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Improving the Potential for Small-Scale Wet-Waste-Fed Biogas Digestors using low-cost design principles and new combinations of microbial consortia

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Solar CITIES e.V., a German-based non-profit organization that works on local renewable energy systems development and training in impoverished communities in Africa and the Middle East, has been working for the past two years on a Blackstone Ranch/ National Geographic Innovation Challenge Grant to develop and deploy small scale kitchen-waste-to-cooking-fuel biogas systems. This paper details the engineering, technical, resource and social challenges faced and overcome by the Solar CITIES team in environments as diverse as the frigid coastal landscape of Alaska, the ghettoes of Los Angeles, the moist cold residential corridors of Sonoma County and Seattle, Washington, the icy rooftops of northern Germany, the arid hills of Israel and the Palestinian territories, the congested urban slums of Cairo, Egypt, the informal shanty-towns of Nairobi, the sensitive savannah landscapes of the Masai tribes of Kenya and the bush-people of Botswana, the residential and rural areas of central Nigeria and the rain-forest and lakeside villages of Tanzania.

Nomenclature

C^3ITIES
Connecting Community Catalysts
Integrating Technologies for Industrial Ecology Solutions
HRT Hydraulic Retention Time
TDS Total Dissolved Solids

I. Introduction

Concerns about climate change impacts on developing economies and their environments have resulted in renewed interest in pursuing nuclear options for the third world. Bill Gates and Toshiba's plans to develop and install "micro-nukes" in "every village in Africa" were announced in the "Big Idea" section of National Geographic's March issue from 2010[15] and the concept has not only become part of public consciousness but is increasingly attracting interest from governments within Africa as well. But even without considering the dangers associated with radioactive materials which the recent Fukushima disaster has once again brought to attention, the notion of simulating energy decentralization through the deployment of micronukes is particularly problematic in that such "small scale" energy solutions potentially derail true localization. The big money backing small nukes gives the illusion of distributed power generation but keeps political and

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price controls centralized to the companies and governing bodies making the micro-nukes. This threatens to make efforts to utilize truly decentralized energy sourcs such as sun, wind, small hydro and waste appear uneconomical.

The Solar CITIES home scale renewable energy initiative works on the other side of the coin, looking at the aggregate impact of bathrooms and kitchens in millions of households, where most domestic energy and water are consumed and most domestic waste is produced, and trying to tackle consumption and production issues in situ through deployment of household scale biogas digestors that utilize household wastes to create climate neutral cooking and heating fuel and even some electricity and fuel for lighting and refrigeration.

Because kitchen and toilet wastes are something that every home produces, and because of the simplicity of transforming these liability causing materials into solution generating assets that have the potential to generate most of the cooking, lighting, refrigerating, heating and even electric needs of households, we see small scale biogas as the most robust of energy conversion solutions avaialable to developing economies today, and hope that rather than putting a micro-nuke in every village, we can put mini-biodigestors there instead.

I.A. Background

Led by Iraqi-American co-founder T.H. Culhane, Ph.D, a 2009 National Geographic Emerging Explorer Awardee, and his German wife, Dr. Sybille Culhane, the Solar CITIES initiative turned its attention in 2008 from building low-cost solar hot water systems out of local materials with the Cairo poor (the subject of two previous AIAA papers in 2007 and 2008) to building biogas systems. We made this shift when the results of Dr. Culhane's research showed a large number of poor families in urban slums had limited solar access[a] .

Culhane traveled to Pune India on a U.S. Embassy grant in January of 2009 and learned about home-scale urban biodigestor technology from Dr. Anand Karve of the Appropriate Rural Technology Institute,[9] then took the ideas and skills to the Christian Zabaleen garbage collectors community and the Islamic historic slum of Cairo and began working with his local Solar CITIES team on customizing them for various different African environments, trying to overcome temperature and resource limitations.

Following successes in Egypt, Dr. Culhane and Dr. Katey Walter-Anthony, an aquatic ecologist from U Fairbanks, Alaska, secured a grant from the Blackstone Ranch Foundation and National Geographic to explore not only new designs for digestors but the use of different combinations and species of bacteria, particularly the psychrophilic bacteria of the arctic circle. Psychrophiles are a group of extremophiles that are now creating potentially dangerous greenhouse gas emissions as the permafrost melts. Culhane, Walter-Anthony and their colleagues believe that the same bacteria can be harnessed to help offset those greenhouse gases by replacing fossil fuel use through the creation of more efficient low- temperature digestors around the world.

Dr. Culhane worked with Dr. Walter-Anthony and graduate student Laurel McFadden of U Fairbanks Alaska and Clay Koplin of the Cordova Electric Power Cooperative on a Denali Commission Grant to pioneer a citizen-science project wherein high school science teacher Adam Low and his students in the fishing village of Cordova, Alaska built a biogas laboratory to test designs and different bacterial combinations for optimal small scale gas production. He then brought Solar CITIES associate and Egyptian garbage recycler Hanna Fathy to Kenya, Tanzania, Burundi and Rwanda to share the technologies they had developed with slum-dwellers in Nairobi, Masai tribespeople in the Ol Donyo Wuas - Amboseli Eco-system, and with peri-urban animal herders in Kigoma, Tanzania and rainforest village people surrounding the Gombe Chimpanzee Reserve as well as other contacts through the National Geographic Society and Jane Goodall Institute.

The need for simple engineering solutions for biogas systems is critical in environments like the hills of Kenya, Tanzania and Rwanda where seasonal temperature drops currently discourage the creation of biogas while forcing ever greater deforestation for heating and cooking fuel. Dependence on wood and charcoal is not only leading to tremendous loss of biodiversity, but creating major public health threats in the form of toxic smoke that have a particular effect on women and children.

The initial successes of this continent spanning initiative led to Culhane and associates building 4 biodigestors in Nigeria at the behest of former Nigerian President Obasanjo (in a school, a university, a hospital and in the home of the former African leader, who is now launching with Solar CITIES a green economy center for research and development at the Presidential Library in Abeokuta) and 3 in Botswana in the

[a]In a sample of 413 households from the Islamic slum area of Old Cairo and the Zabaleen Garbage recyclers informal area of Manshiyet Nasser 7.26 percent reported their dwellings to be in constant shade; broken down by community the data revealed 12.68 percent without full sun in historic Cairo and 1.5 percent in the informal area. As urban density forces more high rise buildings to be constructed, the chances of defending solar access become more and more constrained.

Okavanga Delta, where the group is trying to get eco-tourism and sustainable development initiatives to embrace small scale biogas as a clean energy solution.

With the receipt of a second Blackstone Ranch Innovation Challenge grant, the team is poised to start working in the Himalayas in Nepal, facing even greater challenges at high altitude.

The aim of this paper is to share with the engineering community the successes and difficulties and stimulate a dialog of cross-disciplinary expertise synergies in a project with both technical and social dimensions that, if properly addressed, could help much of the developing world reach its Millenium Development Goals.

I.B. Barriers to effective deployment of small scale digestors

I.B.1. Awareness of appropriate feedstock

The chief barrier to mass deployment of small scale biogas is a lack of awareness of the simplicity and effectiveness of the solution. One of the first myths that we have had to counter is the idea that one needs a constant source of animal manures in order to operate a biogas system.[7]

Such myths are perpetuated by popular media, such as this report on "Ecofilms Australia":

> If you thought making your own biogas for cooking was rocket science stuff and you needed a laboratory of technical wizardry to do it yourself then this guide will show you how easy it is to make your own Biogas plant.
>
> A family of four can be quite self sufficient when it comes to cooking an evening meal provided however you have access to a couple of dairy cows to supply the fuel.

The "provided however" caveat permeates not only popular websites but government policy too. In a personal visit to the SNV development agency in Kigali, Rwanda in April of 2010, the author was told that the Rwandan government was subsidizing construction of 25,000 household biodigestors, but that to qualify for the subsidy a family had to have at least 4 cattle or 6 pigs in a zero grazing environment.

Similarly, when visiting a biogas company in Nairobi, Kenya in April of 2011 we found that the owner was only building for families that had animals in enclosure and had not been aware that there were other feedstocks.

But in fact, as our own research and experience has shown, a good biogas system can be started with human wastes (which are abundant and ubiquitious wherever there are humans) and then fed with unsorted kitchen and cooking wastes as the main input; access to animals or animal manure isn't actually needed at all.

Culhane started several experimental biodigestors in his own bathroom in Germany using 100 liter plastic tanks and loading them with his 2 year old son's diaper wastes. After approximately 3 weeks the tanks began producing flammable methane and have since then been fed mainly with remains from the baby's uneaten porridge. Culhane continues to put the diaper wastes into the tanks for two reasons; first, as a way to deal with the fecal material because Solar CITIES is exploring simple ways to reduce the threat of water-borne diseases in developing countries and anaerobic fermentation of toilet wastes reduces pathogen loads [b] . Second, the continuous introduction of fecal material ensures that there is a constant source of methanogenic bacteria being introduced into the system, protecting against die-off in the event of overfeeding and the build up of acidic conditions. Third, the addition of fecal wastes helps to buffer the pH.

The author replicated this experiment on much larger scales in Botswana when collection of elephant dung (the only manure available) proved problematic. When elephant dung failed to produce flammable gas after several weeks, the author and colleagues pumped sewage sludge from a water treatment facility and septic systems at three lodges, Zarafa, Selinda and Base Camp and filled digestors of three sizes - 5000 liters, 7500 liters and 1000 liters respectively. Flammable gas evovled within 24 hours in the second two cases. In the first the sewage sludge came from the water treatment facility and seems to have been devoid of a healthy bacterial population.

At the base camp the author created an installation with one toilet feeding directly into an Admiral Macerating pump and the output of an Insinkerator Evolution 200 food waste grinder feeding into the side of the macerating pump. The combined wastes were then pumped into the 1000 liter digestor. The experience

[b]see Cote C., Masse D.I., Quessy S. Reduction of indicator and pathogenic microorganisms by psychrophilic anaerobic digestion in swine slurries (2006) Bioresource Technology, 97 (4), pp. 686-691. see also Evaluation of Biogas Sanitation Systems in Nepalese Prisons; note that in this study Helminth eggs were not completely eliminated

in Nepalese prisons cited in *Evaluation of Biogas Sanitation Systems in Nepalese Prisons*[14] corroborate the idea that a mixture of fecal matter and food waste makes for the greatest gas production. In that study they found that,

> The average gas production from using only human waste as feedstock was 28NL per person per day. With additional feedstock of the entire kitchen waste (in one prison), the gas production showed to increase considerably up to 62NL per person per day.

In April of 2011 we visited a public toilet in the Mukuru slum of Nairobi that was using the waste material to provide cooking gas in the hotel and restaurant across the alley[c]. The proprietor, Richie Grim (Richiegrim@yahoo.com) was not aware that the addition of vegetable and food wastes would more than double his gas production.

The second barrier, of course, is people's unfamiliarity with the use of food waste as a superior source of feedstock for the methanogens. As Dr. Anand Karve told me when I visited him, "everybody has been getting biogas wrong for hundreds of years. The bacteria don't want animal manure, they make animal manure. They live in the animal's gut because they want finely chewed up food mixed with water. This is the best feedstock for them."

Karve's model was to simply build an artificial "sacred cow" and try to replicate as much of the natural environment of the bacterial consortia as possible. But even magazines like Popular Science continue to make biogas seem problematic and unpopular. In the July 2008 issue, on page 47, an article reported,

> Potential Uh-Ohs: Getting a high yield requires a perfect recipe of waste ingredients. Municipal wastewater alone produces low yields, so it must be co-digested with other waste materials. Plus, transportation to the digester sites cuts into the efficiency of the process.

Once again we see the danger warned against in the adage, "never let the perfect become the enemy of the good". As described in the next section, many cities are solving the problem of the low yields of wastewater by encouraging the use of food waste grinders like the Insinkerator to add high caloric value wastes into the liquid stream.[13] Using waste water as the carrier the transportation issue is all but eliminated. But at the home scale none of these issues are a problem – the garbage is energy rich, it is easy to transport to the digestor either through the waste water pipes or in a bucket, and the mix doesn't have to be perfect at all – families already eat a fairly balanced mix of food; the resultant wastes produced are certainly good for bacteria. All that is required is a way to grind up the food and mix it with water – and that water can be dirty water.

I.B.2. Use of the Insinkerator to extend feedstock options

It would be false accounting to place the costs of including an insinkerator or other food waste grinder in the ledger sheet for biogas production; Insinkerators have been on the market for more than 70 years and have found popularity in more than half of American households merely as an appliance of convenience. They can also be properly viewed as waste management devices, defraying costs associated with garbage pick up and hauling and landfills, to say nothing of pest control and disease mitigation. Their new role as environmental assets, helping to prevent pollution and greenhouse gases, and allowing for liquid compost, provides another rationale for their use; the fact that they can help produce biogas can be considered an economic side benefit that also offsets the labor and financial costs of having to secure cooking fuel.

Wikipedia, which has become "the people's almanac and encyclopedia", offering what many consider "crowd-sourced peer review"[d] already contains much of the information needed for a popular understanding of biogas feedstock options. It states that,

> Food scraps range from 10% to 20% of household waste, and are a problematic component of municipal waste, creating public health, sanitation and environmental problems at each step, beginning with internal storage and followed by truck-based collection. Burned in waste-to-energy facilities, the high water-content of food scraps does not generate energy; buried in landfills, food scraps decompose and generate methane gas, which is considered to be a potent greenhouse gas.

