biogas production values for winter 2011, normalized to 1000-L of slurry volume. The values represent average gas production within a 24hr period for each tank. On several occasions, built up gas pressure contained in the headspace of the reactors caused tanks to expel some of their liquid contents from the tanks (indicated by *). Dates of occurrences of tanks spills were both documented and undocumented as students may not have reported a spill during several instances when researcher and teacher support was not available.

Gas Production Summary Data (L gas d ⁻¹ normalized to 1000-L of slurry)						
Date	15°C Room			25°C Room		
	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5	Tank 6
12/11/2010	33	0	0	188	195	0.5
12/12/2010						
1/17/2011	23	0	0	308	187	28
1/18/2011	25	0	0	382	210	32
1/19/2011	37	0	0	300	254	49
1/20/2011	56	0	0	491	410	107
1/21/2011	32	0	0	246	247	104
1/22/2011	46	0	0	353	361	244
1/23/2011	68	0	0	514	413	310
1/24/2011	58	0	0	209	218	135
1/26/2011	53	0	0	532	559	390
1/29/2011	41	0	0	*260	236	170
1/30/2011	41	0	0	260	236	170
1/31/2011	73	0	0	230	*218	160
2/1/2011	55	0	0	270	277	201
2/2/2011	54	0	0	266	304	176
2/3/2011	49	0	0	*219	181	*120
2/4/2011	39	0	0	343	298	259
2/5/2011						
2/25/2011	32	0	0	135	191	133
2/26/2011	1	0	0	222	*215	184
2/27/2011	32	0	0	209	235	183
2/28/2011	59	0	0	209	246	191
3/1/2011	25	0	0	246	271	212
3/2/2011	47	0	0	231	241	198
3/3/2011	32	0	0	203	225	185
3/4/2011	28	0	0	*215	*211	192
3/5/2011	37	0	0	217	238	189
3/6/2011	21	0	0	226	254	194
3/7/2011	38	0	0	217	235	194
3/8/2011	45	0	0	241	262	*172
3/9/2011	43	0	0	247	256	185
3/10/2011	41	0	0	319	343	300
3/11/2011						
6/1/2011	47					
6/11/2011	105					
6/12/2011	116					
6/13/2011	86					
Average	46	0	0	275	265	173
Standard Dev.	23	0	0	94	80	82
Daily Max.	116	0	0	532	559	390

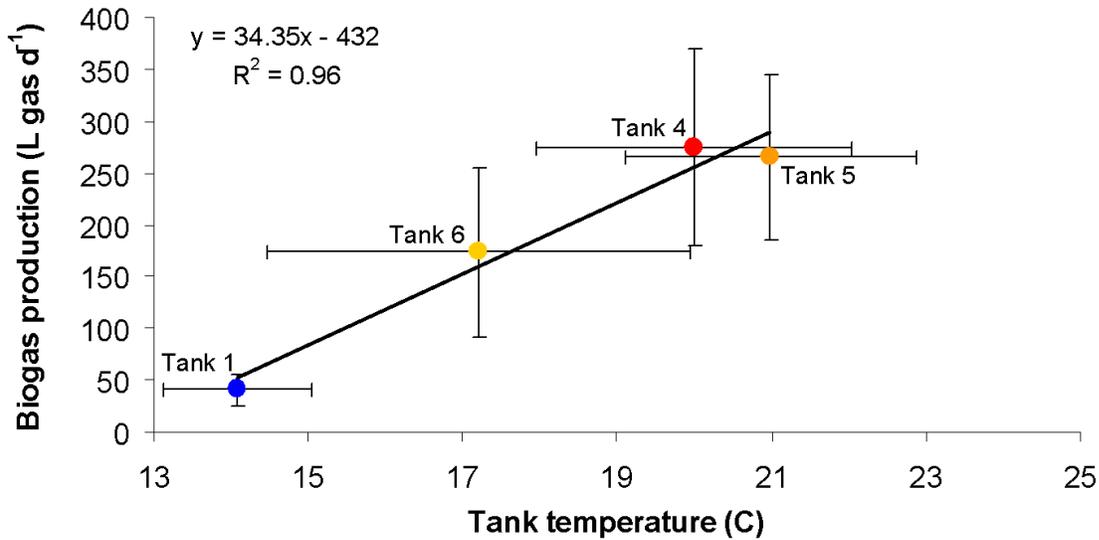


Figure 11. The linear relationship between average daily biogas production and the average temperature of digesters on days of gas production measurements.

3d. Biogas composition

Gas samples collected over the course of the project map the internal environment of each reactor during the experiment. In general, all tank headspace gases exhibited a large increase in methane (CH₄) concentration from the start to end of the study (Fig. 12). Peak methane concentrations were recorded at one time during the experiment as high as 82% by volume. The high concentration was likely due to a pause in feeding over the holidays leading to increased methanogenic/acetogenic activity ratios (Massé, et al., 1997). However, subsequent samples collected during the second year of the project had an average methane concentration of 65% by volume, similar to most anaerobic digester operations (40-60% CH₄) (House, 1978).

Though the target, high-energy molecule in this experiment was methane, other gases also helped illustrate microbial activity as well as overall system health (Figs. 13-15). Atmospheric gases, such as oxygen and nitrogen, were found early in the study in significant quantities (> 5% by volume) among certain tanks, but decreased in samples collected later in phase 1 and 2 of the project (Figs. 6 and 7) after discovered leaks were repaired. Several samples with elevated oxygen and nitrogen concentrations were due to errors in sampling (atmospheric contamination). Finally, a consolidated sample was collected from gas stored in the large biogas collector installed on June 1, 2011. The sample was known to contain trace atmospheric gases as the headspace of the containment vessel was not completely evacuated prior to collecting biogas.

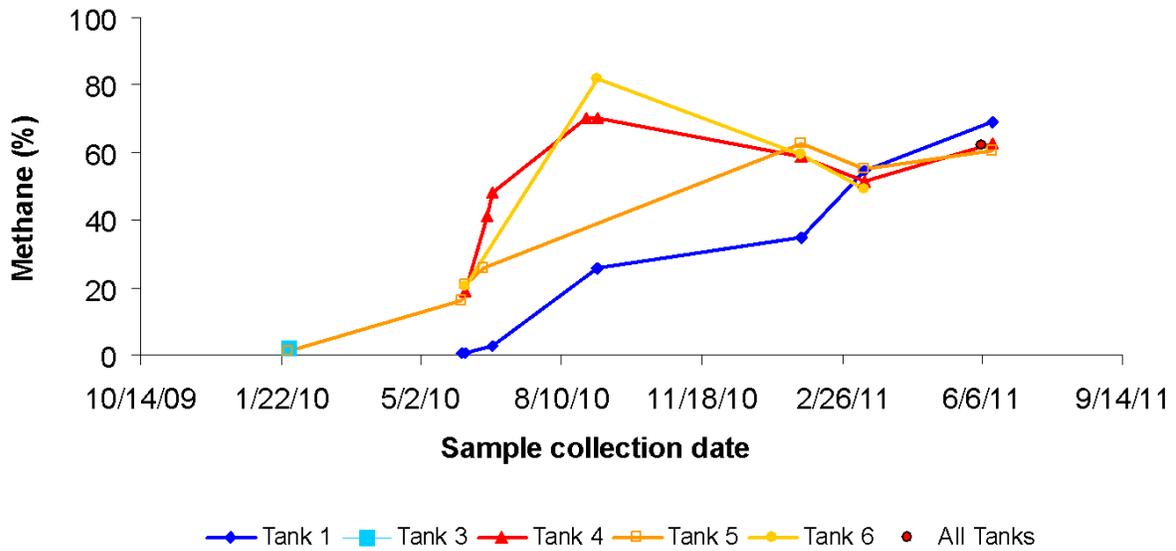


Figure 12. Methane (CH₄) concentration in biogas samples determined on a Shimadzu 2014 gas chromatograph equipped with FID and TCD. The concentration of gases is presented as percent by volume. It should be noted that 70% CH₄ in Tank 4 shown for Aug. 28 and Sep. 5, 2010 was calculated as a correction to lower concentrations measured in samples due to a leak in the sampling system. Both the samples from August/September Tank 4 had the same methane/carbon dioxide ratio - =4.4 Based on a review of the other biogas samples, this should put the methane level of the biogas at ~65-70%, after correcting for presumed dilution from air contamination. The fact that the two samples had the same ratio of these gases, despite a two-fold difference in the methane level, is a good indication that the low reading is due to dilution by atmospheric air in the sample collection stage.

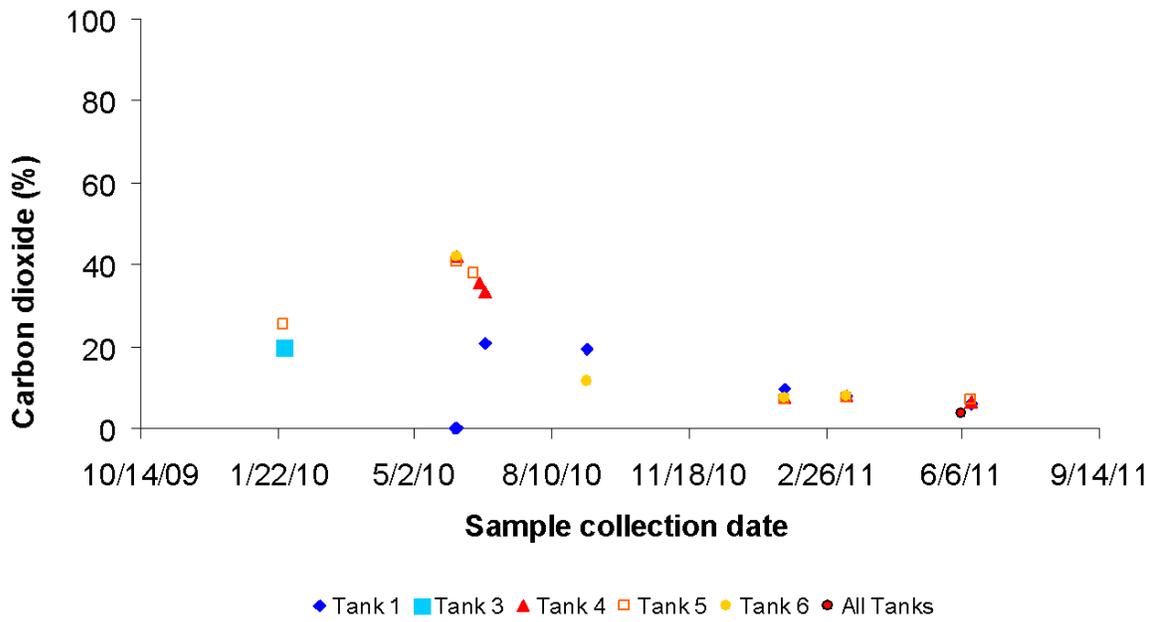


Figure 13. Concentration of carbon dioxide (CO₂) in digesters, presented as percent by volume.