[c]see http://washtech.wordpress.com/2009/05/25/public-toilets-mukuru-biocentres-project-kenya-wins-honorable-mention-in-2009-buckminster-fuller-challenge/

[d]Sai T. Moturu , Huan Liu, Evaluating the trustworthiness of Wikipedia articles through quality and credibility, Proceedings of the 5th International Symposium on Wikis and Open Collaboration, October 25-27, 2009, Orlando, Florida

> The premise behind the proper use of a disposal is to effectively regard food scraps as liquid (averaging 70% water, like human waste), and utilize existing infrastructure (underground sewers and wastewater treatment plants) for its management. Modern wastewater plants are effective at processing organic solids into fertilizer products (known as biosolids), with advanced facilities also capturing methane for energy production.[e]

Garbage disposal units are found in 50% of U.S. homes, but only 6% in the U.K. and a smaller percentage in Germany where officials still fear damage to sewer pipes. However, studies showing the safety of garbage disposals have caused most bans to be rescinded and many governments (such as those of Sweden and Australia) are now providing incentives for the use of food disposals[f]. In particular Swedish municipalities actively encourage the use of garbage disposers so that they generate cost effective biogas, which is purified and compressed and sold as a transportation fuel for cars and trucks and buses, equivalent to CNG.

I.B.3. Creating an artificial "sacred cow" biodigestor

What we have added to the approach of using food grinding to generate methane now being practiced by certain cities[g] is the addition of an Insinkerator Food Waste Grinder as the "mouth and jaws and teeth" of our family sized artificial "sacred cow". With the Insinkerator at the front end of the home scale biogas solution almost anything organic becomes an effortless feedstock for the digestor.

The Insinkerator or any other appliance food waste grinder is certainly not a necessity for the program to work, it just does a much better job than any other form of food grinding and leads to push button operation which can lead to immediate public acceptance.

The key concept is that organic materials need to be broken down into fine particles and mixed with water so that the bacterial consortia can engage in the processes of hydrolysis, acidogenesis, acetogenesis and methanogenisis, respectively.

In India the accepted practice in many households is to put food wastes in a 20 liter bucket with water and set in the sun for two or three days until it softens. Then a family member mixes and mashes it by hand until it is soft enough to flow through the feed pipe.

Because hand crushing takes time and it is hard to get many food items small, families doing this generally use 3" or 4" feedpipes to prevent clogging. We did this in our first two systems in Cairo, but the availability and costs of tank adaptors as well as pipes of that size put the systems a bit beyond the budget of most people and added to the burden of searching for parts.

In Tanzania the families in the village of MKalinzi near the Gombe chimpanzee reserve decided to use their traditional large wooden mortars and pestles that they use for grinding cassava to pulverize the potential feedstock. They would put about 5 liters of food waste into the pestle with about 5 liters of water and pound the food into a pulp which they would then mix with more water and pour into the digestor. Using this method they were able to get away with 3" and 2" pipes and fittings, but there were still items that could not be easily pounded, such as some fruit pits and bones.

Since 2" (50mm) and 1 and 1/2 " (40 mm) fittings and pipes are somewhat standard we elected to use them in most of our systems and decided to find ways to grind the food to a small enough particle size that there would be a lessened risk of clogging.

Our first experiments in Egypt were with the kind of cheap Blenders that most kitchens can afford. However, after burning out the motors of two of them we realized that even this solution required a commitment on the part of families to carefully select which food items to put in, and in what quantities.

With a blender, whose rotary blades tend to twist fibrous material into a motor jamming mess, one can not put in leafy greens or vegetable stalks or chicken skin for example. One is also well advised to blend a little at a time, adding liberal amounts of water.

In general, to keep water costs down, we recommend using grey water from dish washing or clothes washing or bathing. However, many people do not want to put such water into their blender.

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[e] "Food waste helps power wastewater plant". Articles.sfgate.com. 2009-07-24. Retrieved 2011-04-23. "Sumter Water and Wastewater Plants and Maintenance". Sumtersc.gov. Retrieved 2011-04-23.

[f] see studies cited with pdf links at http://www.insinkerator.com/environmental/global.shtml

[g] among them Sweden, where the city of Linkoping runs its entire fleet of buses on biogas, cities in Switzerland, France, Spain and Iceland and Milwaukee Wisconson and Eugene Oregon in the U.S.

The easiest solution we found is the Insinkerator[h] , a device that is "off the shelf" and relatively affordable in the United States but hard to find in many other countries (with the exception of South Africa, which manufactures their own brands).

The nicest thing about the Insinkerator solution is that it makes continuous production of biogas turn-key. In a normal batch fed biogas system, using animal manure, once the methane starts being produced in flammable concentrations, half of the gas per volume of feedstock is made in the first two to three weeks [i] and the other half is produced in the remaining five or six weeks before the energy content is exhausted. One normally thus speaks of HRT or "Hydraulic Retention Time". But finely ground up food waste is much easier for bacteria to digest and get energy out of, so more than half of the food waste energy value is turned into gas within 24 hours. And because the energy is so rich (yielding more than 10 times that of animal manure per kg) there is no problem simply adding another load of food the next day... in fact one doesn't even bother to manage the system, one simply scrapes one's plate and disposes of all organic waste down the sink as it is produced, yielding a clean kitchen, no garbage to attract flies or rats or other animals, and a sufficient quantity of gas for cooking – i.e. yesterday's cooking wastes become today's cooking gas.

I.B.4. Disbelief in simplicity

Just as people often don't trust things that are underpriced, it is hard for many people to accept that a perfectly viable solution to both their waste and basic energy needs, as well as a contributor to basic food security and health, could be so simple to construct and utilize. As we mentioned in the introduction, most people confronted with the idea of "renewable energy" or "energy alternatives" are led to believe the technologies are either exotic, complicated, expensive or big. The notion that one could supply clean cooking gas for three meals a day and provide a superior fertilizer to both compost and market purchased fertilizers simply by grinding food waste and water and putting them in a tank with some animal manures or human fecal wastes almost defies logic.

One of the myths that keeps many people from building the simple ARTI system is epitomized in this facebook post to our Solar CITIES Biogas Innoventors and Practioners Facebook Group.

> " I think it is quite difficult to build I guess as it might have leakage around the fixing of both different diameters of tanks isn't it?"

My reply was the following:

> "This is one of the myths of biogas construction. There is no need to seal the space between the tanks. The floating gas collector is free to rise up as it fills with gas and sink down as the gas is used. Because the bottom tank is filled to the top with water it forms a water seal and no gas escapes from the inverted tank. There are minimal (really tiny) losses from bacteria living on the bottom sides of the tank but they are so marginal as to have no effect. In fact they act as an indicator that you are getting digestion that day (you see microbubbles around the rim in the water). Most of the bacteria around the edges die because of exposure to surface air but that air doesn't penetrate down very far. The bacteria underneath the gas collector are safe and do very well.
>
> In fact it is so simple to build it defies comprehension. Basically just do what I did on my porch – I put a 300 liter plastic garbage can upside down in a 500 liter plastic rain water tank. I ran a pipe to the bottom of the 500 liter tank with an elbow so it went to the center and I put a gas outlet on the top. The end."

II. The Demystification Model

As can be seen from figure 1 the basic biodigestor follows a very simple form, as described above.

In teaching inner city science the motto used was always "K.I.S.S." – Keep it Simple Stupid. The Solar CITIES model is to demystify the process of producing useful biogas from ubiquitious household wastes

[h] There are other brands in the U.S. such as Wastemaid Food Waste Disposers out of Anaheim, CA, Insinkerator is the oldest company, founded by the architect from Racine Wisconson who invented the garbage disposal in 1927 and put it on the market in 1940

[i] when the weather is warm enough – 32 to 37 C is the optimum and the curve is non-linear; almost no gas is made at 15 C and then it ramps up exponentially, dying down again above 45 C which becomes too hot for the mesophylls

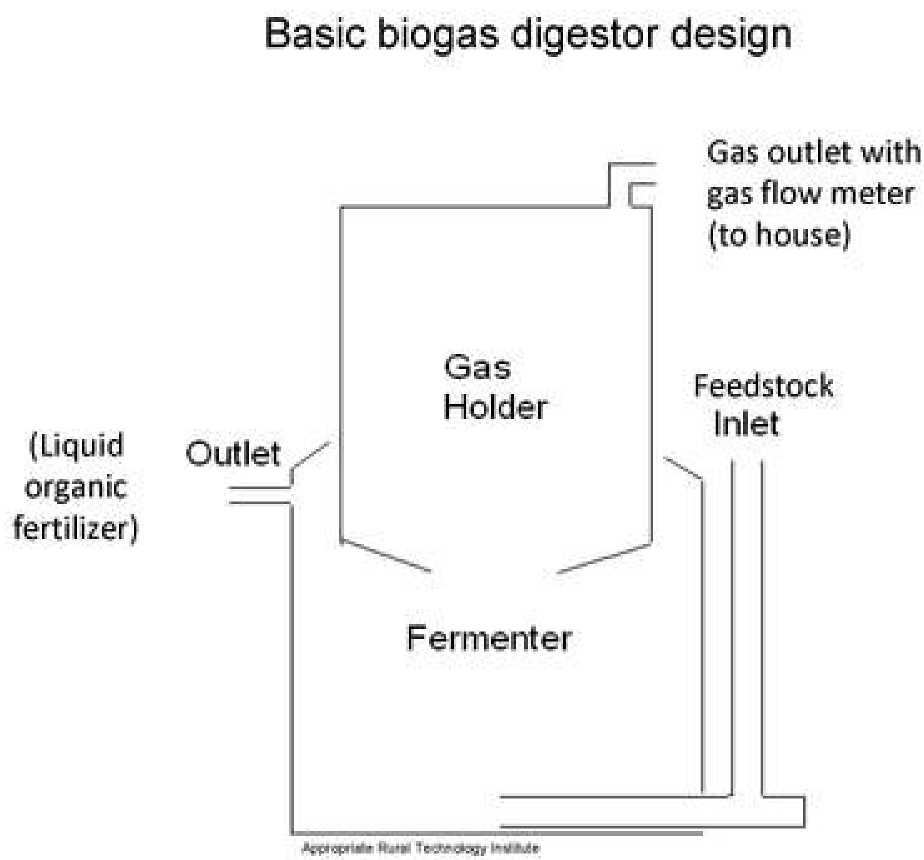

Figure 1. This is the simplest of possible biogas systems that can be constructed, and can be done so using two water tanks or even plastic trash cans.

utilizing locally found and off the shelf materials. Because Solar CITIES focuses on kitchens and bathrooms in low-income and informal urban settings we also strive for solutions that are small scale and affordable.

One of the discoveries we have made in our efforts to demystify is that most people are alienated by presentations that focus on precise measurments. Saying "yields of biogas from organic wastes are roughly 500 liters per kg", or "the ratio of food waste to tank size is about 1:40", while simple to an engineer or scientist, often intimidates laypeople. We find the "Rule of Experts" phenomenon to be a real barrier to acceptance. Instead we use common measures and language such as "a family of four generally produces enough kitchen garbage each day to fill a 750 liter tank and cook for 2 hours on a single stove burner on the following day." Or we will say "Every thousand liter tank you set up can be fed a normal 25 liter bucket of food waste that is half food and half water. If you want to cook for 4 hours you need a 2000 liter tank and you need to load it with 2 buckets of half water, half food."

An overemphasis in the literature on procedures for purifying biogas for the market has also inhibited uptake by people. Raw biogas is perfectly appropriate for all cooking, heating, lighting and absorbtion chilling refrigeration needs, while for engine operation the gas merely must pass through a simple pipe filled with steel wool or iron fillings to capture most of the H2S.

The literature also makes too much of the water vapor content – in Nairobi we created a simple T which we placed in a jug of water placed at the lowest point of the gas tube before it went to the kitchen to condense and catch water vapor that was clogging the line.

The CO2 content of the gas is not an issue at all in household utilization and need not be removed.

Jaffe and Stavins (1994)[8] developed formal equations to help solve "the energy paradox and the diffusion of conservation technology" and modified them for retrofit situations:

$$minPV(T) = \int (kij, ijt) * e - rtdt + w * \int (g(kij, \mu(ijt) * e - rtdt + [L(CiT, ViT)XiT] * e - rt + \int (Dit * e - rtdt) \quad (1)$$

where minPV = the desire on the part of homeowner to minimize costs for three elements: the present discounted value of annual energy costs from the present to the time of adoption of the energy saving technology, the PV of annual energy costs after the adoption, and the PV of the one-time cost of adoption of the energy saving technology.

The one time cost of adopting small scale biogas as an urban energy saving technology is often considered high relative to the marginal costs of continuing to use traditional fuels but calculations done by Naijatomo Holistic Waste Management company in Nigeria showed a payback period of under 3 years. Studies in India have yielded similarly favorable IRRs,[19].[16]

Another issue that has interfered with adoption of small scale biogas is an unfamiliarity with the simple techniques for converting normal gas stoves to be used with biogas. Normal stoves are made to receive a high pressure gas from a bottle or line and have pressure restrictors with tiny holes made to accommodate high pressure fuel. Biogas comes in under a very low pressure (no more than 8 inches water column) so it needs a much larger hole to burn. In both Nairobi and Palestine use of the biogas systems we built was stalled for a year because we were not on-site when the systems started producing gas and the stakeholder's attempts to get the gas to flow through a standard stove failed. They both tried to increase pressure by adding weights to the gas collector tank but it didn't yield satisfactory results for cooking. We told them by email that they should drill through or remove the pressure restrictor pin so that the gas flows freely through but they were intimidated by the process. However once we returned to the sites and showed how easy it was to do word quickly spread and nobody has a problem with this anymore. Still, some people who are now reliant on charcoal or wood for cooking are reluctant to switch to biogas for fear that they might run out of the gas before a meal is finished. Rather than asking them to purchase two stoves an innovative solution to the problem created by biogas innovator and entrepreneur Dominic Kahumbu Wanjihia and Elizabeth N. Kimonge at the Jamhuri Energy Centre, which develops local alternative-energy systems, is to build stoves that can use traditional biomass or charcoal but into which a simply "biogas adapter" can be placed – essentially a coffee can filled with rocks with a perforated lid. The unpressurized gas goes into the coffee can which spreads the flame for cooking. When the gas runs out the can is simply removed and one fills the stove with traditional fuels. Once people see how to convert stoves or even use simple coffee cans as stoves the elegant simplicity of the solution makes them eager to spread the news to others to "please, try this at home".

The real problem with small scale biogas adoption is not economics but perceptions.[9] Not only is unfamiliarity a barrier, but there is a certain type of "club convergence" that impedes its adoption. Basically

Figure 2. Culhane demonstrates the use of the Insinkerator, one of 10 donated to the project around the world by Emerson Electronics, to prepare food wastes for biogas.

Figure 3. A 3D model of the ARTI system developed in Blender to help others work with the technology.

a "culture" of urban biogas use has to be created before it is seen as a desirable solution.

III. Temperature as barrier

Figure 8 shows the range of biogas systems that can operate without heating. Since the "shut down temperature" of mesophilic bacteria is roughly 15 C most people assume that small scale biogas is not feasible in latitudes where the seasonal averages drop below this.[2] PlanET Biogas company in Germany, where over 5000 commercial scale biodigestors operate since 2010, estimates that 20 to 40 percent of the gas produced is used to keep the digestors at operating temperature, but this can be misleading since German biogas systems almost all use the gas produced for electric generation and the heat comes from heat exchangers that capture the waste heat from the generator engines. Since this heat is often sold as hot water (at an average temperature of 70 C) that is piped for central district heating or to spas and swimming pools, it can be argued that having to heat the digestors eats in to profits. But since there is no net loss of heat this can not really be said to be a barrier.

In the small scale model heating the digestor is considered more problematic. The surface area to volume ratio is higher so there is more heat loss the smaller a system you have, and it is impractical to use the small amounts of gas produced to run a generator and capture the heat from that. 1 cubic meter of gas, the household average per day at 35 C, can only run a generator for a little under an hour; this probably would not be sufficient to keep the tank heated, and while using the electricity to charge batteries is a viable option, most families prefer to use the gas to cook with or to run a refrigerator or lights.

The Solar CITIES home model has been to exploit three different sources of heat for two of our systems. The first source of heat is a polycarbonate greenhouse built around the tank. This maintains a daytime

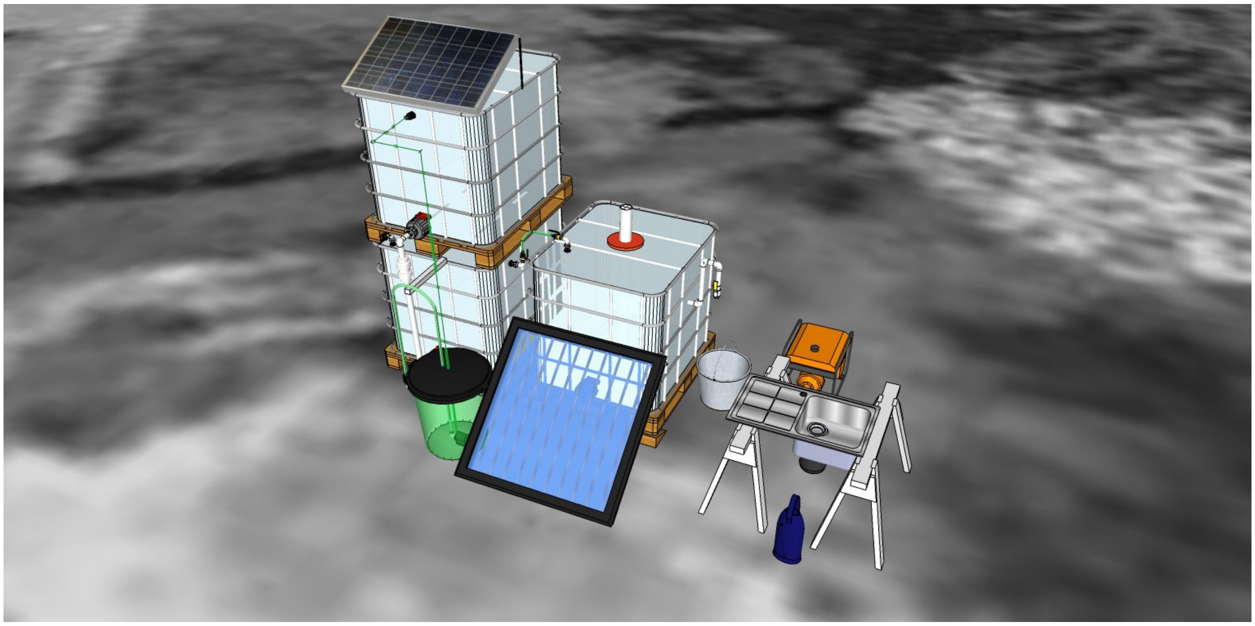

Figure 4. A 3D model of the Solar CITIES system developed in Blender to help others work with the technology.

average temperature of 40 C around the insulated tank and reaches 60 C at different times throughout the day. But it drops to 20 C on spring nights so is really a way of keeping the tank from losing too much heat.

The second source of heat is a small solar hot water panel connected to the tank via a photovoltaic 12 V water pump. Digestate comes out of the digestor into a 110 liter holding tank connected to the water pump which then circulates through the solar heater and into the feeding tube of the tank whenever the thermostat registers a temperature of 35 C or above. In our Seattle experiment the solar hot water doesn't contact the digestate but goes through a heat exchanger in a closed loop instead. (see figure 7

While this is a good system, most of these temperate zone areas lack enough sunlight for this to be a viable year round solution.

In our second biogas system the tank is located next to the bathroom window and connected to the bathtub grey water stream. The second biogas system has a 700 liter IBC tank nested in a 1000 liter IBC tank which is surrounded by 2 layers of 3" styrofoam insulation (see figure 24. The 700 liter tank is the digestor and the 1000 liter tank acts as a water insulating jacket. Each time we take a shower or bath hot water (about 35 C) fills the envelope around the digestor, transferring its heat inside. Overspill from the envelope goes down the drain as the normal hot water would. The difference is that whereas most families use their hot water investment in just a few seconds as it pours over their bodies while showering, we capture that heat to keep the digestor going. Since we have a vacuum tube solar hot water system with natural gas back up, this is another form of solar heating and even when we are using the natural gas we are merely capturing waste heat so we don't incur any heating cost.

IV. The use of psychrophiles to extend the range of biogas systems

Temperature range is a major restricting factor for most existing biogas digestors. Traditionally, ruminant manure is used as both a food substrate and source of methanogens for the microbial community since methane-producing microbes live in animal rumens at 37C. However, these microbial communities consist primarily of mesophilic, or warm-loving (15 to greater than 40C), bacteria, which typically shut down (hibernate, in a manner) in colder winter months outside the animal's body. This requires that the digestor be stored indoors, heated. or retired in the cold season.

If able to solve the cold temperature-limitation problem, small scale biogas digestors could prove an excellent alternative energy source for families dwelling in the temperate and even Arctic and Alpine zones. On our first Blackstone Ranch Innovation Challenge Grant we chose to focus on Alaskans, who face particularly high seasonal fuel costs, and globally where communities experience cold seasons.

Figure 5. A normal cookstove fed with biogas in the home of Hussein Farag, a retired metal worker and Solar CITIES colleague in the urban slum of Darb Al Ahmar Cairo. In this case the restrictor pin was simply removed; the biogas system is on the roof three flights above and simply using two bricks is enough to pressure the gas to go down to the kitchen and through the stove .

We proposed to mitigate the temperature limitation problem by improving existing biogas digestors with the addition of a naturally-occurring, cold-loving (psychrophilic), methane-producing microbial community that is ubiquitous in Alaska.[6] Methanotrophic psychrophiles which thrive across Alaska in lake bottom sediments have been shown to produce strong methane seeps in thermokarst lakes year-round, even during extreme-cold (-40C) winter temperatures when lake bottom sediment temperatures reach nearly to freezing. Despite showing maximum methane production at 20-25C in laboratory experiments, psychrophiles display significant biogas production down to 1C, unlike the conventional mesophiles which shut down when temperatures far below 15C. In mild climates, psychrophilic-based digestors could be kept outdoors above ground; in colder climates the digestors could be buried underground or kept in low-heated outer buildings to maintain the minimal temperature required for psychrophilic activity (0 to 40C). The psychrophilic-based digestor should produce biogas for Alaskans during summer and winter, and has the potential to be marketed globally as a cold-temperature solution elsewhere.[5]

IV.A. Work Plan

With cooperation between the CEC, UAF and the Cordova High School, we built and analyzed a series of digestors to test biogas production rates of mesophiles versus psychrophiles through summer and winter seasons using different types of iocally available and sustainable Alaskan feedstocks, construction materials, and upkeep protocols. Phase 1 of the two-phase project experimented with 6 digestor systems to determine the most efficient biogas production system. Phase 2 utilized the most efficient system in local real-use implementation, such as to power methane-fueled stoves and appliances, lights and an electrical generator.

Figure 6. At the Jamhuri Energy Centre, which develops local alternative-energy systems, Elizabeth N. Kimonge and Dominic Kahumbu Wanjihia build hybrid clay stoves optimized for biogas that can also use traditional wood or biochar fuels. The biogas is piped into a removable coffee can filled with stones with a peforated lid. When the gas runs out the coffee container can be simply removed and biomass put in to continue cooking.

IV.A.1. Phase 1

In research Phase 1, we considered three groups of variables: microbial community (mesophiles vs. psychrophiles), feedstock (food scraps vs. vegetationafishing/hunting mixtures), and temperature (indoor vs. outdoor). Microbes were obtained from Alaskan farms (mesophiles in ruminant manure) and thermokarst lake mud from Fairbanks and Lake Eyak in Cordova (both contained psychrophiles).

We obtained feedstock from the Cordova High School cafeteria and the AC Value Center grocery store excess (food scraps), Cordova canneries and harbor (fisheries offal), and from yard clippings, trail maintenance and other locally and regularly produced leafy vegetation. We maintained carbon to nitrogen ratios in feedstock (C/N = 8 to 20) optimal for anaerobic methane production by balancing ratios of C-rich vegetation and N-rich food and/or fish, using an Insinkerator attached to a circular manifold with six buckets attached to make sure that each of the six tanks got the same amount and consistency of feedstock. Most food scrap falls naturally within this range and need no additions. C to N ratios of feedstock and digestor effluent were measured periodicalJy at UAF .

To test temperature capacity, three insulated 1000-L digestor tanks were maintained inside one room of a converted insulated conex container at 15 C and three insulated tanks were maintained inside another room of the conex at 25 C . Two of the tanks (one in each temperature treatment) were inoculated with proven warm-loving mesophilic microbes from Alaskan manure, one tank in each temperature treatment zone was inoculated with lake mud containing psyhcrophilic bacteria, and one tank in each room was inoculated with a mix of lake mud and cow manure so that we could se in coexistence was possible and if it led to positive or negative effects on gas production.