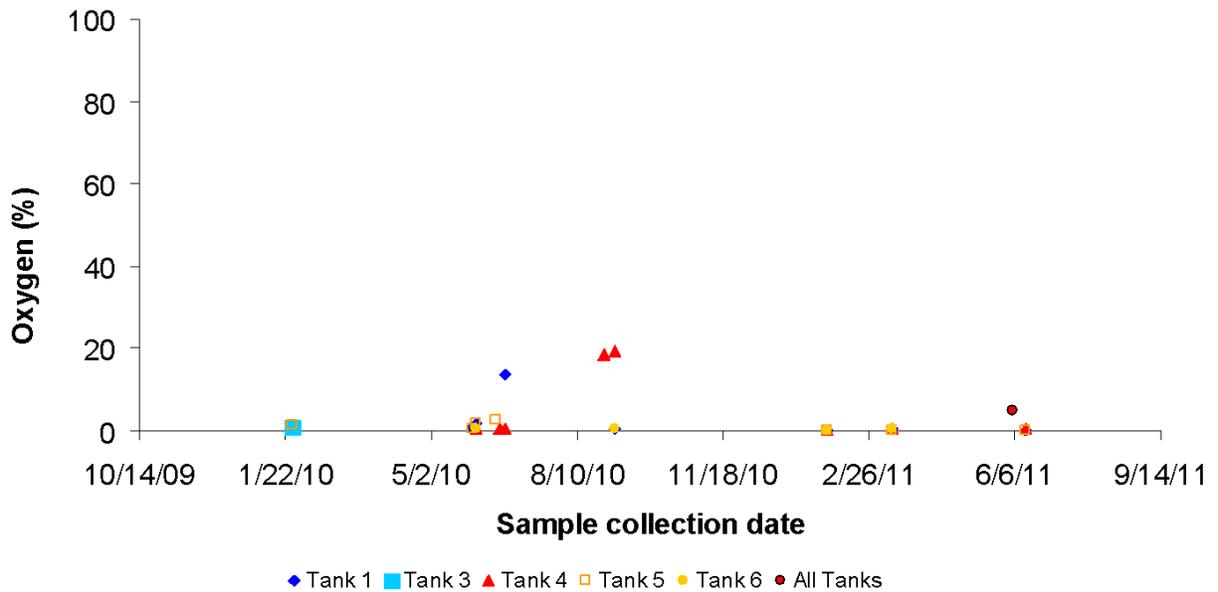


Figure 14. Concentration of oxygen (O₂) presented as percent by volume. Air contamination was known to be present in the samples with O₂% > 2%, and was an artifact of sampling rather than an accurate representation of digester headspace O₂ concentration.

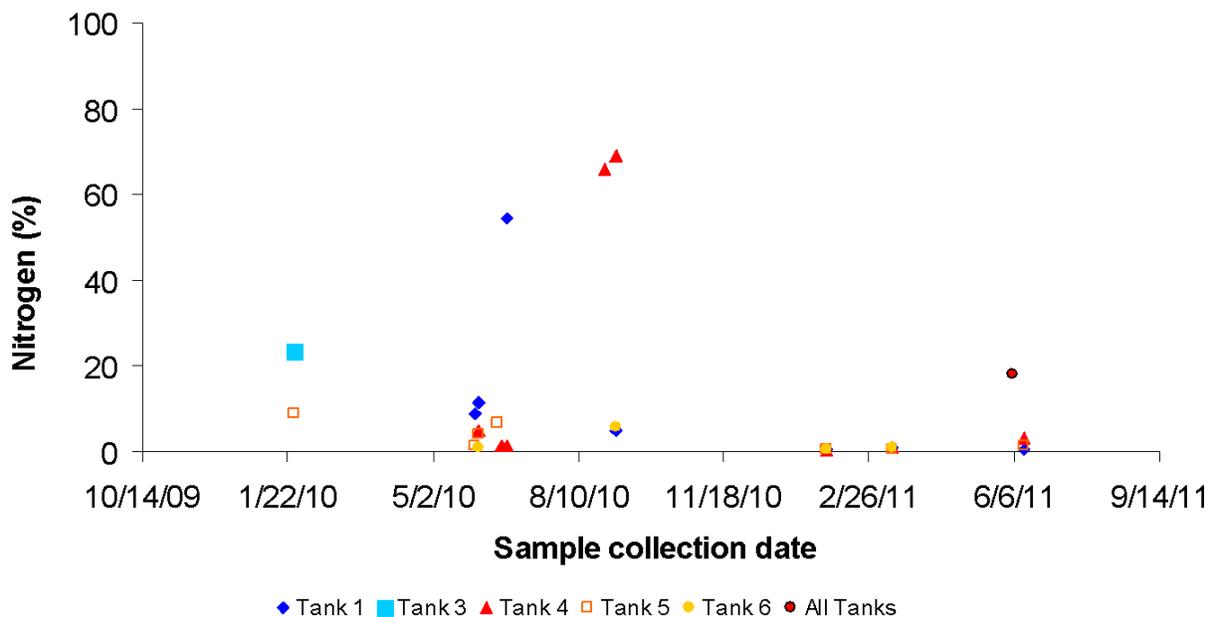


Figure 15. Concentration of nitrogen in digesters presented as percent by volume. Air contamination was known to be present in the samples with N₂% > 25%, and was an artifact of sampling rather than an accurate representation of digester headspace N₂ concentration.

3e. BTU content of biogas

Using Equation 1 together with results of methane concentration in biogas samples we determined the BTU content of biogas. The highest observed production rate of any given 1000-L tank within a twenty-four hour period was 559-L d⁻¹ (Table 2). Combining the observed production rates with the average methane concentration of biogas collected from the site (~67% CH₄ by volume), gas collected at the end the project, had an equivalent BTU rating of approximately 1,275 BTU day⁻¹ per digester. Applying the average methane concentration to the average production rates observed in the tepid room digesters, the average BTU production was 3,950-6,270 BTU d⁻¹ per digester. It is important to note, that this BTU rating is helpful in calculating possible efficiencies of combustion across a range of gas powered devices, but should not be viewed as a static number as the methane content of produced biogas changed over time (Fig. 12) and should therefore be viewed only as a helpful approximation of gas heat content.

Equation 1. Rating BTU content of biogas

$$\frac{\text{Production Rate} \times \text{Gas Composition \%} \times \text{Density of CH}_4 \text{ @ 1bar}}{100} = g \text{ CH}_4$$

$$g \text{ CH}_4 \times \frac{1 \text{ mol}}{16.042g} \text{ CH}_4 = \text{moles of CH}_4 \text{ per daily output}$$

$$n \text{ Mols CH}_4 \times \frac{891kJ}{\text{mol}} \text{ CH}_4 = n \text{ kJ per day*}$$

$$1 \text{ kJ} \cong 0.95 \text{ BTUs} \therefore \text{equivalent measure of gas energy content}$$

* MSDS for Methane (source: encyclopedia.airliquide.com)

3f. Nutrient content of digester effluent

In addition to methane-energy, biogas digesters have the added benefit of producing nutrient-rich organic fertilizer that can be used in agricultural and horticultural efforts. Effluent samples collected over the course of the experiment yielded mixed results with regard to the amount of available nutrients produced from each tank. Analyses were conducted to test the relative concentrations of chloride, fluoride, nitrate, nitrite, phosphate and sulfates using High Pressure Liquid Chromatography. Other tests to measure concentrations of ammonia and ammonium were not available. Samples were run after proper calibration tests were performed to ensure accurate measurement and to track instrument performance during the analysis (Fig. 8).

Concentrations of only chloride and phosphate measured above the detection limit of the instrument used during the analysis. Chloride is commonly used for potable water treatment and showed a strong absorption signal in all samples. This is explainable through the projects use of tap water during the course of the experiment. Phosphate concentrations were observed in most samples in low to moderate concentration(s) – between 5-55 ppm (Table 3).

Table 3. Phosphate concentration in liquid organic fertilizer sampled on n different dates. All samples were run on a Dionex LC 20 chromatograph with Chromeleon data processing software package.

Tank	n	Phosphate (ppm)			
		mean	stdev	min	max
1	1	9.0			
2	4	9.0	6.7	5.0	19.0
3	4	17.3	7.4	12.0	28.0
4	1	42.0			
5	1	30.0			
6	5	36.8	10.6	28.0	55.0

3g. Odor

Qualitative measures of relative odor among tanks were noted during the research phase I of the project. We found that digesters containing lake mud-only had a more agreeable odor than digesters containing manure. Tanks inoculated with psychrophilic methanogens from the thermokarst lake were said to exhibit a smell much like that of a pond or bog. The odor was found to be an earthier and less unsettling smell than that of mesophilic tanks, which smelled of animal manure, the traditional “barn-like” odor commonly used to describe anaerobic digestion facilities, commercial and small-scale. Upon wafting, even the lake-mud-only tanks exhibited a strong ammonia-like smell. Analytical instrumentation was not available for quantification of ammonia, though ammonia is commonly observed in other biogas digesters (Brock, et al. 1970; House, 1978; Gerardi, 2003).

Phase II Results

3h. Biogas storage

Phase II efforts to collect, store, distribute and demonstrate end-use applications of the biogas technology were largely successful. We designed and implemented a new gas collection system suitable for small-scale applications in Alaska and other boreal and arctic communities. The system, based on a telescoping holding tank principal (Fig. 3), is simple and easy to assemble in areas where elaborate mechanized storage and gas delivery systems are not available. Gas pressurization was accomplished by placing additional water weight above the 500 gallon (~2000L) holding vessel, though brick or other weight equivalent could be used in areas where water resources are scarce. During the phase 2 experimental stages, the gas was collected from the primary digesters in the Conex using the telescoping storage system, and delivered for use in a variety of applications to demonstrated biogas utility as a source of combustion fuel. The most notable demonstration projects included the use of biogas as a cooking fuel with a cast iron single-burner stove, powering of a 4-cycle lawn mower engine,

production of electricity using a converted gas-powered generator and use of digester effluent as liquid fertilizer in a student project greenhouse.

3i. End use testing

Demonstrating small-scale applications of biogas technology was the primary goal of Phase 2. Through a variety of projects utilizing combustion, conversion, and transduction capabilities of biogas energy as well as provided educational opportunities for students interested in alternative energies. Phase 2 demonstrations took the form of the continuous powering of a combustion engine and electrical generator, use of biogas as a stove fuel, and application of organic liquid fertilizer obtained from digester effluent. These demonstration projects enhanced the curriculum of Cordova High School students who worked with and presented their findings on the project in multiple appearances at conferences around the state. The following section addresses each of the phase II project results:

Generator. An 1850 Watt electrical generator (Husky) was operated solely on biogas collected from individual project reactors in June 2011. By augmenting the engine carburetor and installing a tri-fuel gas conversion kit, this gasoline powered generator was adapted to run on a variety of gaseous fuels, including biogas. Initial efforts to start the generator were unsuccessful due to limited gas availability and generator requirements for ignition. After raising the pressure of biogas delivery to approximately 0.5-psi and injecting small amounts of ether starting fluid, the generator fired on the first draw of the pull-start cord. At pressures below 0.5-psi the engine was able to maintain idle, but could not achieve sufficient revolutions per minute (RPM) in order to sustain 120V 60Hz AC power. Generator performance was monitored with a 3500K 23W CFL light bulb which maintained continuous luminous quality during generator operation.

We achieved increased gas pressure by adding a second tank on top of the telescoping collection vessel used to store gas and filling it with approx. 175 Gal of water (D_{H_2O} @ 15°C = 1000kg/m³ or 8.34 lb/US gallon). The resulting water weight (approx. 1500 lbs) was enough to increase the pressure in the gas line to about 0.5-psi, sufficient to operate the generator. To this end, the 1850 Watt generator was rated at a consumption rate of approx. 300 gal/hr or ~1,100 L/hr.

Cooking fuel. The primary application for small-scale anaerobic digester technology around the world is in production of biogas for use as a cooking fuel. With minimal amounts of positive pressure, biogas from the Conex digesters sustained a continuous, clean-burning flame once ignited by local spark and/or flame. By adapting a cast iron single-burner stove with natural gas conversion kit, the project was able to boil water and fully cook a variety of foodstuffs using gas collected from project reactors. Using biogas to fuel the stove, 4 liters of water were boiled (T_i = 15°C, placed in a covered pot) within 20 min of exposure to flame. The stove sustained a continuous flame throughout the demonstration despite being in an open, outdoor environment. The stove was used to cook a meal consisting of hot dogs and carrots, consuming roughly 300 L of biogas per hour (~80 Gal/hr).

Liquid fertilizer. In addition to nutrient analysis confirming reactor effluent benefits as a liquid fertilizer treatment for nutrient poor soils (Table 3), Cordova High School students tested samples of reactor slurry in a controlled greenhouse experiment to provide further evidence on nutrient qualities of digester effluent. To duplicate sets of plants, students supplied either the liquid fertilizer from the tank 4 digester, or water as a control. Tank 4 effluent exhibited considerable nutrient values when applied to several different plant species within greenhouse trials. Nutrient analysis of all tanks later confirmed elevated levels of phosphate as high as 55ppm (Table 3), indicating potential use as a fertilizer treatment to soils lacking in sufficient nutrient content (Swift, 2009). Students contend that there was a noticeable difference in height, leaf fullness and health of several plant species treated with effluent over those which only received water additions. The largest differences in growth were observed among the flowering plants, *Lilium Pumilum* and Asiatic Pink Pixies, which responded very well to effluent treatments; however, others like *Lilium Regales* and Asiatic Orange Pixies hardly grew at all when given effluent treatment. Less of a difference in size was noted among the food crop plants, but it was observed that plants fertilized with effluent tasted better on many occasions during blind taste tests. One exception was the root and carrot plants, which were said to not be very appetizing when treated with effluent fertilizer, though no note was provided on whether this was due improper washing/preparation of the crop or if the undesirable taste came from flavors incorporated into the plant roots themselves. No quantitative biomass or root/shoot length measurements were taken.

Curriculum enhancement. Student-led projects were a major component of Phases I and II. In Phase I, students from the high school chemistry class and science club were charged with daily food processing and feeding during Phase I of the study. The students came together on several projects intending to streamline the process which resulted in a number of useful innovations including construction of an industrial sink with built-in insinkerator and improved feeding practices. During Phase II, students and teacher Adam Low took the lead in design, setup and maintenance of a greenhouse experiment to test effluent nutrient characteristics (with assistance from Clay Koplín at CEC). Low and students purchased and converted an 1850W gas-powered generator and 4-cycle lawn mower engine to run on biogas using inflatable tire inner tubes to transport and deliver the biogas from project reactors. Several students went further into performing purification test of biogas by bubbling and collecting gas run through a saturated lime water column. Others still, conducted calorimetry tests in order to approximate the heat value and BTU properties of biogas produced compared to other known and available fuel-types. With these and other demonstrations, students used the biogas project as a platform for state science fair projects in both 2010 and 2011 conferences, held in Anchorage, Alaska. In addition, students presented on the project at a host of difference conference meetings and alternative energy forums.

4. Discussion

4a. Phase I hypothesis testing

Phase I results supported the Hypothesis 1 that biogas production will be greater at tepid (25 °C) temperature than at cold (15 °C) temperature. Gas production rates were on average six times higher in the psychrophile-only tank 4 maintained in the tepid room than the

psychrophile-only tank 1 maintained in the cold room. Similarly, no significant biogas production was observed among cold room tanks containing manure, while considerable biogas was produced in tanks 5 and 6 containing manure in the warm room. At no time during the entire study period did biogas production from cold room tanks exceed daily production rates of adjacent tanks in the tepid room (Fig. 10). The considerable divergence in daily gas production rates observed in tanks between the cold and tepid rooms suggests a strong temperature control on anaerobic digestion and methanogenic activity, such as has been found in other studies (Brock, et al. 1970; Metcalf and Eddy, 1991; Gerardi, 2003). When we plotted average biogas production as a function of average tank temperature, we also found strong temperature dependence among all tanks (Fig. 11).

With the exception of different starting inoculate microbial regimes (psychrophile-rich lake bottom mud vs. mesophile-rich manure), all tanks received identical quality of feedstock treatments and were treated in a similar manner. At times the quantity of feeding was adjusted in some tanks to avoid overfeeding, which can lead to souring, or acidification, of the slurry. Remarkable similarity in digester chemistry among all tanks, except tank 3 (Figs. 7-9), indicates that experimental conditions remained relatively consistent among tanks, and that differences among tanks were likely due to microbial community and temperature.

High variability in biogas production is explained in part by temperature; however other factors likely influenced the health and viability of methanogen populations in tanks. During the early stages of the biogas production test period, we began to observe acidification in most tanks (Fig. 7). We expect that acidification was the result of overfeeding. When the metabolic rate of the methanogen community was insufficient to consume the large quantity of volatile fatty acids (VFAs) and acetate intermediates created by acetogenic microbes within each of the reactors (Gerardi, 2003), acid intermediates accumulate and effectively lower the pH to levels that can further inhibit methanogens, leading to a negative feedback in methane production. When the population and metabolism of methanogens is sufficient, simultaneous conversion of organic feedstock to VFA and acetic acid intermediates to methane and carbon dioxide occurs, and acidification concerns are averted. Excessive feeding prior to adequate establishment of methanogenic populations likely exacerbated the ratio of acetogenic/methanogenic activity and tank acidification to a greater extent in the cold room tanks than in the tepid room tanks, potentially knocking down methanogens more in the cold room than in the tepid room.

Chemical remediation steps were taken to avoid a collapse of each tank's microbial system and were largely successful within the first year of study. Additions of basic chemicals (i.e. Lime, calcium carbonate, and sodium hydroxide) were used to help restore system pH to optimal norms (6.8 – 7.2). These efforts regained digester activity among all tanks by early June 2010, with the exception of tank 3 which continued to exhibit acidic conditions (pH 4.82) through the duration of the project. Biogas production successfully resumed in all tepid room tanks (25°C), but only within tank 1 in the cold (15°C) room. Biogas production apparently ceased in tanks 2 and 3 despite continued additions of feedstock. Low tank acidity for extended periods of time undoubtedly weakened microbial communities within tanks 2 and 3, combined with depressed temperatures which likely resulted in failure of each tank's microbial community. The decreased activity in tank 1 (psychrophiles only) and complete inactivity among tank 2 (psychrophiles and mesophiles) and 3 (mesophiles only) in the cold (15°C) room provides clear evidence in favor of initial predictions about mesophile activity at depressed temperatures. However, evidence from tank 2 suggests that perhaps acidic activity was the predominate cause of tank(s) 2 and 3 becoming inactive as tank 2 contained psychrophilic cultures that would have

been expected to continue production even when mesophilic contributions ceased. Despite acidification under depressed temperatures, no other cause can thoroughly explain why tanks 2 and 3 exhibited crash during the experiment as all tanks in the warmer 25°C room recovered fully from acidification after sufficient chemical remediation.

Through one set of trials, we found that increasing the feeding rate did not result in greater biogas production. However, increasing temperature in the cold room at the end of the study, from 15°C to 35°C increased production in tank 1. It is likely that since the digester had not been fed in several months, we cannot be certain that there was enough remaining organic substrate in the digester to demonstrate its optimal gas production rate. However, these results did suggest that increasing temperature had a positive effect on gas production.

Temperature conditions varied substantially over the course of the experiment. Digester temperatures were lower during colder winter months and warmer in summer, though on average, the temperatures of the cold and tepid rooms were on target: 15.4°C and 25.6 °C respectively. A large effort was put forth during the initial experimental setup to properly insulate the project Conex and keep both rooms at constant temperature; however, electrical heating units and the initial electrical capacity of the site proved to be inadequate in order to maintain proper temperatures (15°C and 25°C respectively) during extended cold winter conditions. These seasonal temperature fluctuations are not unlike what would be expected in many Alaska residences and other cold-climate communities.

Our results are inconclusive to support Hypothesis 2 that at any given cold or tepid temperature, tanks inoculated with cold-tolerant microorganisms (psychrophiles) from thermokarst lakes will produce more biogas than tanks inoculated with warm-loving microorganisms (mesophiles) in manure. While the gas production data alone suggests that digesters containing lake mud had higher gas production rates than the digesters containing manure only in both temperature rooms, when average tank biogas production was plotted against average tank temperature, the data showed a linear relationship between gas production and temperature (Fig. 11). A likely reason for lower gas production rates in tank 6 (manure only, tepid room) was that the average temperature of that digester was lower than tanks 4 and 5. Tank 6 was located next to two exterior walls, and likely lost more heat than tanks 4 and 5. It is possible that a slight inhibitory effect of the mixed culture tank 5 (mud + manure) was observed as the biogas production rate in this tank was lower than what would be expected based on the trend line; however, there was too much variability in the data to draw a firm conclusion. It should also be noted that several recorded slurry spills were noted that obscured flow measurements during the study; however, the magnitude of these spills (<10 L per spill) was small relative to other sources of variability so they likely did not play a significant role.

Without genetic characterization of the microbial communities, we cannot say for certain what the fate of true psychrophiles and mesophiles was in our digesters. While we have no reason to think that cross contamination of the microbes from the lake mud and manure occurred in the digesters, we cannot rule out that this did not happen. It is very likely that the temperature and chemical fluctuations in the digesters benefited some types of microbes and inhibited others, and that the microbial consortium in the digesters at the end of the study was quite different than what it would have been initially in comparison to the original lake mud and manure microbial communities. Ideally, to confirm results of testing Hypothesis 2, microbial culturing and analysis of microbial DNA would have been conducted on the initial lake mud inoculum, manure inoculum, and each of the digester slurries at the end of the study period; however, microbial

DNA work was outside the scope and budget of this project. Microbial analyses would be an exciting direction for future work in this field to go in the future.

Phase I results supported Hypothesis 3 that, biogas production at cold temperatures (15-25 °C) will not be as efficient as at warm temperatures (35-50°C). The maximum daily biogas production rate we measured was 0.559 L gas per liter of slurry per day (L/L/day). Average values ranged from 0.046 (tank 1) in the 15°C room to 0.173 (tank 6), 0.265 (tank 5), and 0.275 (tank 4) L/L/day in 25°C room. These production rates were lower than those observed in other household scale digesters in warm climates and in warm, temperature-controlled projects in Alaska. Biogas production from Alaskan fish waste was demonstrated at 1.0 -1.1 L/L/day in traditional mesophilic batch digestion scenarios at warmer temperature regimes (35°C) (Hartman, et al., 2001). At the 1000-L scale digesters, we measured up to 559-L of biogas production per day under relatively cold temperatures. In comparison, typical 1000-L household scale digesters in India and other countries are known to produce 1000-L of biogas per day, but they are located in warm climates where temperatures (35-40 °C) are more optimal for mesophile metabolism (Karve, A. D., 2011). Extrapolating the linear relationship we observed between the average rate of biogas production and the average tank temperature in this study [Biogas production (L/day) = 34.35*Temperature (°C) – 432], then at 35-40 °C, biogas production rates in our digesters could have increased to 0.77-0.94 L/L/day (770-940 L d⁻¹ per digester), similar to warm temperature biogas digester production rates. However, without knowing the temperature response from the microbial communities in our specific digesters, it is not possible to extrapolate these results with a high level of certainty.

4b. Lessons learned and recommendations for the technology

Through this project a great deal of information was gained regarding the benefits and limitations of biogas technology at the small-scale in Cordova, Alaska. Data on the relative labor required to build and maintain small-scale digesters, as well as the affects of temperature, acidity, feeding and BTU rating/fuel offset characteristics of produced biogas from mesophilic and psychrophilic bacteria cultures were well documented.

Challenges of flow data measurement. Prior to this study, little information was available on gas production monitoring techniques for small-scale biogas technology. Approximate production rates were estimated at around 1,000-L gas per 1,000-L digester fed 2kg food per day, but this was not an analytical measurement. The inherent difficulty is due in large part to the very low volume and pressures generated at the small-scale. Commercially available instrumentation is difficult to calibrate when flow rates are on the order of fractions of mL/sec. During the project, several techniques were developed that answered this question and are a major accomplishment of this study. First we achieved a labor-intensive method of allowing gas to build pressure inside of the digesters for 6-8 hours so that when the outflow valve was opened, the gas flow rates were high enough to obtain reliable data within the calibration range of Sierra flow meters. Second, we developed a less expensive, less labor intensive method for measuring lower flow rates using a submerged tipping cup coupled to an event data logger. Based on the results of this study, two separate techniques now exist for testing and quantifying gas production for biogas digesters at the small scale.