Interior temperature data loggers, inserted through the inner diameter of the feed tubes and then attached

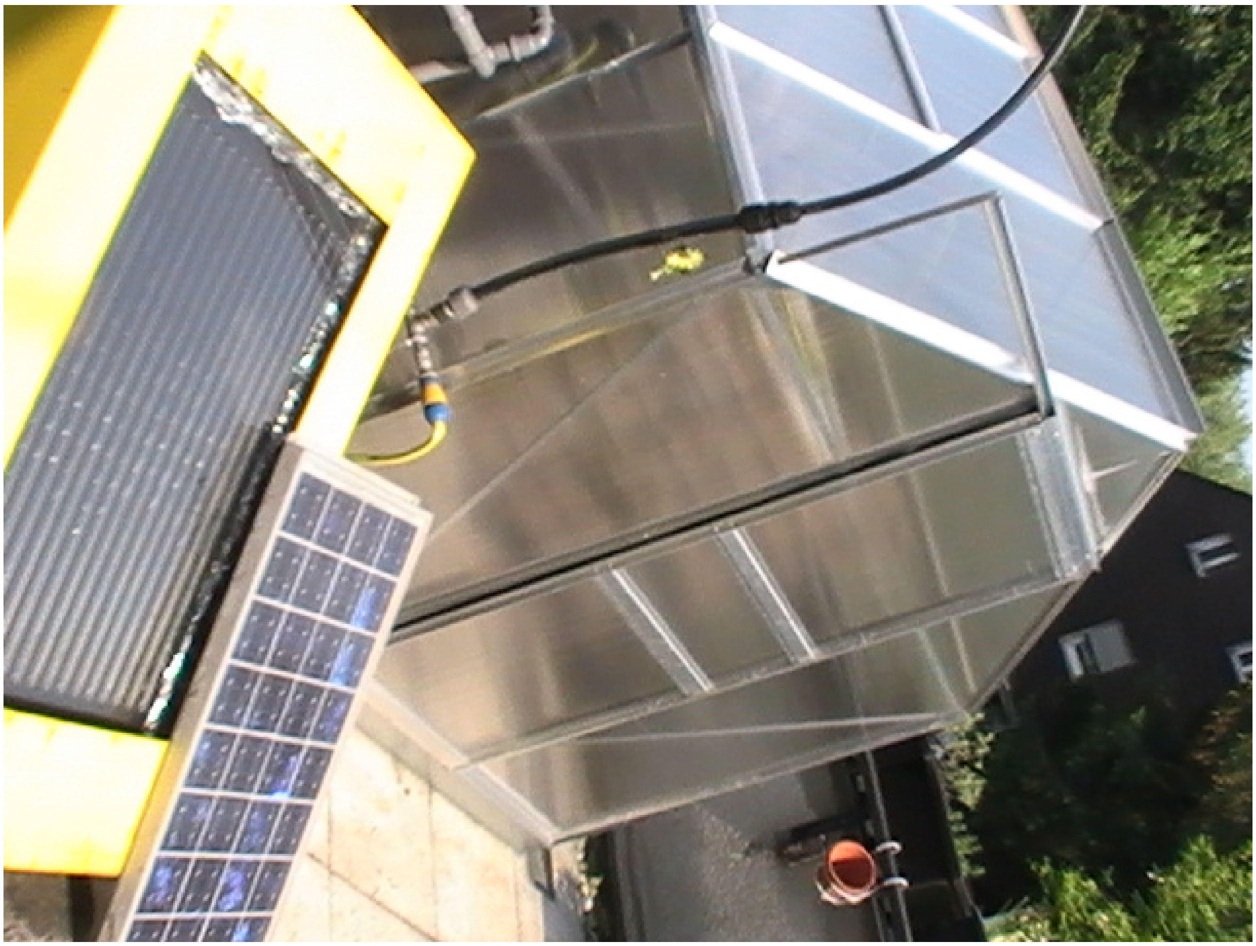

Figure 7. Culhane's 1000 liter IBC biodigestor in a polycarbonate greenhouse heated by a home-built solar hot water panel made from a recycled radiator with effluent recirculated via a 12 V Photovoltaic powered pump

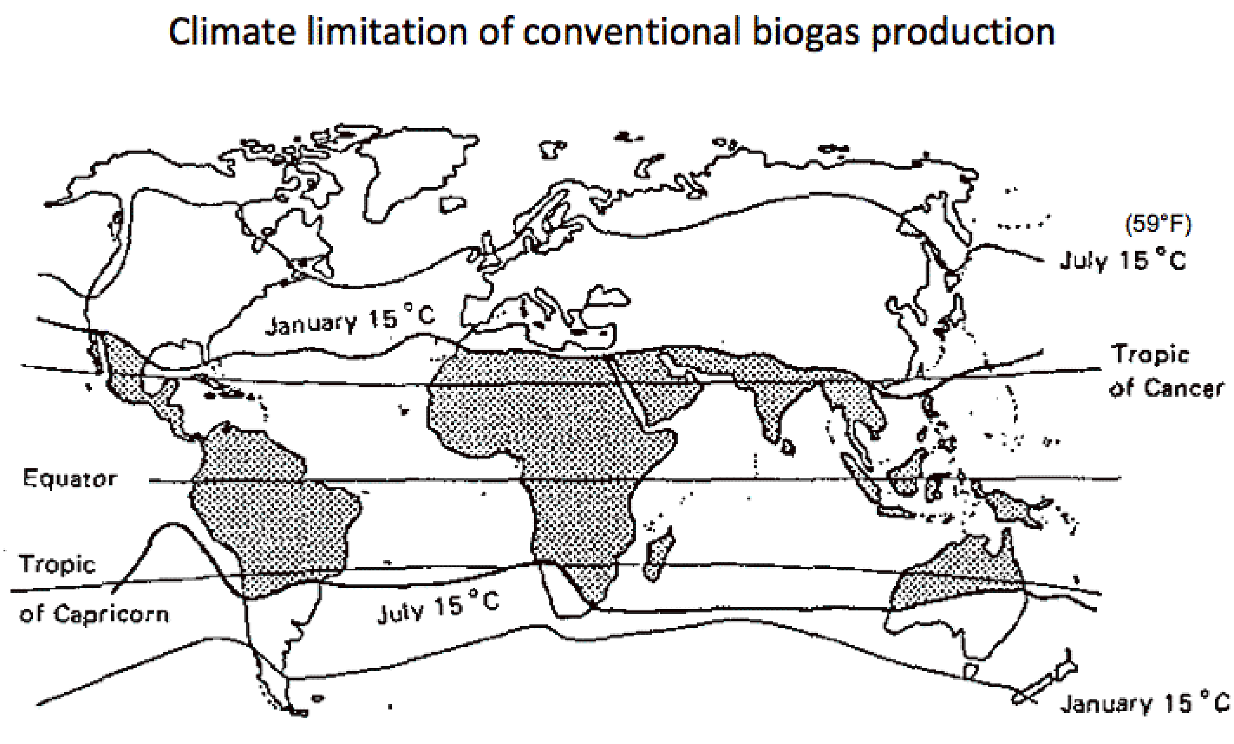

Figure 8. Range of unheated biogas systems

half-way up the outside diameter of the feed tube, recorded temperature data from the mid-point of the tank throughout the study. Additional data loggers collected ambient indoor and outdoor air temperature external to the digestor tanks. Substrate quality (C/N), fermentor conditions (pH, temperature, dissolved oxygen, salinity, conductivity), and gas composition (percent CH4, C02, N2, 02) were monitored regularly (weekly to monthly depending on stage of experiment and parameter). Qualitative assessment of odor was made weekly. Units of effort (hours) to build and maintain the biogas digestors were be recorded.

IV.A.2. Phase 2

In Phase 2 we collected the gas from all of the systems combined (with gas production rates for individual treatments being recorded as the gas evolved from each tank) to power gas-burning stoves, a modified electrical generator, and other gas-appliances and lights. These applications of conventional biogas digesters have been proven and are commonly used during warm seasons in households, industry, and community buildings in Germany, California, India, and China,[18],[21].[11] In our study we sought to create public awareness and get home-scale biogas accepted as one of the sustainable technologies under consideration in Alaska for public buildings (such as the Cordova High School) and local residences.

For the digestor implementation, some primary materials were donated (six 1000 L tanks for the primary substrate containers were donated to the project by a local fish processing factory). Many of the necessary construction materials were recycled from local waste. Some items, such as tank fittings and plumbing supplies, needed to be purchased from local hardware stores or, in the case of some scientific equipment such as the data loggers, were ordered by UAF. Mesophilic substrate material was freely procured in the form of manure from an Alaskan ruminant farm. Psychrophilic material was collected from thermokarst lake mud near Fairbanks. Feeding substrate was locally collected around Cordova: kitchen waste was collected by students from the high school cafeteria and grocery waste disposal, fisheries waste was collected for pick up at the canneries; due to budget and time concerns we decided not to build a 3-phase biodigestor to handle cellulosic material so we abandoned the idea of having vegetative scrub piled and shredded by local organizations for pick-up by students helping to maintain the digestors. This activity could occur in a Phase 3 if we secure more funding; Dr. Martin Denecke of the University of Essen in Germany has shown us his patented "3A" biogas system that can be used to win fuel and fertilizer from urban street wastes such as leaf litter, branches, bush, shrub and grass clippings and paper residues.[4] The trick to using these materials as sources of carbon for biodigestors is to first treat them aerobically for 24 to 36 hours so that the hydrolytic bacteria can simplify the complex polysaccharides,[1] but this takes a different design set up and is most efficient if an air blower and a sprinkling system are built in, adding to cost.

IV.A.3. Stretch Goal

A stretch goal for this project is implementation at Chena Hot Springs after Phase 2 to utilize local food scraps and vegetable waste produced onsite for biogas production; gas will power greenhouse lanterns to supply heat and C02 for growing tomatoes to offset the current use of bottled, delivered propane. The project team will track the time and effort of construction and maintenance of digestors as a baseline for wide spread deployment in Alaska. Several trips were made to visit owner/Engineer Bernie Carl and explore possible synergies with his existing Organic Rankine Cycle Micro-turbines and Adsorption Chillers with currently use low temperature water from the thermal baths to provide electricity and refrigeration.

V. Looking toward the Future

Regardless of the type of bacterial consortia used (psychrophilic, mesophilic, thermophilic or a mix of the three) certain mechanical considerations can radically improve the volumes of biogas produced not just per kg of feedstock but per liter of tank volume. William Throndset of Genencor, writing about the quest to improve biofuel production in his lab through bacterial enzyme production, writes,

> ... several options exist for meeting the needs of increased enzyme demand. The first is to increase capacity by building additional plants. The second is to discover or invent an enzyme product with higher specific activity so that less enzyme can be used to accomplish equivalent end-product formation Finally, the host organism can be genetically altered to produce more enzyme per unit of volume, i.e. increased volumetric productivity. [20, p. 346]

Gas Production Summary Data (Raw Data)

	15°C Room			25°C Room			
Date	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5	Tank 6	All Tanks
12/11/2010	28	0	0	127	151	0	
1/17/2011	20	0	0	208	145	24	
1/18/2011	21	0	0	257	163	28	
1/19/2011	32	0	0	202	197	41	
1/20/2011	49	0	0	330	318	91	
1/21/2011	28	0	0	166	192	89	
1/22/2011	40	0	0	238	280	208	
1/23/2011	59	0	0	346	320	264	
1/24/2011	50	0	0	141	169	115	
1/26/2011	46	0	0	358	433	332	
1/29/2011	35	0	0	175*	183	145	
1/30/2011	35	0	0	175	183	145	
1/31/2011	63	0	0	155	169*	136	
2/1/2011	47	0	0	182	215	171	
2/2/2011	46	0	0	179	236	150	
2/3/2011	42	0	0	148*	140	102*	
2/4/2011	33	0	0	231	230	220	
2/25/2011	28	0	0	91*	148	113	
2/26/2011	1	0	0	150	166*	157	
2/27/2011	27	0	0	141	182	156	
2/28/2011	51	0	0	140	191	162	
3/1/2011	22	0	0	166	210	181	
3/2/2011	41	0	0	155	186	169	
3/3/2011	28	0	0	137	174	157	
3/4/2011	24	0	0	145*	163*	163	
3/5/2011	32	0	0	146	185	161	
3/6/2011	18	0	0	152	197	165	
3/7/2011	33	0	0	146	182	165	
3/8/2011	39	0	0	163	203	146*	
3/9/2011	37	0	0	166	198	157	
3/10/2011	35	0	0	215	266	255	
6/1/2011	41	0	0	12	72	30	155
6/11/2011	91						199
6/12/2011	100						189
6/13/2011	74						120
Average	**35.4**	**0.0**	**0.0**	**179.4**	**201.4**	**143.7**	**166.0**
Standard Dev	**12.8**	**0.0**	**0.0**	**69.6**	**65.3**	**71.6**	**36.1**
Total	**1131.4**	**0.0**	**0.0**	**5741.0**	**6446.0**	**4597.7**	**663.8**

* Days in which a documented leaks occurred (exact volume released is not known)

Figure 9. This table excerpt, taken from the Denali Quarterly Report[10] shows gas production from the 6 treatments in our laboratory in Cordova. Tank 1 contained psychrophiles at 15 C, Tank 2 psychrophiles and mesophiles mixed at 15 C, tank 3 just mesophiles at 15 C; Tank 4 contained psychrophiles at 25 C, Tank 5 a mix of psychrophiles and mesophiles at 25 C and Tank 6 mesophiles only at 25 C. For reasons that are unclear the consortia in tank 2 did not recover from the acidification in an overfeeding event but had been producing flammable gas early on in the experiment. Tank 3 has a similar history. Thus we cannot rule out that the psychrophile and mesophile mix and the mesophiles alone would have kept producing; we must consider this data missing. What is of note is that the mix of psychrophiles and mesophiles in tank 5 outperforms either group alone in all cases except 3/4/2011 when production is tied with mesophiles alone and exceeds psychrophiles.alone. Of note is that on this day there was documented leakage from tanks 4 and 5 so these figures are actually underestimates. In any event what we see is a strong indication that a mix of extremophiles and normal biogas bacteria does seem to improve production.