Limitations of the technology at the small-scale. Based on the findings of this study, several recommendations for the future of biogas technology in cold climate communities, such as Alaska, can be offered at this time. It is clear, that of all variables which influence biogas production, temperature still remains the most formidable obstacle for digester projects at the small-scale. Though psychrophilic additions were demonstrated to improve digester conversion efficiency at low temperature, the BTU quantity of gas produced was not sufficient to meet the heating requirements of digesters at this scale. At elevated temperatures (>30° C) in other climatic zones, household-scale biogas reactors are used in millions of homes to produce enough fuel to be used in practical daily applications, typically as a cooking fuel. In Alaska, however, replication of biogas technology is not economically viable because digesters require external heat sources. In situations where excess thermal or waste heat can be diverted in order to heat digesters, projects of smaller-scale (1000-2000L) may still be justifiable for the additional products they offer by way of secondary energy recovery (i.e. the formation of a clean-burning gaseous fuel), reducing waste stream and waste water treatment costs and production of liquid fertilizer for seasonal crop production.

This study aimed to test the feasibility of small-scale biogas digesters in Alaska that are typically intended for use by single-family, traditionally low-income rural peoples located within the equatorial region. For homes in places like India and China for example, daily per capita energy consumption is much lower than that of the typical Alaskan home of similar size and therefore additional scalability would be required in order to meet Alaskan individual heating and energy needs. Likely infrastructure and capital requirements to operate at this scale would not be cost competitive with current alternative fuel-types. For this reason, anaerobic digesters intended for the individual family-scale are not likely to catch on in great number within Alaskan (or other U.S) communities; however, they have higher potential for use in other world economies.

5. Economic feasibility assessment of the project

UAF researchers worked together with the Institute of Social and Economic Research (ISER) to perform a Benefit-Cost Analysis and Sensitivity Analysis to assess the economic feasibility of small-scale biogas technology in Cordova, Alaska, make recommendations regarding the future of the technology for Alaskans interested in installing a reactor of similar scale within an individual home, and determine the technology's level of marketability to Alaskan communities at large.

The following section of this report was compiled by Sohrab Pathan, research associate at ISER, and has not been edited by UAF and Solar CITIES researchers who wrote the Final Report.

Introduction

The psychrophile bio-digester in Cordova is a new technology that aims to produce low cost biogas for the rural Alaskans who live in extreme cold temperatures. The production of biogas varies significantly depending on ambient temperatures. The technology is in its research and development (R&D) phase which makes in-depth economic analysis challenging. This paper describes a preliminary economic analysis of this new technology. In order to provide a comprehensive study at this early stage in technology development, the analysis was prepared using a benefit-cost method and sensitivity

analysis that show the impacts of variations in methane output, and diesel fuel, electricity and propane prices.

Assumptions

- (1) The analysis is based on a conceptual bio-digester, not based on the actual bio-digester located at Cordova
- (2) Project life of 10 years
- (3) Real discount rate of 3%
- (4) The biogas output at 30°C was not tested during the demonstration project's operation, it is an assumption based on literature review of the technology. Microbial metabolic rates were tested at 15°C and 25°C in Cordova. There is no extensive data to support that at 30°C this particular digester will produce 1,000 liter of methane in one day.
- (5) The price projection of propane was done using propane prices as published by the University of Alaska Fairbanks, Cooperative Extension Service Food Survey¹. All base prices are for year 2010. The base price was \$4.2275 per gallon for propane and was set to increase over time at 4.64%, the average percentage increase from 2007 to 2010. The electricity base price was \$0.2942 per kWh, and the projection was set to increase at 5.73%, the average percentage increase from 2003 to 2010². The 'after Power Cost Equalization (PCE) adjustment' electricity base price was \$0.1824 per kWh, and the projection was set to increase by 12.0%, the average percentage increase from 2003 to 2010. Two diesel fuel price projections, medium and high were used, based on projections previously published by ISER³.
- (6) Cost for food waste is assumed zero since those can be collected from the neighborhood with minimal effort.
- (7) Labor cost is assumed to be \$10/hr, adjusted for the opportunity costs of unemployed rural Alaskans (high estimate).
- (8) O&M costs are projected to increase 2.53% per year, the average percent change of Anchorage CPI over last twenty years⁴.

Benefit-Cost Analysis and Sensitivity Analysis

Methane production levels from a bio-digester differ significantly depending on ambient temperatures. Methane production levels determine the amounts of fuel potentially displaced. Hence this analysis reviews benefit cost ratios based on three different ambient temperatures: 15°C, 25°C and 30°C, and fuel price projections for three types of fuel: diesel (\$ per gallon) - medium projection, diesel (\$ per gallon) - high projection, propane (\$ per gallon), electricity (\$ per kWh) - before PCE⁵ and electricity (\$ per kWh) - after PCE.

Estimates of displaced fuel quantities were based on the methane production at three temperature levels. The following heat values were used⁶: Methane: 1 cubic feet = 1000 Btu, Diesel: 1 gallon = 138,690 Btu, Propane: 1 gallon = 92,500 Btu or 1 cubic feet = 2,500 Btu, and Electricity: 1kwh = 3,412 Btu. Table A shows *displaced fuel quantities* for diesel, propane, and electricity at different temperatures:

Table A. Estimated Fuel Displaced from a Psychrophiles Bio-Digester

Displaced Fuel Quantity		
15 °C	Diesel (gallon)	5
	Propane (gallon)	7
	Electricity (kWh)	188
25 °C	Diesel (gallon)	32
	Propane (gallon)	49
	Electricity (kWh)	1,319
30 °C	Diesel (gallon)	93
	Propane (gallon)	139
	Electricity (kWh)	3,767

Benefit-cost (B/C) analysis shows that B/C ratios for this developing technology are low (Table B). At 15°C, the benefit-cost ratio is 0.01 for displaced diesel with the medium-price projection, 0.03 for the displaced propane, and 0.04 for displaced electricity-after PCE. Higher ambient temperature assumptions yield higher bio-gas production, hence B/C ratios improve marginally. At 30°C, the B/C ratios increase, but are still below one; 0.25 for diesel at the medium price projection; 0.53 for propane and 0.96 for electricity-after PCE. As Table 2 shows, the only scenario that yields a B/C ratio higher than one is at 30°C for electricity-before PCE which results in 1.06. Table C shows the net present values for each scenario.

Table B. Benefit-Cost Ratios Estimated for a Psychrophiles Bio-Digester

Benefit-Cost Analysis Scenario		B/C Ratio
15 °C	Diesel - medium projection	0.01
	Diesel - high projection	0.02
	Propane	0.03
	Electricity - before PCE	0.05
	Electricity - after PCE	0.04
25 °C	Diesel - medium projection	0.09
	Diesel - high projection	0.13
	Propane	0.18
	Electricity - before PCE	0.37
	Electricity - after PCE	0.34
30 °C	Diesel - medium projection	0.25
	Diesel - high projection	0.38
	Propane	0.53
	Electricity - before PCE	1.06
	Electricity - after PCE	0.96

Table C. Net Present Values Estimated for a Psychrophiles Bio-Digester

Displaced Fuel Cost		2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	NPV of Benefit
15°C	Diesel - medium projection	15	17	17	18	18	18	19	19	20	20	21	\$168
	Diesel - high projection	17	21	25	27	28	29	30	31	32	33	34	\$254
	Propane	31	32	34	35	37	39	40	42	44	46	48	\$356
	Electricity - before PCE	59	62	66	69	73	77	82	87	92	97	102	\$716
	Electricity - after PCE	34	38	43	48	54	61	68	76	85	96	107	\$579
25°C	Diesel - medium projection	106	116	120	123	126	129	132	135	139	142	146	\$1,178
	Diesel - high projection	117	147	173	188	196	203	211	218	225	231	236	\$1,775
	Propane	215	225	236	247	258	270	282	296	309	324	339	\$2,490
	Electricity - before PCE	410	434	459	485	513	542	573	606	641	677	716	\$5,010
	Electricity - after PCE	269	302	338	379	425	476	533	597	669	750	840	\$4,539
30°C	Diesel - medium projection	302	332	343	350	359	367	376	386	397	407	416	\$3,367
	Diesel - high projection	335	421	495	536	560	581	602	624	642	659	675	\$5,073
	Propane	615	643	673	704	737	771	807	844	884	925	967	\$7,113
	Electricity - before PCE	1,172	1,239	1,310	1,385	1,465	1,549	1,637	1,731	1,830	1,935	2,046	\$14,315
	Electricity - after PCE	770	863	966	1,083	1,213	1,359	1,523	1,706	1,912	2,142	2,400	\$12,969

Conclusion

Operating a bio-digester in an arctic environment remains challenging. In order for a psychrophiles bio-digester to be cost effective, a number of factors are necessary such as higher ambient temperatures (30°C), higher prices of displaced fuels and/or electricity, and lower cost of construction or labor. Therefore, according to this preliminary economic analysis, the psychrophiles bio-digester is not yet a cost effective system to produce energy and/or to reduce energy costs of rural Alaskans. However, changes of the factors previously described could improve the cost effectiveness of this technology.

1 University of Alaska Fairbanks, Cooperative Extension Service - Food Survey. Survey data is available at <http://www.uaf.edu/ces/hhfd/fcs/>

2 The average price increase for propane was calculated using prices for 2007 to 2010 due to limitations in available data.

3 Fay, G. and Villalobos Meléndez, A. and Pathan, S. 2011. Alaska Fuel Price Projections 2011-2035, Technical Report, Institute of Social and Economic Research, University of Alaska Anchorage, prepared for the Alaska Energy Authority, 13 pages.

4 Consumer Price Index for Anchorage Municipality & State of Alaska Department of Labor and Workforce Development. Data is available at <http://www.labor.state.ak.us/research/cpi/cpi.htm>

5 The Power Cost Equalization program is State assistance program that lowers electricity rates for eligible rural customers.

6 Conversion factors as published by the U.S. Energy Information Administration at www.eia.gov

Phase III

In Phase III, we took the knowledge gained from Phases I and II to help improve small-scale biogas digester efficiency in various other regions of the world, including where seasonally cold temperatures challenge biogas production. After building and testing biogas systems in Alaska and at his home in Germany, where he could monitor, work on the systems and use them on a daily basis, PI TH Culhane led the effort of Phase III to travel to the sites of other National Geographic Society explorers to train teams and build digesters there. During this project period, Culhane has trained communities in developing countries and personally built a total of 52 biogas systems around the world. PI Walter Anthony assisted with outreach and international expansion efforts in 2013. We chose sites around the world where the immediate environmental

challenges created a need for biogas as a solution and where warm season temperatures were high enough to create great instant enthusiasm for biogas during the set-up period but where cold season lows would require later improvements to encourage year round operation. Activities and results are reported in chronological order.

Egypt

PI TH Culhane traveled to Egypt in 2009 and 2010 to develop inexpensive biogas digester systems out of ubiquitous local materials that could be found in every country in the world. There are two basic kinds of biodigesters in the world – the Chinese fixed dome system and the Indian Floating Drum digester. Neither seemed suited for temperate zone climatic zones or for small scale builders with limited resources. In Egypt, Culhane developed a low cost do-it-yourself biogas system based on the use of palette-based 1 cubic meter International Bulk Containers (IBC Tanks) that are relatively easy to find on the aftermarket (normally they are used for shipping liquids and other amorphous materials around the world) and can be sealed and insulated for use in cold climates. We knew that the traditional Indian Floating Drum digester, even when built from local plastic water tanks, and the Chinese fixed dome digester, built using local bricklayers, both of which we were experimenting with in Egypt, would not be appropriate for colder climates or situations where space and land use permissions were limited. The IBC Tanks were used (and modified) in Phases I and II of this project in Alaska.

Germany

At his home to Essen, Germany, from 2009 until the present, PI Culhane experimented with small scale biogas on his porch. PI Walter Anthony sent Culhane a bottle of lake-bottom mud from Alaska containing psychrophiles which Culhane successfully bred in a tank on his porch and introduced into a mixed 1 cubic meter system identical to the one they built in Alaska. He also gathered mud during the German winter from a local duck pond and proved that the psychrophiles in that mud were also effective at producing biogas and that one need not depend on exotic bacteria to exploit some of the lower temperature regions of the tanks (although the extremophiles from the arctic seem to have higher rates). Culhane also gathered sediment from a small frozen pond at Mount Everest base camp that seemed to be producing methane, brought the sediment back to Germany and proved that it contained biogas producing methanogens (this has implications for climate change as it appears that psychrophiles at high altitudes as well as high latitudes are now releasing methane into the atmosphere as the glaciers melt). It is now established that almost every cold region has lake mud and sediments that contain cold temperature methanogens which can be used for biogas, but that the bacteria from the most extreme regions seem to have higher production rates.

PI Walter Anthony and senior personnel, Anthony visited Culhane in Germany in January 2013. They observed and consulted about Culhane's home digesters, installed temperature data loggers in his tanks, greenhouse and outside wall (Fig. 16) and visited a local, larger scale biogas operation on the Imbrahm farm, just outside of Essen Germany, where restaurant food scraps are converted to produce commercial biogas. see <http://www.bioenergie-ruhrtal.de/>

On his home porch Culhane was able to create a reliable system that provided about a half hour of cooking (and occasional gas lamp lighting and electricity generation) most days of the year, including winter. Innovations such as using solar heated shower and bath and grey water to keep the tank temperatures above 20 °C helped. In addition to using psychrophiles

gathered in the winter from local duck ponds Culhane started mini-digesters in his bathroom using his baby's diaper wastes. He also demonstrated that in cold climates we could use PVC bags for reliable gas storage rather than a water based system, eliminating the need for anti-freeze or heating as long as the digester itself were kept at 20 °C or higher.

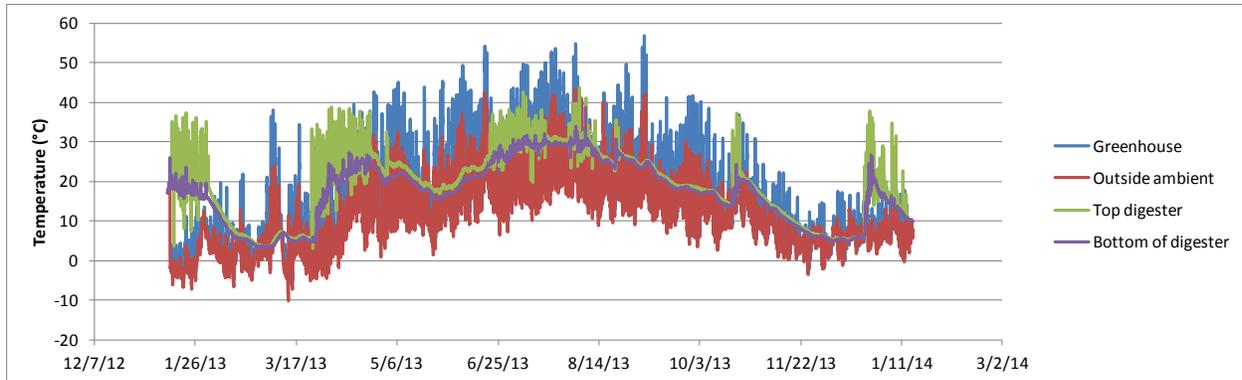


Figure 16. Temperature measured using pendant Hobo data loggers placed outside on the Culhane porch, in a greenhouse on the porch, and at the top and bottom of a 1000-L digester on the porch outside the greenhouse.

	Temperature (°C)			
	Mean annual \pm	stdev	Max	Min
Ambient, outside	11.3	9.0	43.5	-10.2
Greenhouse	13.7	10.5	56.8	-6.2
Inside digester, top	19.0	8.4	43.8	3.2
Inside digester, bottom	17.4	7.9	38.8	3.5

Findings related to Hobo temperature data loggers in Germany

The Culhanes 'feed' very warm water with feedstock into their digester periodically near the top of the digester. The periods of feeding are seen in Fig. 16 as periods of elevated temperature. The data also show that temperature in top of digester fluctuated far more than temperature at the bottom of the digester (bottom digester temperature was most stable). On average, the top of the digester was 1.6 °C warmer than the bottom of the digester. During periods of digester feeding, the top of the digester was up to 28 °C warmer than the bottom of the digester. Since optimal biogas production occurs under stable temperature regimes (not dramatic fluctuations), our recommendation is to use mixing or some other mechanism to stabilize digester temperature throughout the whole tank. This experiment also showed that the greenhouse was on average 2.3 °C warmer than the ambient outside temperature; however, the greenhouse temperature also fluctuated dramatically on diurnal time scales.

Botswana

PI T.H. Culhane visited the Selinda Reserve in 2010 where he and the staff built five different digesters out of locally available materials. In Zarafa and Selinda lodges the idea was to build systems similar to but larger than those systems used in the Cordova experiments. Since IBC

tanks were not available we had to use existing cylindrical polytanks trucked in from the town of Maun at considerable expense. At Selinda, based on the number of guests and an inspection of the amount of food wastes, we chose to use a 5000 liter water tank as the primary digester and a 2500 liter tank with inverted telescoping 2000 liter tank as the gas holder/secondary digester. The idea of using the gas holder tank as a secondary digester came from visits to commercial Imbrahm biogas and Sonderman biogas facilities in Germany where we were told that in continuous feed systems using food wastes approximately 80% of the energy is gained from the first biogas tank and that a second tank continuing the fermentation of the resulting slurry overspill can reclaim the remaining 20%. For this reason we designed the systems so that the sealed 5000 liter tank overspilled its slurry to the bottom of the telescoping digester and the gas from the first tank filled the floating drum in the second. This way both tanks were producing gas and larger volumes of food could be accommodated.





Figure 17. Photographs of Botswana digesters built by TH Culhane in 2010. At Zarafa Culhane created an identical system but because there were half the number of guests on average, Culhane kept the primary digester 2500 liters, identical to the size of the gas holder tank.

A complicating factor working in Botswana was that in contrast to other countries, tanks of a given size class all have the same diameter. In other words a 2500 liter tank has the same diameter as a 2000 liter tank with the former simply being taller. Therefore in order to create a telescoping gas holder we had to painstakingly cut one of the tanks in sections, cut out strips to reduce the diameter and then carefully heat weld the tank back together and fiberglass any resulting pores that would leak. This difficult “plastic surgery”, which had to be done with primitive tools (iron bars heated in charcoal pits) took many days and ultimately could not provide a completely hermetic seal resulting in unacceptable losses of gas over time. This is not an issue in any other countries we have worked in where different volume tanks have correspondingly different diameters. In addition, the base tanks, like most rotomolded plastic water tanks, do not have hermetically sealable lids (the screw threads are too wide). We spent additional hours trying to heat weld and fiberglass seal the lids on the tanks but ultimately microleaks were discovered. The company Rotoplas in Mexico who we are currently designing biogas digesters with tell us that while tanks are made from polyethylene, the lids are deliberately made from polypropylene -- a different material -- precisely so that they won't accidentally stick together in hot weather. While this is good for water tank applications it frustrates efforts to retrofit these tanks as biogas digesters since the lids cannot be easily or effectively connected to the tanks in a gas tight way.



Figure 18. Photograph of small-scale digester built at Selinda Camp.

In Selinda Base Camp we also built several other styles of smaller biogas digesters for the staff out of local materials (fiberglass septic tanks, cut and welded steel oil drums) and demonstrated the effectiveness of biogas from food and toilet wastes. But, as with the larger systems at the tourist lodges, getting a satisfactory hermetic seal was problematic and we recommended that having learned the principles of biogas construction and operation they ultimately turn to factory crafted systems that are designed specifically to hold the temperatures and pressures generated by methanogenic activity without leakage. Another issue that plagued the Botswana builds was a truck breakdown that impeded the delivery of 50 mm pipes we had ordered, forcing us to use 40 mm pipes for plumbing the digesters. Insinkerator corporation had generously donated 2 industrial and one domestic food waste grinder to the project for preparation of the feedstock and these were essential to ensure proper breakdown. But the available 40 mm pipes created several instances of blockage and backup that compromised proper usage. As this was an experimental situation these experiences were good to go through so that we can now make better recommendations about what not to do and how to improve locally made systems.

This effort was a good introduction of biogas technology to the Selinda Reserve staff, and they decided they would like to increase biogas production capacity at their camps. They opted for a commercially available below-ground digester system purchased from South African manufacturers, ProAgama Biogas (<http://www.biogaspro.com/>). Because this system was larger and below ground, it required less maintenance by camp staff, which is good given that there is a large seasonal turnover of camp employees.

PI K. Walter Anthony and participant P. Anthony traveled to the Selinda Reserve in the Okavango River Delta in August 2013 per the invitation for Dereck and Beverley Joubert to provide follow-up assistance on improve small-scale biogas digester operation at their remote tourist camps, Zarafa and Selinda. We enjoyed working with the staff at both of these camps. While we were highly impressed with the success of biogas production system already in place, we were able to help make some improvements, including suggestions for cold-season sustainable gas production.

When Walter Anthony and Anthony arrived, the Zarafa camp was getting four to eight

hours of biogas for use in the kitchen each day. This is excellent and reflects really good practice by the camp staff. However, it appeared to us, based on the records the camp's chef, Katherine Mackinnon was keeping of the loading rates, that at Zarafa they were far from maximizing the loading for the 4,000-L system. The feedstock loading rate at Zarafa was 3.5-10 kg every two to three days, whereas the manufacturer's documentation for the system suggests that up to 35kg of wet food waste could be added daily. This implies that if they increased the loading rates to the Zarafa digester, perhaps by using wet waste generated in other camps, that they could further increase biogas production at that camp, possibly as much as 10-fold. We recommended a gradual increase in the feeding there, together with careful observations (and record keeping) of loading rates and biogas production. Based on our experience in Phase I and II, we advised that if they notice a decline in gas production, they should ease off on the feeding until the gas production rates resume at the higher levels. Katherine MacKinnon, the head chef, said she would continue to record the mass of the food scraps put into the digester, and would begin to monitor more quantitatively the amount of time of gas usage they have daily in the kitchen. We installed two temperature data loggers at Zarafa- one in the white overflow pipe to measure the temperature of the digester slurry, and the other on the back kitchen wall next to the thermometer, to record hourly ambient temperature.



Figure 19. Peter Anthony installing a Hobo temperature data logger in white overflow tube at Zarafa Camp in the Selinda Reserve, Botswana (left) and Katherine MacKinnon using the biogas as part of daily food preparation at the camp (right). Note that the large biogas digester is completely buried in the ground, beneath the green plastic covers on the right.

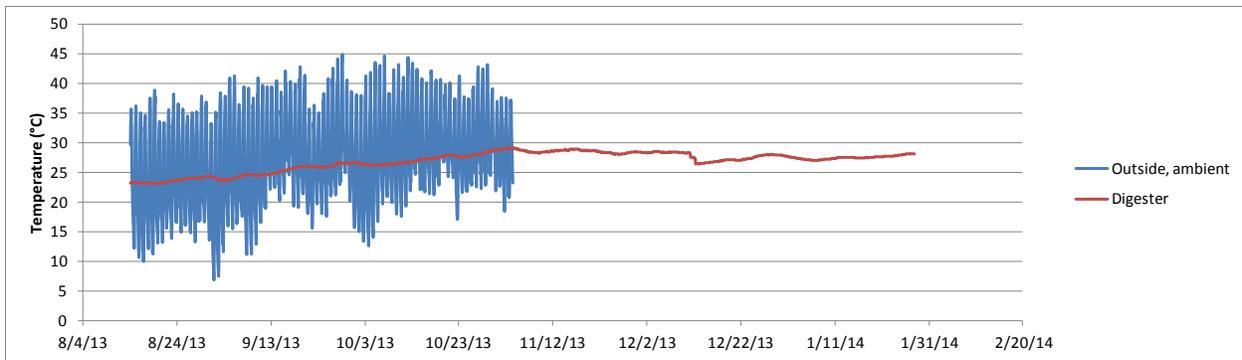


Figure 20. Temperature data from Hobo loggers installed by Katey and Peter Anthony at the Zarafa Camp in the Selinda Reserve. The biogas digester logger data covered the period of August 2013 through January 2014, while the logger monitoring outside, ambient temperature ceased to work in early November, 2013. The logger data showed large (20-30 deg C) diurnal temperature fluctuations outside, with far more stable temperatures inside the digester, which was buried in the ground. Warm, stable temperature is good for biogas production.