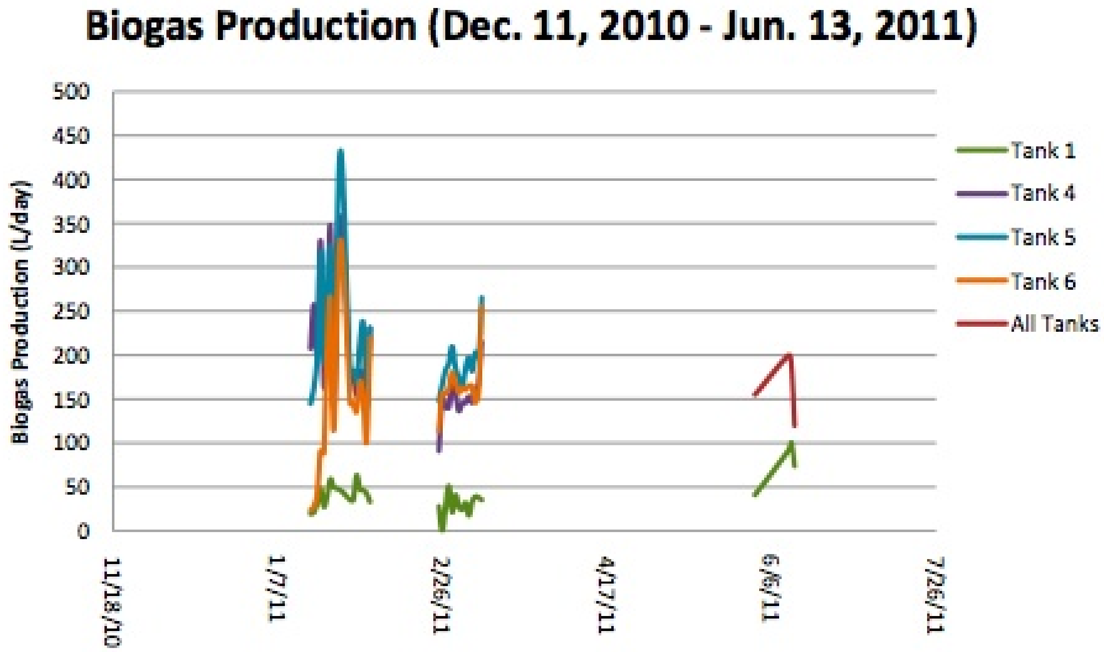

Figure 10. Here we see the data from the Denali Report displayed graphically. It is clear that tank 5, the mix of psychrophiles and mesophiles, outperforms all of the others. It is likely that the psychrophiles adapted to the colder regions of the tank and mesophiles to warmer regions and were able to win more gas than treatments where the microbes must work alone and can only exploit those regions of the tank optimal for their growth. This suggests further experiments into designing microclimates into tanks for the growth of the best microbiomes for production.

In our case, vis a vis option 1, working with limited space in urban slums and with limited materials budgets in both slums and rural villages, the building of additional plants is often both geographically and economically unfeasible. As indicated in the previous section we have already set about exploring option 2, discovering bacterial consortia (Alaska, Mt. Everest Base Camp) that can widen the gas production's effective temperature range and we are placing them together with mesophiles in tanks to allow for the possibility of gene transfers that may allow for the selection of a more productive organism. But the easiest option to tackle in the short run is to increase volumetric productivity by increasing the surface area for biofilm formation and the flow characteristics to deliver feedstock efficiently to the bacteria colonizing surfaces. Arava Institute of the Environment Biogas expert Yair Teller (now founder of the Israeli company "EcoGas") and Marine Archeologist Beverly Goodman and I, when we were building flexible bag or "salchicha" biodigestors together near Eilat, Israel, likened the process to creating an environment analogous to a coral reef where nutrients can flow through dendritic and racemose vertical substrate areas throughout the tank rather than relying on the sludge granule bacteria that build up at the bottom of tanks.

A vertical substrate for biofilm formation would also allow psychrophiles, mesophiles and thermophiles to occupy their preferred niche spaces in the same digestor.[12] Because water naturally stratifies into thermoclines and mixing is mechanically and energetically costly, a passive design that allowed the three types of microbes to "choose their microbiome", given that the coldest water is naturally at the bottom of the tank, the hottest water at the top and the "goldilocks" water in the middle could radically increase productive capacity.[3] As temperatures change the biofilm populations on vertical contiguous surfaces would no doubt adapt faster.

For the past two years Culhane has been working with the idea that we can reduce the size of the necessary biogas reactors by increasing the internal surface area using inexpensive means. Culhane has experimented with inserting what we call "bacterial fuel rods" or "high-rise bacterial condos" in the tanks (like a cluster of calliope pipes) because they connect the cooler and warmer parts of the tank for optimal biofilm production (or so the theory goes).

The idea was independently suggested by a young Maasai boy in Kenya and his middle school age American guest when they were building a digestor with Culhane in the Ol Donyo Was nature reserve between Nairobi and Mombasa (see figure 12). Dissatisifed that a 1m3 digestor provides a maximum of 2 hrs of cooking fuel per day the Maasai child asked the obvious question "if we feed the digestor more food

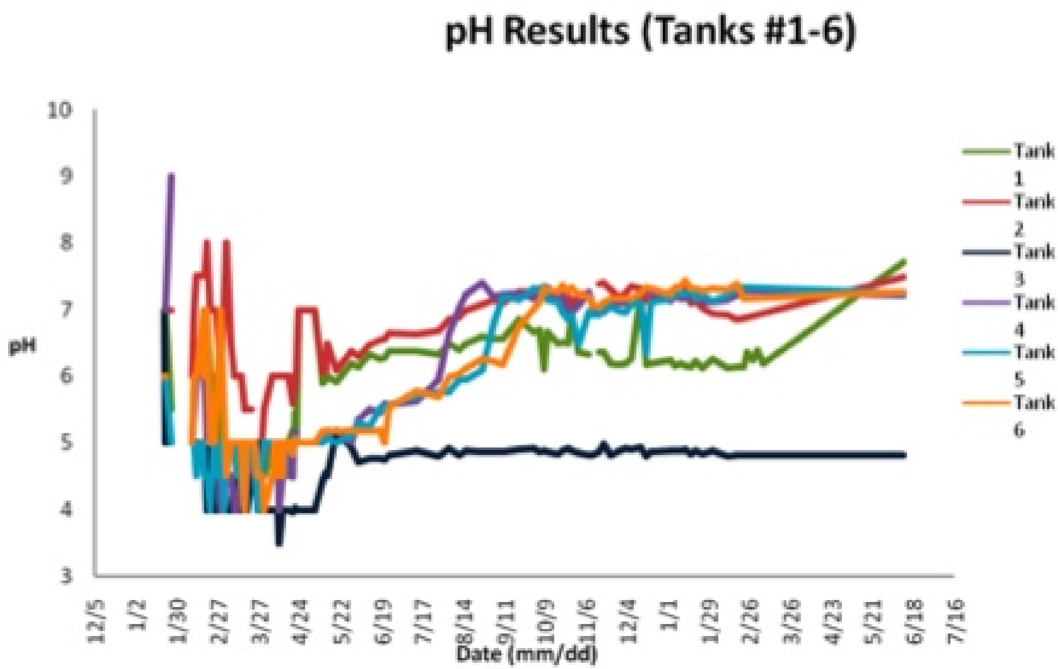

Figure 3. Results indicate that the pH in Tank 1 fell slightly since Y1Q3 report, but has recovered to almost neutral pH following the cessation of feeding on April 18, 2011 (currently pH 7.71). We halted daily feeding to allow the opportunity for pH to recover on its own, without reverting to chemical remediation treatments. pH was measured with Macherey-Nagel litmus paper January 21-April 16 2010, and with more precision using an Oakton PC510 pH meter since April 17, 2010 until the present.

Figure 11. The graph of pH results taken from[10] shows that tank 3, the mesophile only tank at 15 C never recovered from the acidity event which would explain why it stopped producing methane. Given the low temperature, at the threshold for mesophilic activity, it would make sense that the methanogens, which are very pH sensitive, would not be able to recover. Harder to explain is tank 2, a mesophile/psychrophile mix, but it is quite possible that on the way to pH neutralization recovery the hydrolytic bacteria, the acetogens and acidogens were able to recover but not the methanogens; biogas production depends on a chain of events at the end of which the methanogens convert what the others have produced into methane. We can see that tank 2 experienced wild pH swings early on and at the low temperature of 15 C it might have been difficult for the consortia of bacteria to balance themselves while tank 6 at 25 C seems to have gone through similar swings but, being at a comfortable range for its mesophiles, seems to have recovered fine.

Figure 12. Maasai guide Edwin, his son and a foreign guest feed an ARTI reactor at Ol Donyo Was Nature Reserve in Kenya. The boy independently came up with the idea of using pipes as "bacterial condominiums" and cut them to look like calliope pipes to let feedstock in and methane bubbles out.

waste will we get more gas?" The problem is that this seemingly common sense response to the problem of limited gas production is actually responsible for the failure of many food-scrap biogas initiatives. For example, SNV, a Dutch agency promoting biogas in Rwanda, told us that they stopped encouraging food waste as a feedstock because people tend to overfeed, particularly when trying to increase gas production, causing a drop in pH that is catastrophic to their methanogens. Recovery is not hard to effect (in many cases one can simply stop feeding for a few weeks and wait for the pH to balance and for gas production to start again; in other cases one can force an immediate return to a neutral pH through the addition of calcium carbonate or sodium hydroxide or simply apply baking soda or baking powder[j], and finally one can add more manures or sewage sludge to rejuvenate the bacterial population). However the "down time" while attempting recovery can be a disincentive to people whose culture doesn't yet embrace the home scale biogas solution and can lead to abandonment. For this reason SNV, which is working with the Rwandan government which is now subsidizing up to 50 percent of domestic biogas system costs, demands that to qualify for the subsidy the families must have at least 4 cows or 6 six pigs in a zero grazing situation to ensure the proper amount of feedstock for robust biogas production. The problem with this is that to handle those volumes of animal wastes a tank must be very large (on the order of 10m3) to achieve the same amount of gas production as a 1 m3 kitchen-waste fed reactor (producing roughly 1 m3 of gas per day). Furthermore, disposing of the prodigious amounts of effluent each day, even though it is a fertilizer, becomes problematic for most small holders. In the case of the food-waste fed reactor, one gets comparable gas from a couple of kilograms of foodwaste ground in a standard water pail[k] and the effluent volume each day is the same as the feed volume going in producing easily utilized quantities of liquid fertilizer. Nonetheless, there is enough worry about overfeed acidification and subsequent gas inhibition that many people and agencies refuse to recommend small home scale digestors fed on kitchen scraps. The trick is to find ways to keep size small and increase the volume of feedstock it can handle.

When confronted with the problem of acidification from overfeeding wiping out the methanogens the young Maasai boy asked "what if we can make more places for the "vijidudu" (microbes) to live so they can eat more?" Grabbing old plastic pipes we had lying around and holding them upright in a cluster he said, "what if we put them in the tank something like this... as if they were apartment buildings". Culhane had conceived of the same solution by thinking of the pipes as "microbial fuel rods" (from a nuclear reactor metaphor) which can increase the rate of reaction by allowing for more active microbes in the reactor. Since this time Culhane et al. have built the "vertical microbial fuel rods" into all of their digestors.

In addition to experimenting with vertical pipes to increase surface area in the tank Culhane has been experimenting with hundreds of "bioblocks" and "bioballs" acquired from aquarium shops and is using them in various configurations within the tanks, in some treatments free floating, in others clustered into hanging "socks", the goal being to give the microbes places to live and feed far beyond the sludge granules on the bottom of the tank (see figures 17 and 18) . Culhane also is working on treatments using corrugated plastic electrical tubing. In some treatments we simply put the coil of 1/2" or 3/4" tube in the tanks, in others we chop up the tube into 2cmx2cm tubelets. It is unclear which provides better results at this point; certainly eliminating the need to invest the labor in chopping up the tubes can lower costs and increase acceptability. We are aware that the Chinese company Puxin is now using what look like test tube brushes suspended vertically in the tank. And so the quest goes on to make the smallest artificial cow stomach with all its surface area and invaginations and villi for microbiomes to form in those marvelous city-like multispecies biofilms.

What makes biogas production unlike, say, cheese or yoghurt or ethanol, is that it "takes a village"; i.e. the production of biomethane requires a complex microbial consortia working like different parts of a factory with all sorts of specialists handing down products to others. So it is really about creating the habitat for this marvelous ecology. Culhane is currently running 5 different reactors of various sizes on his porch (and in the upstairs bathroom) in Germany but doesn't yet have the equipment for proper analysis so the work is still a hit or miss home grown experiment.

[j]This treatment was done at Cordova High School by Casey Pape and Adam Low and his science classes when the tanks were inadvertently overfed by overzealous students; the only danger with trying to manipulate the pH with bases is that it can become too alkaline and, according to scientists at Blue Marble Energy whose Seattle biotechnology lab we visited, the alkalinity is far more lethal to the bacteria than acidity since the methanogens metabolise organic acids like acetate to make methane.

[k]this makes intuitive sense to most people we've worked. Most people, particularly farmers, get the idea that the caloric value of a food is reduced by the animal eating it as it uses the energy in the food to maintain homeostasis and engage in activity and grow; the animal manure can be considered "spent fuel"

Figure 13. The bacterial "fuel rods" or "bacteria hotels" here are cemented into the ground and provide vertical surfaces for biofilm formation This solution doesn't work so well for above ground plastic tanks.

Figure 14. To use bacterial fuel rods in a completely plastic tank, In Nigeria we decided to insert the "fuel rods" into the cover of the tank with nail-pins on either end to allow them stay submerged as the gas collector rose and fell, sliding past them.

Figure 15. Solar CITIES co-founder Sybille Culhane at home in Germany loads the family biogas reactor with floating "socks" filled with bioballs to increase vertical surface area for biofilm formation. Recently we have wondered if clustering the balls into socks isn't counterproductive, preventing the center balls from getting enough food and releasing enough gas so we now simply pour the balls into the tank and let them float, putting enough in so that they fill various temperature clines in the tank.

Figure 16. Another experiment for placing the bacterial fuel rods was conducted in the Mukuru Slum in Nairobi by our Solar CITIES interns Minke Noordam and Nils Andersch, art instructor Dave Redmond and teacher Henry Okeyo. In this case they suspended the rods using plastic bottles and weighted them with stones .