Summary of Botswana temperature data:

	Temperature (°C)			
	Mean annual \pm	stdev	Max	Min
Ambient, outside	27.2	7.8	44.8	6.9
Digester	26.8	1.6	29.1	23.0

At Selinda camp, managers Pete Unwin, Dave Pahl and Eva Spiridis also discussed with us some ways to potentially improve biogas production and usage. We advised that the finding ways to make usage of the biogas more attractive to the kitchen staff. This could include getting a new burner that is easier to operate and potentially adding a charcoal or other type of filter (iron clay pellet filters such as sold by Puxin biogas company in China work perfectly; see http://www.alibaba.com/product-detail/Puxin-Biogas-Desulfurizer_1586780426.html) to filter out the volatile organics that cause the bothersome odor, which many of the kitchen staff complained about. We informed them, based on results from Phase I and II in Alaska, that the use of local river sediments (instead of manure) in their digesters could cut down on odor. Another option could be to install a fan at the window that pulls the biogas odor out of the kitchen pre and post burning. The camp managers agreed to encourage kitchen staff to use all of the biogas every day so that there is not a buildup of unused gas in the system, which could ultimately lead to problems of acidification if feeding exceeds usage (also a lesson learned in Phases I and II in Alaska). At Selinda the staff could do a better job of sorting organic waste, leaving out some of the more recalcitrant material such as squash rinds, etc or resume use of the Insinkerators to grind food prior to digester feeding. Smaller pieces should digest easier. They plan to increase the volume of water so that the ratio of food to water is closer to 1:1. We also recommended they consider stirring the digester tank once per day after feeding, a well-established practice at the Zafara camp digester site. Both camps were concerned about honey badgers opening the valves on the digesters. We suggested inserting a small wire in the stainless steel ball valve to lock this valve so that the honey badgers can't open it.

Finally, at Selinda PI Katey Walter Anthony stirred the mud in the river next to the boat dock, collected the large gas bubbles that came out of that mud (Fig. 21), and lit the gas on fire. Since the gas ignited, we could be sure that the gas contained methane- the main energy constituent of biogas. This demonstrated that there are viable methane-producing microbes living in the mud right outside the lodge. Because these microbes are adapted to the temperature fluctuations experienced in this region, these microbes would be a good addition to the digesters. At Selinda and Zarafa, the river mud microbes could be used as supplements, in addition to the buffalo dung which is currently used in the tanks. (Culhane noted that elephant dung in the region did not readily produce biogas for some reason, though the Culhane's were only on site for 3 weeks; it may be that elephant dung based digesters take longer to establish). It would be helpful to log feeding rates and biogas production rates at Selinda in order to optimize production and compare to production at Zarafa.



Figure 21. Katey Walter Anthony and Gobusamang Mokopi collect stir river sediments and collect methane gas to demonstrate natural, flammable biogas production in the river system in front of the lodge (left). River mud containing methanogens was then collected and added to the digester (right) as a more convenient way of inoculating digesters with methane-producing microbes tolerant of ambient temperature conditions.

In summary, we were really encouraged to see that the Botswana systems had been working well for the past year, and that biogas has the potential to provide even more energy to the camps. We have remained in touch with the camp staff and mailed to Dereck Joubert and Pete Unwin data from the temperature loggers and two project summaries. These collaborators seem to have appreciated the contributions from this project to their successful effort with biogas at Selinda Reserve.

Kenya

In 2010 Culhane went to Cairo Egypt picked up Solar CITIES trainee Hanna Fathy from the Zabaleen garbage pickers society and took him to Kenya. Their first stop was at the Ol Donyo Was nature preserve run by Dereck and Beverly Joubert in association with Great Plains Conservation, located between Nairobi and Mobasa. Working with local staff, Culhane and Fathy created a garden of biogas possibilities, experimenting with traditional ARTI India style

digesters and the 1980s FAO welded oil drum style digester along with 3 Solar CITIES IBC/ARTI Hybrids like the one's described for Cordova (IBC tank primary digester and floating drum gas holder). Culhane and Fathy conducted workshops in Maasai villages (bomas) surrounding the park and invited community participation. It was upon the suggestion of a young Maasai boy (the son of Edwin, one of the guides in the preserve) who was building with us that we began to use discarded PVC pipes inside the digesters to potentially increase the amount of feedstock a given unit of volume could ingest and increase the amount of gas. Upon learning about the limitations of food waste based biogas systems (no more than 1/40 of the volume of the tank should be fed each day to prevent acidification, hence about 20 to 25 liters of food waste per 1000 liter IBC volume) the boy asked "what would happen if we gave the microbes more places to live, like skyscrapers that we see people build in the city? If they had more homes and there were more microbes, couldn't you feed them more and get more gas?". His suggestion for creating "microbe motels" was to cut holes in PVC pipes so they looked like apartment towers where food could get in and gas could get out, and suspend them from the gas holder tank using nails. We experimented and it worked well from an engineering perspective, increasing surface area and allowing biofilm formation inside the pipes that would not be disturbed by dilution or mixing. This concept has since enabled us to also feed tanks in cold climates with warm discarded bath water to keep them up to temperature but without flushing out all the bacteria.

In the spring of 2011 Culhane returned to Kenya with Ahmed Khalifa from the Solar CITIES e.V. board and members of Simama e.V., a German NGO that supports the Mukuru Art Academy in the Mukuru slum where Simama members, trained in Culhane's home in Germany, had built a "microbe motel" enhanced ARTI biodigester at the school. Culhane was also accompanied by Popular Science writer Hillary Rosner and photographer Myriam Abdelaziz who wrote an article for the July issue of Popular Science called "The Low Hanging Fruit". (see <http://www.popsci.com/technology/article/2011-06/kenyas-ingenious-biogas-system-might-be-model-america> and <http://www.insinkerator.com/en-us/Documents/Disposer/Popular-Science-July-2011.pdf>)

The journalist delivered a hand carried Insinkerator as a gift for the school from Emerson Electronics which Culhane installed with the teachers and demonstrated food waste to fuel and fertilizer. Rosner and Khalifa and Culhane met with Dominic Wanjahia Kahumbu, owner of Simply Logic Flexi Biogas and visited a series of different biodigester designs on display at a renewable energy research center with Dominic. Culhane purchased two of Wanjahia's special hybrid biogas Jiko cook stoves, one for the Mukuru School and one for Kakenya's Dream school, and began plans to work together on international small scale biogas initiatives (a project that goes on to this day, facilitated by the facebook group Solar CITIES Biogas Innoventors and Practitioners (<https://www.facebook.com/groups/methanogens/>))

After the successful demonstration in Nairobi Culhane and Khalifa travelled overland to fellow National Geographic Emerging Explorer Kakenya Ntaiya's Dream School for Girls in Enosaen. There Culhane and Kakenya's cousin, Salenta Ntaiya, built a 5000 liter hybrid biogas system identical to the one Culhane built in Selinda lodge in Botswana. Culhane installed an Insinkerator in the school kitchen donated by Emerson electronics and connected everything to the biogas system. Like the systems in Botswana, to help insulate them in cold periods, Culhane and Ntaiya buried the systems underground with a surrounding layer of hay and manure. While the telescoping digester/gas holder worked well in this build because different size tanks have

different diameters, we faced the same problem with sealing the lid on the primary digester tank and are still looking for easy ways to make water tanks gas tight.

One result of this trip was that we learned that the new sugar cane factory on the hill above Kakenya’s Dream School threatens to pollute the local stream. However Culhane and the village chief and teachers from the school met with the factory owner and he guaranteed that if we could raise funds for the materials for a digester for his wastes he would provide in kind labor and machinery and space for the build and supply the resulting fertilizer to the community while using the gas to offset uses of bagasse, firewood and charcoal and purchased gas making the factory and environment cleaner.

Katey Walter Anthony and TH Culhane mailed Hobo temperature data loggers to Dominic Wanjahia in Kenya. Dominic placed one logger outside in the shade to monitor ambient temperature, one logger inside his tunnel which functions like a greenhouse, and one logger inside the biogas digester (Flexi Biogas BG6 model) in the tunnel. Data were analyzed and returned to Dominic for his use.

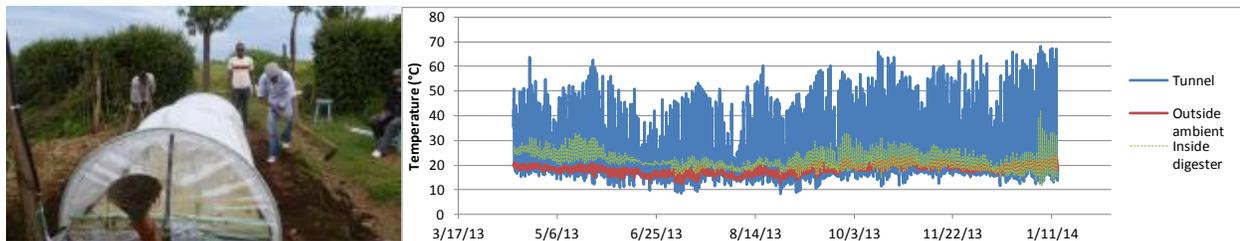


Figure 22. Photograph of a biogas digester inside a 'tunnel' built by Dominic Wanjahia in Kenya (left); photo from <http://www.biogas.co.ke>. Hobo temperature data logged from April 14, 2013 through January 13, 2014 showed that the digester temperature was on average 3 °C warmer than outside ambient temperature, and sometimes up to 28 °C warmer. The digester and tunnel temperatures fluctuated far more than outside ambient temperature. Such temperature fluctuations are not ideal for biogas production since microbial communities in the digesters prefer stable, warm conditions.

Summary of Kenya temperature data:

	Temperature (°C)			
	Mean annual \pm	stdev	Max	Min
Ambient, outside	18.3	1.8	23.3	12.3
Tunnel	23.8	11.0	68.1	8.3
Inside digester: Flexi Biogas BG6 model	21.5	3.3	42.3	11.4

Tanzania

As part of the 2010 trip to sub-Saharan Africa with Hanna Fathy, Culhane visited Tanzania, Burundi and Rwanda, sharing small scale biogas techniques with local NGOs and international agencies. In Rwanda Culhane met with SNV, a Dutch agency promoting biogas, and learned that the Rwandan government was providing a 50% subsidy for home biogas systems for families that have confined livestock. They will not, however, subsidize or encourage food-waste based biogas systems based on experiences identical to those Walter Anthony discovered in South Africa -- a tendency for families to overfeed in an effort to make more gas and cause acidification of the systems which then leads to their disuse rather than reinoculation. The safe

bet is to work only with families that keep animals since animal manures, while energy poor, have a neutral pH and the necessary microbial inoculants.

Culhane, being an urban planner by training, sees food wastes as a superior feedstock (containing 10 to 100 times the recoverable energy as manures) and often the only viable feedstock in congested city slums. His own experience has shown that if proper attention is paid to capacity building and the establishment of a culture of small scale biogas the systems work fine. There are often gender issues involved here; women tend to be the ones who understand the husbandry and nurturing and feeding of living systems better than men, and are usually in charge of kitchens and bathrooms and the wastes they produce, yet women have not been actively invited to participate in biogas technology implementation. With this idea in mind, Culhane and Fathy went to Tanzania to work with ethnobotanist Grace Gobbo.

In Tanzania, Fathy and Culhane built digesters and led workshops with Grace Gobbo and the Jane Goodall Institute at the village of M'Kalinze near the Gombe Chimpanzee reserve and in the town of Kigoma where Grace lives (including a system in her home and one in the home of her apprentice Joram Samson who continues to do outreach in the villages around Gombe). The work here related to the goal of providing high-elevation tropical forest edge communities in Tanzania an alternative to the use of firewood and charcoal, both of which are major contributors to deforestation. At Gombe's tourist lodge, for example, Culhane found that some of the cooking was done on propane stoves but most of it on charcoal and wood. In Kigoma, as in Nairobi, the results of deforestation can be seen in the huge piles of charcoal and charwood being sold and used in local markets. Solar cookers and so-called "clean biomass cook stoves" have been introduced as alternatives (Culhane and Gobo dined in restaurants in Kigoma that use sawdust as their fuel supply) but during the colder rainy season dry useful biomass and sunshine are in short supply, putting more pressure to deforest for charcoal.

Using jerry cans of slurry from an existing underground Chinese style fixed dome digester at the home of a doctor in Kigoma who had been using it for more than a decade, Culhane and Fathy and Gobbo built and quickly started up two Solar CITIES improved ARTI biodigesters in two villages near Gombe in the backyards of the respective chiefs and another two in the city of Kigoma in the home of Joram Samoan and in the home of Grace Gobo. The use of the fertile slurry from an active digester shortened the time to first flame from two or three weeks to two days. Because of the expense and dearth of adequately sized plastic water tanks, the builds were done with brick and cement for the base tanks and plastic tanks for gas capture. The systems worked very well during the warmer months but declined in production during the colder months.

July temperatures in the high-elevation tropical forests in Africa commonly reach 11-19 °C, well within the temperature regime of arctic microbes. During this testing and expansion phase we will continue to collaborate with Gobo to implement solar and aerobic compost heating exchanger technology to produce natural gas from food scraps to offset deforestation as a means of providing cooking and heating fuel. At one villager's home we explored the potential for compost heat to keep digesters at an adequate temperature (see <https://www.youtube.com/watch?v=eUIDnhGIVK0> and https://www.youtube.com/watch?v=x8lgn0_Pr-k)

Nigeria

In September of 2010 Culhane was invited with Ohio State Urban Planning professor Charisma Acey and Nigerian-German Solar CITIES technician Paul Chido Iwunna to stay with former

Nigerian President Oluwasegun Obasanjo and build biodigesters and do trainings, presentations and workshops at the presidents home and at hospitals, schools and universities in his home town of Abeokuta. Culhane was invited by the Nigerian president after presenting his “Biogas song” at UNESCO in Geneva where Obasanjo was presenting on methods to fight deforestation in Africa. During our time there we also met with the head of Naijatomo waste management company, Balogun Oluwasegun, who built small biodigesters with us and is including a scale up in his company plans for dealing with food waste. We also introduced hand-made treadle pumps in both Abeokuta and Port Harcourt as an electricity free way of getting water into the tanks, circulating heated water in cold times and pumping the fertilizer into fields and gardens.

Israel and Palestine

Since 2010 Culhane has been making yearly trips with the US Embassy to Israel and Palestine to conduct biogas workshops. In early February of 2011, Culhane was the keynote speaker at the Arava Institute for Environmental Studies alumni conference in Aqaba, Jordan and presented with the Arava’s small biogas expert Yair Teller and with Palestinian Engineers without Borders director Amer Rabayah and fellow National Geographic Explorer Beverly Goodman. The four of them crossed the border to Israel after the conference and Yair led them and the Arava alumni in building two flexible “salchicha” style plastic bag biodigesters at the Institute. Culhane also visited Goodman’s home in Caesaria and evaluated its potential for home biogas. While at the Arava Culhane learned about the Chinese Puxin biogas system that Yair had imported to Israel. Culhane continued to visit Israel and Palestine yearly in 2012 and 2013, conducting more biogas builds with the US Embassy and Palestinian universities and working with Yair’s newly formed home biogas company “Eco-gas Israel”

In January 2014, Culhane returned to Israel and Palestine to introduce his new Solar CITIES Hybrid IBC solution there (<http://kibbutzlotan.com/blog/2014/01/17/we-built-a-biogas-digester/>). He took his Envisaj Mercy students and a young man from our project in Brazil on a two week “Biogas research and construction tour” from the occupied West Bank to the Arava Institute for Environmental Studies and Kibbutz Lotan Eco-Village. It culminated in a workshop build of the new improved biogas system we had tried out at Mercy College (see New York) based on our initial work in Alaska in Phases I and II.

Philippines

In March 2012 PI Culhane traveled to the Philippines with a group of German doctors from the medical NGO “Chance for Growth” doing preventative medicine in the slums of Pasay City and at a retreat school on the island of Palawan for abused girls from those slums of Manila. Culhane helped raise the money to purchase a Puxin Chinese family sized biogas system (fiberglass 2.5 cubic meter factory made plug and play system) and the steel molds and fiberglass gas holders for a 10 cubic meter concrete institutional system to be installed at the girls school in Palawan. Together with Bernard Pierquin of the Allouette Foundation they held the first annual biogas conference in Palawan and installed and built both the home and school scaled biodigesters. Palawan is famous for charcoal production which is taking a huge toll on the mangrove forests there. Palawan was voted in 2011 as one of the world’s most desirable destinations by National Geographic, but that reputation is threatened by wood fuel consumption throughout the archipelago. It is hoped that the larger turnkey Puxin biodigester, which is field tested in over 60 countries can make a significant impact on this situation.

Iraq and Turkey

Through the networks of development specialists Culhane had worked with in the US Embassy in Jerusalem and contacts he had made through National Geographic, in the spring of 2013 Culhane was invited to his mother's native Baghdad Iraq, Kurdistan, and Turkey to continue the trainings and builds. From the US Embassy in Baghdad to the “Greening of the Blue” at the United Nations to the Ministry of Science and Technology to Kurdistan and on to the streets of Istanbul we did builds, trainings and lectures that showed how small scale biogas systems turning kitchen and toilet wastes into clean fuel and rich fertilizer was the “missing piece of the sustainability puzzle.” Culhane even put his Iraqi grandfather's ashes into one of the tanks in Erbil to celebrate the cyclical and transformative nature of this technology which Popular Science magazine, in an article on our work, declared the “low hanging fruit.” One of the technologies we brought to Baghdad was the same kind of steel molds for the Puxin 10m³ digester we had built in the Philippines. The molds can be used hundreds of times to make duplicate low cost yet effective concrete biodigesters. Working with engineer Taha Majeed from the Baghdad Ministry of Science and Technology a successful Puxin digester was recently completed at the holy Al Najah Shiite shrine.

China

Solar CITIES Solutions sent Culhane to China to work directly with Puxin inventor and CEO Dr. Jianan Wang and his engineers and staff to redesign the 10m³ system molds so that they could be used in difficult field environments more reliably. The result was a set of molds that can be used to build 4, 6 and 10 m³ concrete systems. Culhane was then able to order these new molds for projects in both New York and Brazil.

To work on extending the reach of Puxin style biogas systems, the Blackstone Ranch foundation funded Solar Cities Solutions so that Culhane could bring seven of the world's small scale biogas experts from Israel, Iraq, Egypt, Italy, Oregon, Washington and New York to New York in November 2013 to gain experience in building the Chinese Puxin mold system. Through this Blackstone Grant we were able to create what we call the “Best BET” – an international Biogas Education Team – that can improve systems and do trainings all over the globe.

Brazil

In June 2013 and again in August 2013, Culhane took a trip funded by his US NGO “Solar Cities Solutions” to take knowledge gained from the preliminary experiments done through this project to the favelas (slums) of Niteroi and Rio De Janeiro in Brazil to start teaching small scale biogas construction with colleagues from Architecture for Humanity and Catalytic Communities, an NGO dedicated to empowering local groups in poor areas. The effort led to funding from Insinkerator corporation (manufacturer of food waste grinders) to build larger scale Chinese Puxin biodigesters sized for entire communities. We now have three digesters at a new elementary school in the impoverished section of Niteroi that is near the site of a landfill collapse that claimed many lives, and one under construction in a favela called “Vale Encantado” in the rain forest overlooking Rio.

South Africa

In a series of meetings in August 2013, Katey Walter Anthony, Yvette Spangenberg and Zach Spangenberg discussed with Piet Lodder, (CEO of AgriEden), Dr. Sonette Marx (North West University), and Ludwig Everson (Earthship, S.A.) the status and potential of small scale biogas

digesters technology in South Africa. At this time, despite its large potential and need, particularly within refugee shanty towns, biogas is not a significant source of energy in South Africa. It is used primarily by enthusiastic individuals such as Ludwig Everson, who leads a sustainable living effort (www.aardskip.com) and is willing to pay for and maintain a household-scale digester based on his personal philosophy about sustainability and the environment. Another example is the Lynedoch Eco Village in the Cape Province of South Africa, where a biogas digester is used to provide cooking fuel in an old corrugated iron building has been converted into a safe and sustainable community project consisting of a primary school for 475 children from farm worker families in the region, Montessori-based preschool, large all-purpose hall, and offices and classrooms of the Sustainability Institute. In the southern Cape Province of South Africa solar energy is the main infrastructure of alternative energy. Solar panels, seen on tops of most buildings, including the roofs of shanty-town shacks, are manufactured with an 80% government subsidy. Furthermore, legislation requires solar panels for all new houses. Given the rising cost of electricity, power shortages caused by insufficient energy supply in the country, and large populations of refugees without jobs, there is a tremendous potential role of household-scale biogas digester technology in South Africa. Dr. Sonette Marx explained several reasons why biogas, and other sustainable energy projects she has attempted to introduce to under-privileged communities in South Africa have failed. First, most people don't have the discipline to maintain the digesters once they are built. When a problem is encountered, such as souring of the tanks, people don't have the expertise to solve the problem, and end up abandoning the effort altogether. Second, and more important according to Dr. Marx, South Africans have a poor attitude when it comes to do-it-yourself, manual labor projects. She said that the history of apartheid in this country has produced an attitude in people such that everyone wants to be treated and served as an affluent "Mr.", leaving a paucity of people who are willing to shovel the manure required in biogas production. Dr. Marx suggested that it will take another one or two generations before people will have the mindset and self-confidence to attempt and succeed in do-it-yourself projects such as biogas production. At larger scales, there is no government incentive to produce biogas. In fact, South Africa lacks a grading system for the gas, so that if biogas were produced, there is no regulating framework to assess its quality. Ironically, South Africa is the manufacturing location of the best biogas digester hardware PI K. Walter Anthony and participant, P. Anthony have ever observed for small-scale biogas systems (ProAgama Biogas <http://www.biogaspro.com/>). We observed these systems in highly successful operation at the Great Plains Conservation camps, Selinda and Zarafa, in Botswana (see Botswana).

New York, USA

As a visiting faculty researcher at Mercy College, New York in January of 2013, PI Culhane created an indoor lab based on the design of experiments conducted with PI Walter Anthony in Alaska to test various scenarios for food and toilet waste based biogas production. In this unventilated and confined space Culhane and Mercy College students captured the gas in truck inner tubes and demonstrated the safety of closed tank biogas system for indoor use. We kept methane alarm sensors on hand and demonstrated that we could get useful yields throughout the winter without extra heating using food scraps from the cafeteria. We also demonstrated that we could grind the cafeteria waste using a bicycle powered food grinder.