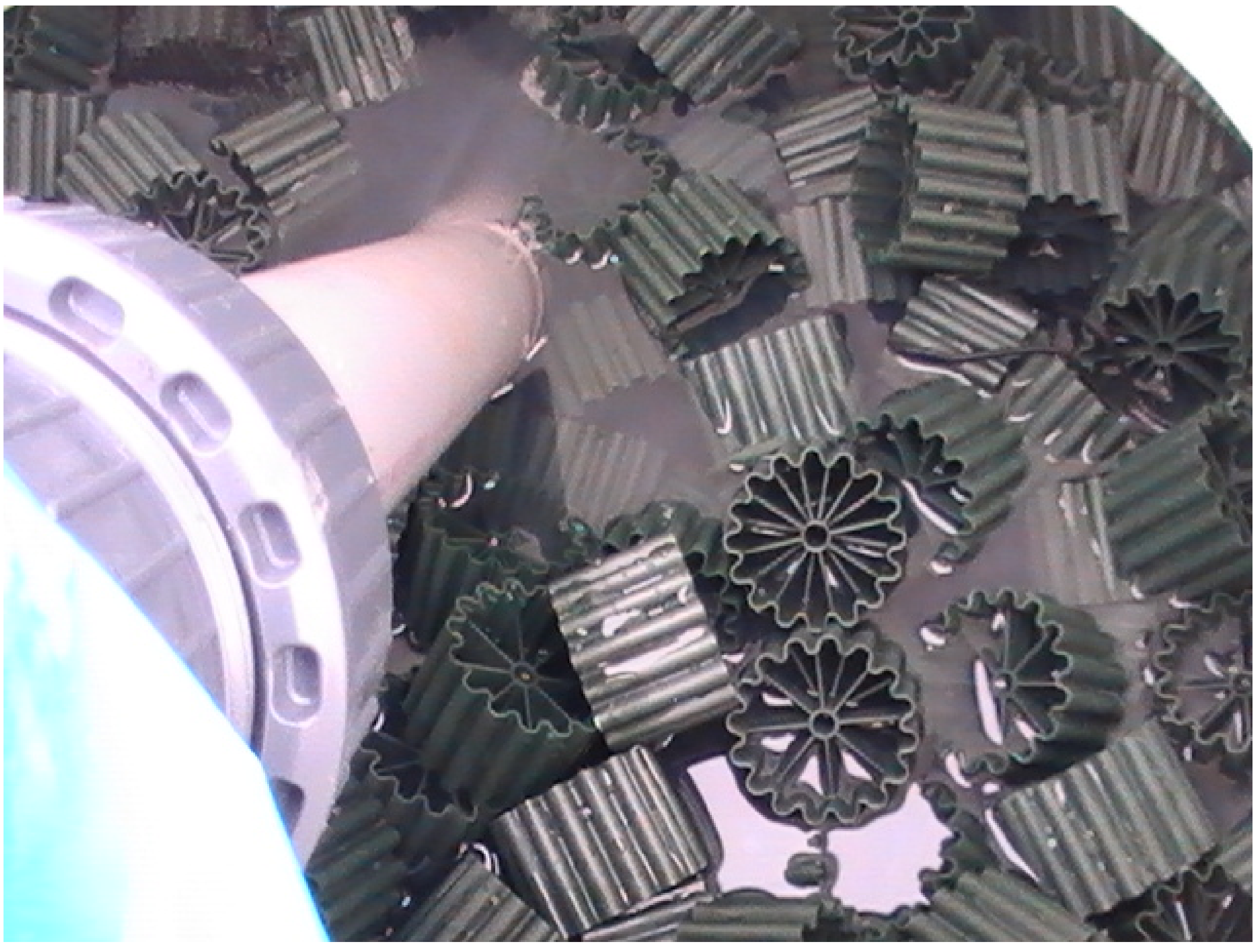

Figure 17. Aquarium and pond filters use microbial consortia to clean water and there is a wide range of plastic "bioballs" and "bioblocks" and other media available to increase the surface area for bacterial growth in a tank while still permitting water flow. Above we show one of the Culhane home treatments in a 700 liter IBC tank. At an average sale price of 10 cents per plastic ball, however, we have had to find ways to replicate the idea using cheaper materials, such as chopped up corrugated electrical conduit.

Figure 18. At an average sale price of 10 cents per plastic "bioball", the "aquarium filter" solution is too expensive for developing country applications so we have had to find ways to replicate the idea using cheaper materials, such as the corrugated plastic electrical conduit shown above. We are still uncertain as to whether the extra labor involved in chopping the conduit into bits achieves significantly better results or if we can resort to simply stacking coils of conduit in the tank.

The goal remains, however, particularly for those involved in urban planning for slums where size matters, to create something that will work in the congested urban fabric. Culhane's work is geared toward creating an IKEA/Home Depot appliance-sized biodigestor for the domestic market.

VI. Results

Dr. Katey Walter and Dr. Thomas Culhane, along Dr. Alton Byers and with Casey Pape, Clay Koplin, Adam Low, Laurel McFadden and the students of Cordova High School, want to see if they can harness arctic and alpine bacterial consortia to improve the capacity of small scale biogas digestors. This would be helpful, for example, in situations where there is thermal stratification in tanks – the psychrophiles could occupy the colder layers and the mesophylls the intermediate temperature layers. Theoretically tanks could be designed to also allow thermophilic activity at the top of the tank thermocline.

So far our results suggest that psychrophiles and mesophiles do perform together in the same tank, although more research is needed to verify that they are both doing well.

We started our work in Egypt by replicating the ARTI India style telescoping digestor made from cylindrical water tanks. However when we tried to build systems at home in Germany and in Alaska we found that such water tanks were either completely unavailable (certainly on the local market) or fantastically expensive.

To solve the problem of building in countries without plastic water tanks we went back to Egypt and started experimenting with another type of local tank that is readily available around the world but which we had never seen used before for a biogas system. The tanks we decided to use are the HDPE IBC Tote Tanks that many food grade substances and chemicals are shipped around the world in. They are generally made of semi-transparent white HDPE in oblong cube form surrounded by a metal cage and on either a wooden or plastic pallete. They tend to come in 700 liter and 1000 liter sizes.

Since the author had observed these takes in almost every country he had been to they seemed to be the logical choice for an inexpensive biogas system that anybody could build. The problem was that they would not permit telescoping action, i.e. one could not replicate the ARTI style digestor simply by putting the smaller tank in the larger tank.

At the authors home in Germany in the summer the average cooking time from a 200 liter container was 30 minutes in a day with a maximum of 52 minutes – enough to cook vegetables and then boil water to make pasta. For some reason, however, this is the maximum we have observed from using a square HDPE 1000 liter tank, even when the internal temperature has been raised to 30 degrees. In general we get about 100 liters per day, yielding 15 to 25 minutes of cooking time.

This could be due to the physical properties of the digestor and how it encourages gas collection. The square tanks output the gas through a 1/2 inch plastic tube and that is piped to the gas collector; there may be some inhibition. In the floating digestor type there is a much wider surface area for gas to evolve and as it collects over the diameter of the digestor it lifts the collector up. In these systems we have observed a much higher rate of gas collection.

In Cairo, using a 1000 liter tank with a 750 liter gas holder, the 750 liter gas holder tends to fill up every day during the hot months and becomes about half full during the colder months. The average cooking time on a single burner is 2 hours. This is generally enough for 3 meals a day.

Table 1 shows the number of digestors we have built around the world so far. Without exception they have produced reliable gas. Only 5 of the digestors used psychrophilic bacteria. Culhane is now working at home on ways to use psychrophiles shipped from Alaska and brought down from Mount Everest Base Camp in his home in Germany. He transfered the bacteria with wood chips from the bottle they were sent in (a 2 liter bottle of Alaskan psychrophiles) and sediments (a .5 liter cola bottle of Everest psychrophiles) into their own 60 liter plastic fermentation vessels (sold at the German Bauhaus Appliance store for beer making). After initial successes, feeding on sugar, the bacteria seemed to have died in both cases and the authors were tempted to believe that, given the difficulty of obtaining the Alaskan and Alpine psychrophiles it would be better to try and keep the mesophilic tanks at temperature. But after appromixately a month the psychrophiles in both containers were producing methane again at about 15 C and in excess of the amounts made by the mesophilic tanks at the same temperature. From Walter-Anthony and Pape's research in Alaska it is clear that the amount of gas being produced at 15 C and 25 C is less than a fifth and a third of that which mesophiles produce at their preferred temperatures so it seems clear that low temperature production will always be lower than higher temperature production. But given that mesophiles stop producing at 15

C and don't produce at their maxima at 25 C, which is the temperature most tanks will settle to without additional heat input, using psychrophiles seems to hold a lot of promise. This will be particularly be true if we can design our reactors so that the appropriate bacterial consortia are producing at their optimal rate at the temperature ranges that they are best adapted to.

The greatest impediment to adoption of this simple technology is a perception that providing clean energy requires special tools or technology and expertise. Misinformation about the kind of feedstock and the conditions necessary for effective fermentation hamper people from actually starting.[1] But as table 1 shows, we've been able to build more than 50 digestors in 15 different areas in 10 different countries and our observations teaching biogas construction and use around the Earth is that once families and communities see for themselves how simple it is to transform common household and community wastes into clean energy and fertilizer, they themselves become pioneers in improving the efficiency of the systems and we build a culture of innovation.

More research will be needed to get quantitative data on volumetric production rates at various temperatures by different bacterial consortia with different designs, but the initial work we've done around the world gives us confidence that small scale biodigestors can be improved, both in design and species composition, so that they can operate effectively at the home scale level everywhere in the world. Hopefully small-town small-scale bioreactors will become the next "Big Idea" rather than the "small-town micro-nukes" currently being publicized as the way out of our energy crisis. In the latter case we have to worry about the question "what will we do with the waste?". In the former, we don't have to worry because the fuel IS the waste.

VI.A. Field Implementation of the Solar CITIES Biogas Initiative

Table 1. Installations of household biogas systems by Solar CITIES from Spring 2009 to Spring 2011

Location	Number of Digestors Built	Installation with Insinkerator
Urban slum areas of Cairo Egypt:	8	2
Rural areas of Egypt	6	0
Suburban Germany	5	2
Urban slums of Nairobi, Kenya	1	1
Rural Masai areas of Kenya	6	1
Urban areas of Tanzania	2	0
Rural areas of Tanzania	2	0
Residential areas of Abeokuta, Nigeria	4	2
Urban Areas of Ghana through OSU group	2	0
Wildlife Conservation areas of Botswana	4	3
Urban Areas of Old Jerusalem and Palestine	2	0
Rural Kibbutz in Israel	2	0
Urban ghettoes of California in the United States	2	2
Suburban area of Seattle, Washington	1	0
High School and local restaurant in Alaska	5	1
Total	52	14

VI.A.1. Egypt

Manshiyet Nasser: 3 1000/750 liter ARTI systems (Hanna Fathy, Roh El Shabab NGO, Moussa Zekry; see figure 20)

Darb Al Ahmar: 1000/750 liter ARTI system (Hussein Farag) SEKEM farm, Bilbaes: Figure 21 shows 1 ARTI System 1000/750, 1 white HDPE tank connected to ARTI system surrounded by heating coils

[1]The most pervasive of myths is that one needs animal dung both as a feedstock and as a starter culture. The ability to use human sewage is rarely talked about.

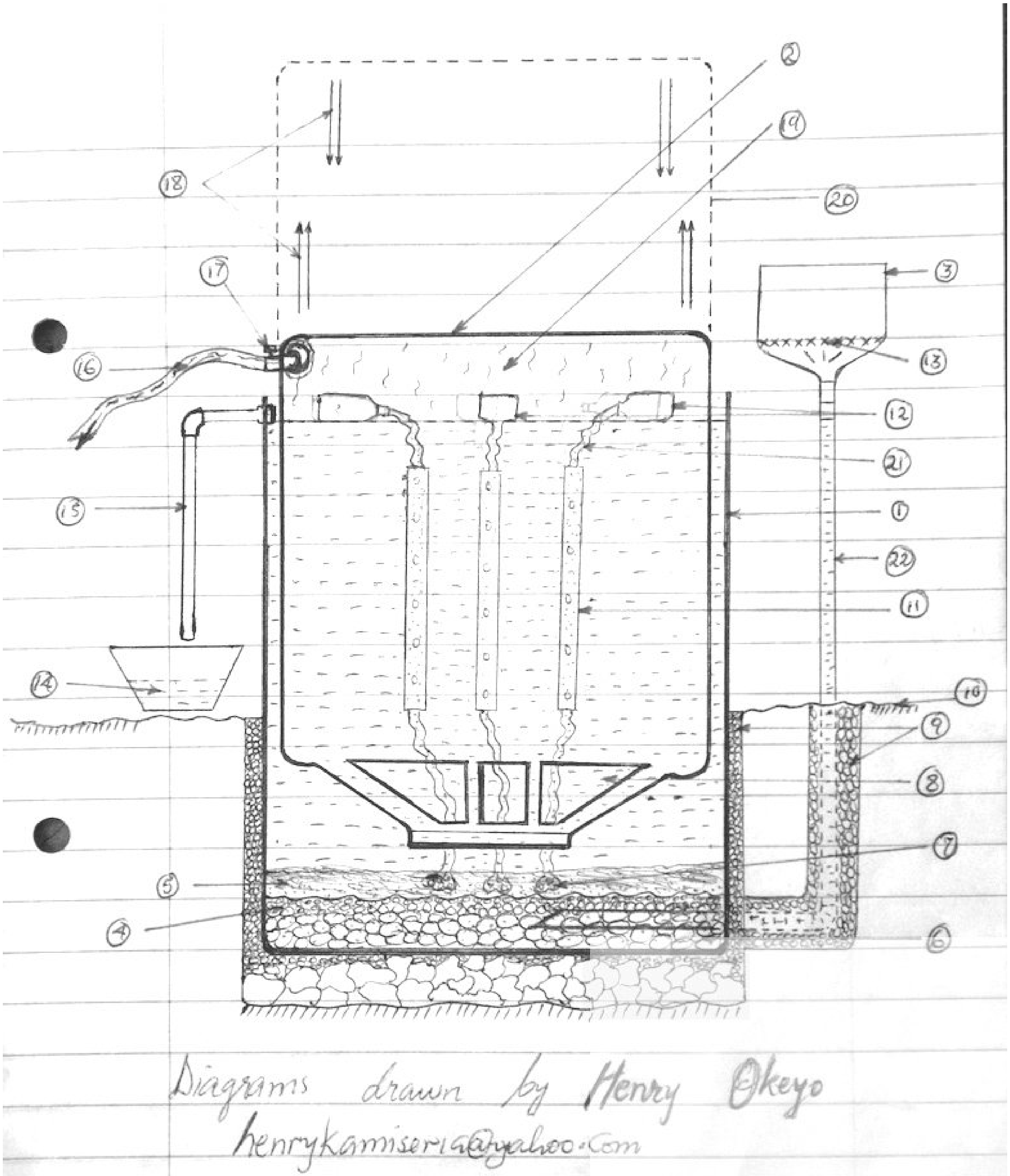

Figure 19. Figure shows a schematic of the digestor we built with Simama e.V. at the Mukuru School in Nairobi, done by teacher and plumbing specialist Henry Okeyo Kamiseria (who is now the local biogas expert