Using Mercy college as his academic home base PI Culhane has since started experiments outdoors on campus with Envisaj Mercy, the Environmental Sustainability and Justice Club and began working with the Greenburgh Nature Center and Hartsbrook Nature

Preserve. We designed a new way of using the IBC tank so that it more nearly approximated the engineering of the Chinese Fixed Dome digester design, and hybridized it with the ARTI type Indian floating digester design for gas collection, creating the “Solar CITIES IBC/ARTI Hybrid”. This system enables both tanks to be used in the warmer months but permits the gas collector to be located outdoors and the main digester indoors so that one of them can work all year round. Discharge of warm water in the overflow to the gas holder helps keep it unfrozen in winter in most situations. With the students in our Envisaj Mercy club we also developed a classroom based mini-digester demonstration system, made public appearances, and did workshops that led to collaborations and further fund raising opportunities. Culhane was able to leverage these experiences into a new grant from the Blackstone Ranch foundation that enabled him to purchase a new design of Puxin Chinese biogas molds that were created for Culhane by the company when he was in Shenzhen, China in summer 2013. Culhane and Solar Cities Solutions executive director Dr. Gail Richardson will be building Puxin 10m³ biodigesters in June 2014 at an Amish Farm Greenhouse in Lancaster PA to complement their vertical farming aeroponics business (supplying heat and biofertilizer) and in September 2014 at the Permaculture Design Institute in Ellenville NY with Instructional leader Andrew Faust.

Bicoastal USA

There was also interest in the work of this project the US. Several community leaders in impoverished areas of California and Washington DC asked TH Culhane if he could help them get started in home scale biogas. Culhane did a training workshop in January 2011, in between trips to Alaska, and built a digester equivalent to the ones in Cordova in “the hood” in a gang area in South L.A. with a former student of Culhane’s. In July of 2013 Culhane built the same system with off the grid libertarians in the San Pedro National forest area. He was also able to build at a foreclosure house in Northern California. In November 2011 Culhane brought one of his original Solar CITIES Egyptian colleagues, carpenter Mostafa Hussein, from the slums of Cairo, to Washington DC and New York to assist in the effort of building in inner city schools, continuing a practice of East/East, South/South, Community/Community technology and knowledge transfer that Walter Anthony and Culhane had started when we brought a former Egyptian garbage collector (Zabaleen) to four countries in Africa to share knowledge.

The mission continues

Culhane and Walter Anthony continue to actively disseminate knowledge gained from this project. Walter Anthony helped connect Dereck and Beverley Joubert with Dominic Wanjihia (Kenya biogas) for assistance in expanding biogas technology to their camps in Kenya. Walter Anthony provided technical advice to surveyors in Chile interested in collecting methanogens in local cold-temperature lakes for use in biogas digesters. Following the data analyses in this report, Walter Anthony will return temperature data loggers disseminated through this project to collaborators in Botswana and Germany to continue monitoring the seasonality of biogas production at those sites. Culhane returned to Nairobi to teach in the Mukuru slums. He worked with Christian missionary groups to introduce small-scale biogas digesters to Hungarian and Slovakian gypsies. Through his facebook group “Solar CITIES Biogas Innovators and Practitioners” our solution has also been adopted in several other countries, including Senegal. Culhane recently formalized Solar Cities Solutions as a 501C3 non-profit in New York with a board of directors that includes the president of Insinkerator (our first sponsor for larger scale systems) and Mel Kurtz of Quasar Energy, one of America's largest industrial biogas companies,

as well as Executive Director Dr. Gail Richardson, Kenneth Miller (on the board of the Smithsonian) and J.D. Lindeberg, a waste engineering consultant with Peace Corps experience.

Conclusions

The impacts of this project are global. The collection and utilization of methane, one of the strongest greenhouse gases, prevents its release into the atmosphere when garbage otherwise decomposes in landfills. The introduction of psychrophiles into existing, conventional biogas digesters improves their performance. The development of cold-region digesters can be used as a local, sustainable, alternative energy source for home cooking, heating, and electrical power. The energy can be cost effectively produced and utilized on a dwelling scale (construction cost in Germany \$300 per household), or upscaled through utilization of restaurant, cafeteria, grocery store, fish, meat and vegetable market, slaughter house, dairy farm, fast food chain and food processing, beverage facility and agricultural waste product composting. Most communities have access to waste streams that can be deployed as fuel stock. These waste streams often present a liability to communities by filling landfills and posing environmental and health hazards. The overall impacts of the project include protection of the environment, reduced energy costs, and development of an export technology or products. The positive impacts can be realized in both rural and urban settings, and from residential to community scale applications. Even in the tropics, this cold-temperature energy technology can be used to prevent deforestation.

Public outreach and dissemination

This project, performed through collaboration among Solar CITIES, a local public utility (Cordova Electric Cooperative), city high school and a research university (University of Alaska Fairbanks), the National Geographic Society and Blackstone Ranch, as well with all of the national and international organizations participating in Phase III was intended from the beginning to have a large emphasis on public outreach and information dissemination. The project received a substantial amount of publicity since ground broke in winter of 2009 and has enjoyed high praise and support from multiple areas of local and state government in Alaska as well as national and international press. Students, researchers and other team members have traveled to numerous conferences to discuss the project and its goals as well as share information about biogas technology.

Cordova, Alaska high school students and UAF researchers were given the opportunity to present on project ideas and preliminary results at meetings with the Alaska Power Association and Alaska state legislators in Juneau, Alaska and at a variety of conferences, including the Alaska Rural Energy Conference (April 27-29th, 2010) and the Alaska Forum on the Environment (February 7-11th, 2011). In February 2010, the chemistry students took a class trip to the Alaska Power Association, where students C. Bailer, D. Hess, C. Morrissett, J. Smyke, S. Lindow, and T. Kelley presented on the project. The project research was featured during ACEP's lecture series for the month of June 2011 in Fairbanks, Alaska and at the Alaska Rural Energy Conference in Juneau (September 27-29, 2011).

Culhane made numerous presentations at school and university around the world about this project, including in South Africa, Europe, the Middle East and the Americas. Details, photographs and data from all these trips can be found in Culhane and Walter Anthony's paper "Improving the Potential for Small-Scale Wet-Waste-Fed Biogas Digesters using low-cost design principles and new combinations of microbial consortia" which Culhane presented at the

AIAA Energy Conversion conference in San Diego in August, 2011. Through conferences, workshops, symposia, facebook groups, Google Plus circles, youtube channels and the National Geographic Explorer's family, Culhane has created a network of synergies for future expansion of the small-scale biogas technology.

Titles of our project presentations and other public dissemination documents are reported chronologically:

Walter Anthony, K., Culhane, TH., Koplín, C., McFadden, L., Low, A. "Improving Cold Region Biogas Digester Efficiency." McFadden, L. Alaska Forum on the Environment. Anchorage, Alaska. February 8-12, 2010.

Bailer, C., D. Hess, C. Morrissett, J. Smyke, S. Lindow, and T. Kelley, "Methane Digesters using Psychrophiles", Invited talk, Alaska Power Association, Juneau, Alaska. February 2010.

Walter Anthony, K., Culhane, TH., Koplín, C., McFadden, L., Low, A. "Improving Cold Region Biogas Digester Efficiency." Low, A., Hess, E., Allen, J., Americus, I., Americus, B., Zamudio, A. Alaska Rural Energy Conference. Fairbanks, Alaska. April 27-29, 2010.

New Scientist article featuring this project: "Cold climates no bar to biogas production". November 4, 2010.

<<http://www.newscientist.com/article/mg20827854.000-cold-climates-no-bar-to-biogas-production.html>>

Pape, C. and the Project Team, "Energy from Psychrophilic Bacteria: A Cold-Region Alternative for Biogas", ACEP Community Energy Lecture Series, Fairbanks, Alaska, June 21, 2011.

The project was featured by Alaskan Dispatch Magazine in an article on rural Alaska entitled, "Biogas could bring new energy to rural Alaska". January 17, 2011.

<<http://www.alaskadispatch.com/article/biogas-could-bring-new-energy-rural-alaska?page=0,0>>

Low, A. "Youth Participation: Improving Cold Region Biogas Digester Efficiency." Low, A., Bailer, C., Allen, J., Americus, B., Zamudio, A. Alaska Forum on the Environment. Anchorage, Alaska. February 8, 2011.

Walter Anthony, K., Culhane, TH., Koplín, C., Low, A., Pape, C. "Improving Cold Region Biogas Digester Efficiency." Low, A., Bailer, C., Allen, J., Americus, B., Zamudio, A. Denali Commission Public Forum on the Emerging Energy Technology Grant. Juneau, Alaska. February 14-15, 2011.

Pape, C. and Walter Anthony, K. (2011) "Biogas Technology in Alaska". ACEP Flyer Publication. Cooperative Extension Services, Fairbanks, Alaska.

Americus, B., Allen, J., Zamudio, A., Pape, C. "Cold Climate Anaerobic Digestion: Psychrophiles in Biogas Digesters" Alaska Rural Energy Conference. Juneau, Alaska. September 27-29, 2011.

Byers, Alton, Thomas Culhane, Debbie Marcinkowski, Shankar Lal Vaidya and Caroline Howe. 2011. Protecting and Restoring the World's Alpine Ecosystems through NGS Explorer Collaboration and Exchange: The Role of Awareness Building, Improved Conservation Practices, and High Altitude Alternative Energy Development. Report to the National Geographic Society-Blackstone Challenge Grant Program. Interim Report: Upper Imja Valley, Sagarmatha (Everest) National Park, Nepal, Washington DC: The Mountain Institute.

Culhane, Thomas, Katey Walter Anthony, and Casey Pape. Improving the Potential for Small-Scale Wet-Waste-Fed Biogas Digesters using low-cost design principles and new combinations of microbial consortia. 9th Annual International Energy Conversion Engineering Conference. July 2011

Byers, Alton, Thomas Culhane and Chris Rainier, 2012. Protecting and Restoring the World's Alpine Ecosystems through NGS Explorer Collaboration and Exchange: The Role of Awareness Building, Improved Conservation Practices and High Altitude Alternative Energy Development. Report to the National Geographic Society-Blackstone Challenge Grant Program Final Report: Hinku Valley, Makalu-Barun National Park and Buffer Zone, Nepal. Washington D.C. The Mountain Institute.

Acey, Charisma Shont'E., and Thomas H. Culhane. "Green jobs, livelihoods and the post-carbon economy in African cities." *Local Environment* 18.9 (2013): 1046-1065.

Byers, Alton (2014) "Contemporary Human Impacts on Subalpine and Alpine Ecosystems of the Hinku Valley, Makalu-Barun National Park and Buffer Zone, Nepal," *Himalaya, the Journal of the Association for Nepal and Himalayan Studies*: Vol. 33: No. 1, Article 8

Other forms of dissemination:

Solar CITIES, Connecting Community Catalysts Integrating Technologies for Industrial Ecology Solutions, blog: <http://solarcities.blogspot.com>

Solar CITIES Biogas Innoventors and Practitioners Social Media group:
<https://www.facebook.com/groups/methanogens/>

Media articles on Culhane work in biogas and renewable energy:

<http://www.csmonitor.com/World/Making-a-difference/2014/0516/Thomas-H.-Culhane-teaches-people-to-build-fuel-sources-powered-by-garbage>

http://www.rivertownsenterprise.net/Rivertowns_Enterprise/ENTERPRISE_NEWS_122713.htm

<http://energyblog.nationalgeographic.com/2013/05/24/iraqs-green-zone-gets-greener-with-biogas-and-other-clean-energy-solutions/>

Popular Science article: "Gas from Garbage" <http://www.insinkerator.com/en-us/Documents/Disposer/Popular-Science-July-2011.pdf>

<http://www.tamera.org/project-groups/autonomy-technology/articles/biogas/>

<http://www.tamera.org/project-groups/autonomy-technology/biogas/>

How to Build a Biogas Plant: http://www.tamera.org/fileadmin/PDF/biogas_digester.pdf

http://www.americanalpineclub.org/uploads/Executive_Summary.pdf

UCLA Quarterly, Urban Planning: <https://grad.ucla.edu/asis/library/gqwinter09.pdf>

<http://curiousonhudson.com/class-details.php?id=194>

"The Solar C3ITIES Solar Challenge" to Joe the Plumber (and Ahmed the Plumber and Mohammed the Plumber!)."

http://www.riaed.net/IMG/pdf/The_Solar_C3ITIES_Solar_Challenge.pdf

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Alternativenergie (IPS) <http://www.schattenblick.de/infopool/umwelt/internat/uiee0059.html>