Figure 20. Moussa Zekry on his roof in Garbage City

connected to a hand built solar hot water system made from black polyethylene irrigation pipe, 1 black IBC tank connected to the solar CITIES style water pressure gas collection system.

Figure 21. Several of the experiments we conducted at Sekem Farm

VI.A.2. Essen, Germany

See figure 23

The author constructed an ARTI style system in March of 2009 using a 500 liter round rain-water tank as the digestor with a 300 liter round water-tank as the gas holder. He filled the large dead space gap between the top of the collector and the water surface with styrofoam because it was felt that this would help force all of the gas out; it is still undecided whether this is worth the effort or not. We now call this a "200 liter ARTI system" based on its holding capacity. About 50 kg of horse manure was used to start this system.

The second system built in March of 2010 was a 1000 liter HDPE IBC tote tank system similar to what was built in Alaska, but instead of using two more 1000 liter tanks for the gas collector and water pressure, the author used two 110 liter tanks due to weight and space considerations. The output of the gas collector then went to the floating holder of the 200 liter ARTI system. Eventually the 110 liter tanks were taken down and the gas from the 1000 liter tank was piped directly to the gas holder of the 200 liter ARTI system. This system was started with effluent from the 500 liter tank in the 200 liter system only. This effluent had survived a winter freeze but was still found to be active.

On the first of May, 2011, While the temperature probe in the top of the digestor read 33 C, the effluent coming out still varied between 20 and 25 C, which explains why we are only averaging 100 liters of gas per day. The tanks stratify with a thermocline and most of the bacteria live in the sludge granules at the bottom of the tank which could be as low as 15 C. Putting floating plastic "bioblocks" is supposed to help somewhat, but it is taking a long time for the tank, which is insulated, to thaw from the winter freeze. Hopefully it will

Figure 22. The IBC plus ARTI combination

Figure 23. Experimental tanks

get hot this summer and the greenhouse may keep it from freezing next winter.

The solar hot water feeder tank also serves as a fertilizer source for the garden; there is a valved Y hose at the bottom allowing me to pipe the liquid fertilizer to the garden. I'm passing the fertilizer through the 12 V pump first in case I need to fill other buckets with it.

Our newest system uses heated waste water from the shower and bathtub to heat the bacteria inside a nested tank.

Figure 24. The Culhane's second family size biodigestor is made from a 700 liter IBC tank nested inside a 1000 liter IBC that is insulated with styrofoam. Hot water discharged from baths and showers surrounds the internal tank and keeps the bacteria at their desired temperature.

VI.A.3. Alaska

On the grounds of Cordova High School in Alaska we converted a 40 foot container into a laboratory with two separate treatment rooms, one a 25 C chamber and one a 15 C chamber. Each had identical set ups – 3 tanks, one with mesophiles from cow manure, one with a mix of mesophiles and psychrophiles and one with psychrophiles from lake mud collected from permafrost thermokarst lakes by Laurel McFadden in Fairbanks.

We also constructed a Solar CITIES system at the local pizza restaurant on the bay, inoculating it with psychrophilic bacteria from a single core taken from lake mud in Cordova.

The systems in the school lab, run by science teacher Adam Low and his students, were fed from an Insinkerator that was ported via a manifold to six different buckets so that each digestor would receive the same mix of food.

The psychrophiles in the digestors suffered a population collapse thought to be due to overfeeding (high acidity levels) but were brought back into operation via new innoculant and the addition of sodium bicarbonate buffer.

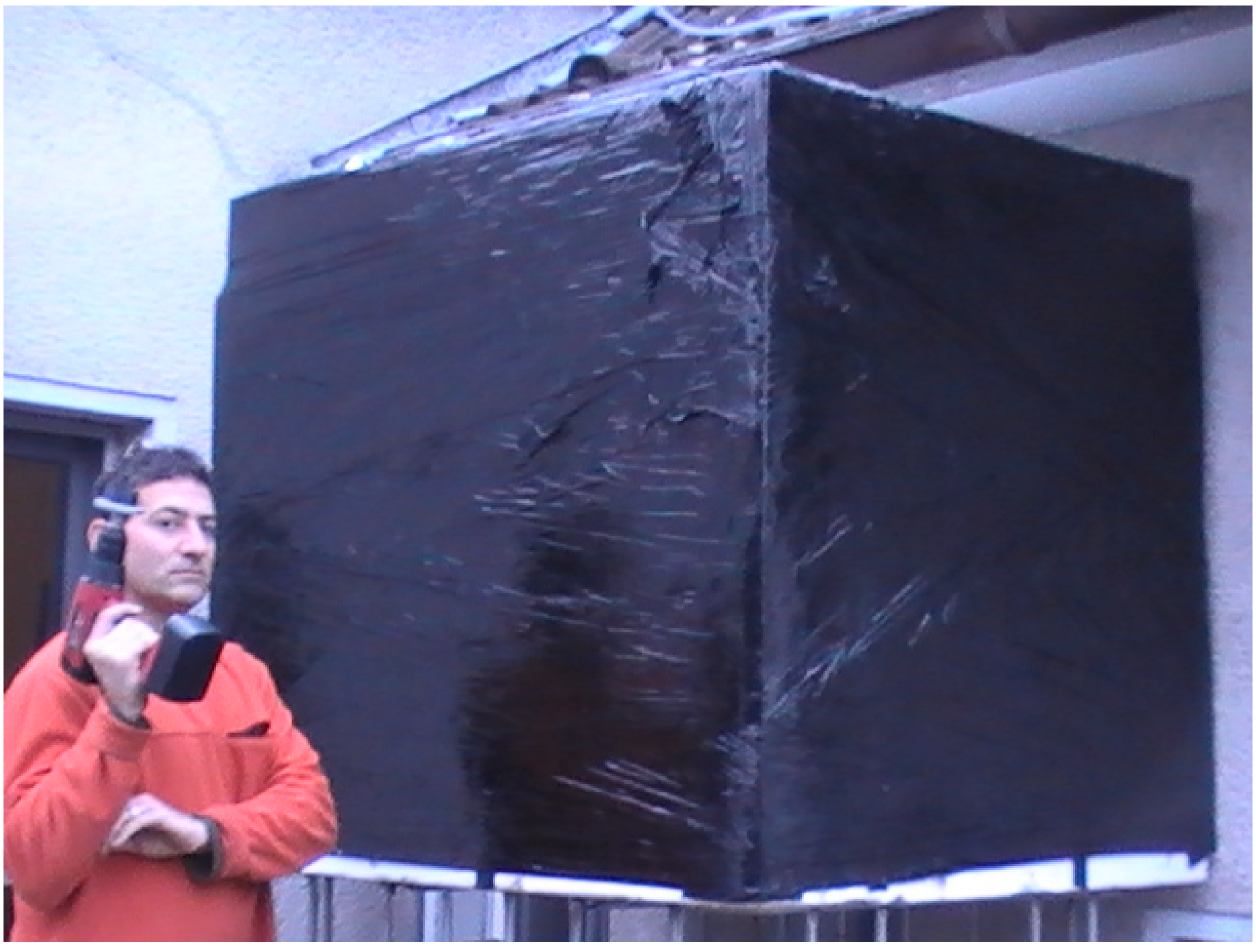

Figure 25. The nested tank digestor was elevated and placed next to the bathroom window.

Figure 26. In the Culhane's upstairs bathroom in Germany a two chamber biodigestor made from 110 liter beer fermentation tanks takes their baby's diaper wastes and turns it into cooking gas and fertlizer. The system was started with baby fecal material only and once it started producing flammable gas left over baby food was used to dramatically increase production. This experiment proved that biogas could be done without odor or problems indoors using only wastes found in the average home.

VI.A.4. Los Angeles

In South Central Los Angeles, Alvaro Silva, a former student of Culhane's, built a system with Culhane and Mike Rimoin and Mike Bonifer in his back yard for the Latino community to see. It was of the Solar CITIES IBC Tote Design, as shown in figures 27 and 28.

Figure 27. Figure showing how gas is piped from digestor to collector

VI.A.5. Santa Rosa CA

See figures 29 and 30

VI.A.6. Seattle WA

In this system we used an HDPE 1000 liter IBC tank and ported the gas to a 30 gallon floating drum in a 55 gallon drum. For heating we placed an autmotive heat exchanger inside the 1000 liter tank with a special set up to allow hoses to go into the tank without creating leaks.

VI.A.7. Nairobi, Kenya

At the Mukuru Arts and Crafts slum school in Lunga Lunga we installed an Evolution 200 Insinkerator connected to a partially buried 2300/1800 liter ARTI system.The tank only had to be submerged to 1/3 its height because the kitchen sink was in an elevated building.

Figure 28. Figure showing how gas is piped from digestor to collector

Figure 29. Figure showing how gas is piped from digestor to collector

Figure 30. The plumbing set up for the Solar CITIES gas collection system

Figure 31. The system in Seattle

Figure 32. The heat exchanger plumbing

Figure 33. The heat exchanger plumbing

Figure 34. The heat exchanger plumbing

VI.A.8. Ol Donyo Waas, Kenya

In the Ol Donyo Waas conservation area run by Great Plains Conservation we experimented with several different forms of biogas digestor to deal with different resource scarcity issues. Getting plastic rain tanks to the site was problematic, but they had cement bags and natural stones. We therefore decided to dig holes for the digestors and line the holes with rocks and cement so that we only had to use the tanks as gas collectors.

Figure 35 shows the size of the holes we created. Fortunately there was a ready supply of labor and the soil was easy to work.

Figure 35. Digging digestors made from cement in the Ol Donyo Waas conservation area with the Maasai when plastic water tanks were in short supply

VI.A.9. MKalinzi, Tanzania

In MKalinzi at the edge of the Gombe Chimpanzee reserve, working with staff from the Jane Goodall Institute and local beneficiaries (the chiefs of the village) we built two underground digestors (lined with local brick and cement) using 1800 liter plastic tanks as the gas holder.

VI.A.10. Kigoma, Tanzania

Because of the difficulty of repairing tank problems that we encountered in MKalinzi when the bottom of one of the digestors cracked and leaked (forcing us to dig a deep trench so workers could repair it) we decided to build at Joram Samoan's home (1000 liter) and Grace Gobbo's home (2000 liters) above ground. The digestors were made of brick and cement and the gas holders from plastic polytanks.

Figure 36. Our Kenyan colleague suggested that we try to make a system out of old oil barrels since plastic water tanks were scarce or expensive. This was similar to an idea the FAO had promoted in Africa in the 1980s. The problem is that it is very difficult to keep micropores from opening up at the weld joints. We had to cover the welds with inner tubes and pitch and still found tiny leaks appearing.

Figure 37. An ARTI style digestor with the primary tank made of cement and brick sunken into the ground and a 1000 liter inverted water tank as the gas holder; this solution is advisable when tanks are more expensive or difficult to obtain than cement and brick. The digestor need not be submerged – this only adds to the difficulty of making it because of the labor required to dig, but it does allow for eventual connection to an Insinkerator for gravity feeding.

Figure 38. Next to the chief's hut in Kalinzi near the Gombe Chimpanzee Reserve, fellow National Geographic Emerging Explorer Grace Gobbo of the Jane Goodall Institute and JGI Intern Joram Samoan built this digestor as an alternative to deforestation to help preserve endangered habitats. Instead of fuelwood and charcoal the village can now use food and agricultural wastes

Figure 39. Joram Samoan's home digestor on their peri-urban farm next to Lake Tanganyika in Kigoma, Tanzania. Joram (far left) was trained by Egyptian Zabaleen (Trash Recycler) turned Renewable Expert Hanna Fathy of Solar CITIES

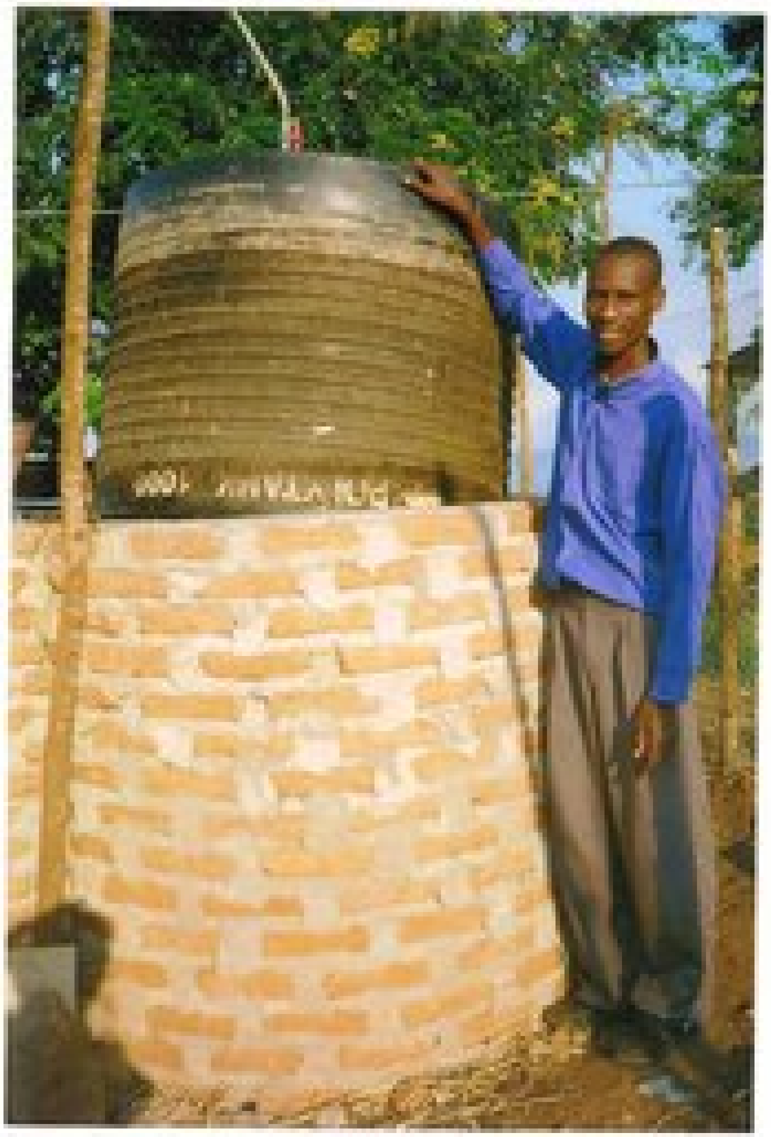

Figure 40. One day's production of gas in Joram's system in Tanzania. One can estimate from the kitchen window approximately how much cooking time one has on a single burner by looking at the rings of the tank. Each ring on this 1000 liter tank yields approximately 5 minutes of cooking. On tanks with wider spaced rings it can be 15 minutes a ring. On a 2000 liter tank it is about 30 minutes. With experience, watching the tank go up and down one can get a reliable metric of the remaining amount of gas and plan accordingly. Most families use a hybrid stove that can also burn biomass fuels if the gas runs out. The amount shown here is nearly 2 hours. This same amount can also run a gas refrigerator for nearly 24 hours and a 2kW 4 stroke engine for about 45 minutes. Gas lamps can be run for more than 24 hours.

VI.A.11. Beit Sahour, Palestine

In 2010 we built Palestine's first home scale biodigestor at the Palestinian Wildlife Society's Eco-home demonstration with Palestinian Engineers without Borders. At the Palestinian Wildlife Authority Eco-Home Demonstration we built a 2000 liter/1800 liter ARTI system above ground and modified a standard gas oven by drilling out the injector.

Figure 41. Culhane (white shirt) with Amer Rabayah of Engineers without Borders and Imad Atrash of the Palestinian Wildlife Society to his right (and colleagues) in front of the ARTI style digestor at the PWS Eco-home demonstration center near Bethlehem

VI.A.12. Abeokuta, Nigeria

In Abeokuta we built all ARTI systems using 2000 and 1800 liter tanks. The first system was below ground outside of former president Obasanjo's kitchen, connected to an Insinkerator 65 model that we installed. The second was an above ground system outside of the Bells School (a high school) kitchen. The third was at the Sacred Heart Hospital and the fourth at the home of University Professor Moses Oyatogun.

VI.A.13. Selinda Reserve, Botswana

Here we built 4 different digestors. At Selinda lodge we used an Insinkerator 550 ported to a 5000 liter tank buried underground and surrounded by straw and elephant dung as insulation. The 5000 liter tank overspilled to a 2500 liter tank with a 2000 liter gas collector; in this case, because the tank diameters were identical, we had to cut the 2000 liter tank into 4 pieces, remove 10 cm from each piece and heat weld the entire thing together again and then fiberglass the seams because of leakage. Ultimately, after 4 days of cutting and plastic welding we got it airtight.

Figure 42. Former Nigerian President Olusegun Obasanjo (center) drops scraps from his kitchen into his new insinkerator, a gift from Solar CITIES and Emerson Electronics/Insinkerator Corporation, at a press ceremony where he explained how food wastes in Nigeria will now go from being a problem to being a solution for a healthier, cleaner and more secure Africa.

Figure 43. Former Nigerian President Obasanjo's digestor is located under ground outside his kitchen so that the Insinkerator's output gravity feeds into the digestor tank. The tank was surrounded by an insulation gap filled with recycled plastic water bottles and straw to keep heat from escaping to the earth during the night.

The Zarafa lodge used the same setup (with the same painstaking cut and weld operation) but we used a 2500 liter sealed tank for the primary digestor and the same 2500/2000 liter ARTI set up for the collector.

The base camp set up used a fiberglass oblong water tank as the primary digestor, spilling into two different small floating digestors. One was a two-oil-drum setup (55 gallon drums) as shown in the FAO manual from the 1980s – what they don't tell you is that you have to cut up one of the drums and steel weld it back together and this is a difficult operation. We ran out of welding sticks and tried epoxy but have microleaks to deal with. The second collector was a 50 gallons plastic drum with a 30 gallon plastic container inverted in it. It gave about 15 minutes of cooking gas when full.

It has not been the author's observation that the digestors produce enough gas continuously to be able to cook from the digestor directly as gas is evolving. Storage is critical. The digestors seem to produce gas in pulses as if they were building up and burping methane, much as a cow does.

Figure 44. The Culhane's 2 year old son working with a two-stage 7,500 liter digestor at the Selinda Wildlife Reserve in Botswana. When children grow up seeing dreams made reality and innovations being applied directly to the improvement of others lives, how can they help but feel part of the Great Conversation that inexorably lifts humanity toward the good place and away from dystopian despair?

VI.A.14. Arava Institute of the Environment, Israel

Working with Yair Teller and Beverly Goodman and many Arava Institute Alumni we built two PVC "salchicha" digestors in trenches. Yair also took us to see two other systems made in Bedouin villages in Hebron where he has combined the Salchicha as primary digestor with ARTI tanks for storing and pressurizing the gas.

VI.A.15. East Jerusalem, Israel/Palestine

In Jerusalem and the West Bank we built two typical ARTI floating digestors using a 2000 liter and a 1800 liter tank. This year we built one with a high school in East Jerusalem as part of an evolving program funded by the US Embassy that included making presentations and holding workshops with farmers in the West Bank and video conferences with stakeholders isolated in Gaza.

Figure 45. Where the Selinda system called for a 5000 liter primary tank because of the volume of kitchen waste, we only needed a 2500 liter tank for the Zarafa lodge. The difficulty in both cases is sealing the lid so that it doesn't crack and leak. Heat welding seems to work with some tanks; in Kenya the lid is made of a different plastic and won't weld properly.

Figure 46. The most difficult challenge in building the gas collector in Botswana is that the 2500 and 2000 liter tanks both have the same diameter so one will not fit inside the other. To make the telescoping system work we had to cut the 2000 liter tanks into four pieces, cut out strips to make them smaller in diameter and then heat weld them back together with the plastic strips. Tiny micropores that still leaked forced us to then fiberglass over all the sutures making for a difficult construction project.

Figure 47. "Salchicha" flexible bag digestors being built at the Arava Institute of the Environment

VI.A.16. Enosaeen, Kenya

In Enosaeen we followed the two phase model we created in Botswana (two phase models favor production by giving acidogens and methanogens a chance to work without competitive exclusion (see[17])) , the chief difference being that we decided to put all piping from the sealed 5000 liter digestor through the cover so as not to damage the tank, given its expense. The feeding pipe went to the bottom of the tank, the digestate overflow came from about half way down and spilled over into the inlet pipe for the floating digestor to give the possibility of winning an estimated extra 20 percent of the gas from the undigested food and to give a longer hydraulic retention time; this may come in handy if people put human or animal manures in. We purchased a 5000 liter tank for the main digestor connected to the Insinkerator and a 2300 liter tank with an 1800 liter tank inverted in it as gas collector. The total came to 79,985 Shillings but Mr. Shah gave us a nice discount to 75,000 with transportation to Enosaeen on a big truck because this is where he has his sugar cane factory and this was the start of our cooperation to try and make an industrial ecology success out of the situation there.

5000 liter tank: 41,995 Shillings
4200 liter tank: 37,995 Shillings
3200 liter tank: 29,995 Shillings
2300 liter tank: 19,995 Shillings
1800 liter tank: 17,995 Shillings

$_{1}{}^{00 shillings=1.20 US}$
1 dollar = 83 Shillings
75000 shillings = 899 dollars (actually more than 900 due to poor exchange rates on the ground).

Figure 48. The Chief of the Maasai village of Enosaeen, who has been studying the potential for biogas production in his village, receives an Insinkerator from Culhane to help turn food waste into feedstock at the Kakenya Center for Excellence

Figure 49. Because of the high cost of the 5000 liter tank (nearly 450 Euro) at Kakenya's Center for Excellence we tried out a technique that would enable us to use the tank without damaging it. The idea was to use the lid of the tank, which is easily replaceable, for all penetrations – feedstock inlet in the center had a T to permit automatic loading by the insinkerator and manual loading from the top with the 50 mm feedpipe going to 50 cm above the bottom of the tank. Another 50 mm pipe coming from about half way up the tank goes out of the tank via an elbow into the gas collector/secondary digestor. Because the elbow is lower than the feed inlet pipe's mouth it overflows with each feeding, making the gas collector also a gas producer. We estimate the gas collector accounts for about 20 percent of the yield based on Germany's commercial experience with dual digestors. The gas pipe is located at the top of the tank with a valve and goes to the gas collector too.

VI.A.17. Dingboche, Nepal

In the highlands of Nepal's Himalayan range, in the village of Dingboche at 4400 meters above sea level, we have begun a National Geographic project with Dr. Alton Byers of the Mountain Institute exploring how to make biogas a viable energy solution to replace the use of fossil fuels and the endangered soil-binding and slow growing juniper shrub ecosystem, both of which are used for cooking fuel. Research into the use of low-cost and reduced volume biogas systems at psychrophilic temperatures in Nepal is occurring but research into the use of psychrophilic bacteria themselves is scarce.[5] In May of 2011 Culhane collected viable methanogenic bacteria from sediments under the ice in a lake near Everest Base Camp and cultured them at his home in Germany where they are now producing methane under a regime of sugar feeding at approximately the same rate as those brought back from Alaska. Culhane also built a small mesophilic reactor in the village using Yak and horse manures as the bacteria source and placed it in a sunlit window at the Khumbu Alpine Conservation Center in Dingboche where a photovoltaic and wind powered Insinkerator that their group installed will eventually provide the feedstock. The intent is to keep the digestor at mesophilic temperatures using a combination of the vacuum tube solar hot water system that Culhane, Byers, Howe and Marcinkowski installed, and a modified traditional raised composting toilet system for extra heat and insulation. The tank will be designed to that the Everest psychrophiles (harvested at 5300 meters) can occupy the lower temperature bottom zones in the tank while mesophiles occupy the hotter zones with vertical surfaces (like the bacterial fuel rods mentioned earlier) acting as a surface for biofilm formation. It is hypothesized that in zones where the temperature enables overlap some hybridity may occur.

Figure 50. Culhane collects psychrophilic bacteria from a frozen pond at the base of Everest Base Camp in Nepal. These methanogens are now producing flammable CH4 from food waste in an experimental tank on Culhane's porch in Germany

VII. Conclusion

In all cases the materials and skills to build functional digestors were locally available. Stakeholder participation was high. Biogas is the simplest of all technologies to implement at a local scale and at relatively low cost. The greatest technical difficulties come only from a dearth of inexpensive tank fittings in many localities, but otherwise all of the parts can be found or made locally. With proper investment, with insulation and heat exchangers and if integrated with solar hot water systems and appropriate waste water pumps (macerating toilet pumps, water pumps, treadle pumps) there are no reasons why small scale biogas will not work literally everywhere in the world. It is really a question of the will to make the initial investment. From then on one can meet basic cooking needs, and even lighting, refrigeration and limited heating and electric generation needs, using nothing but the organic wastes that are normally considered a nuisance or even a life threatening problem in most densely populated areas.

Appendix

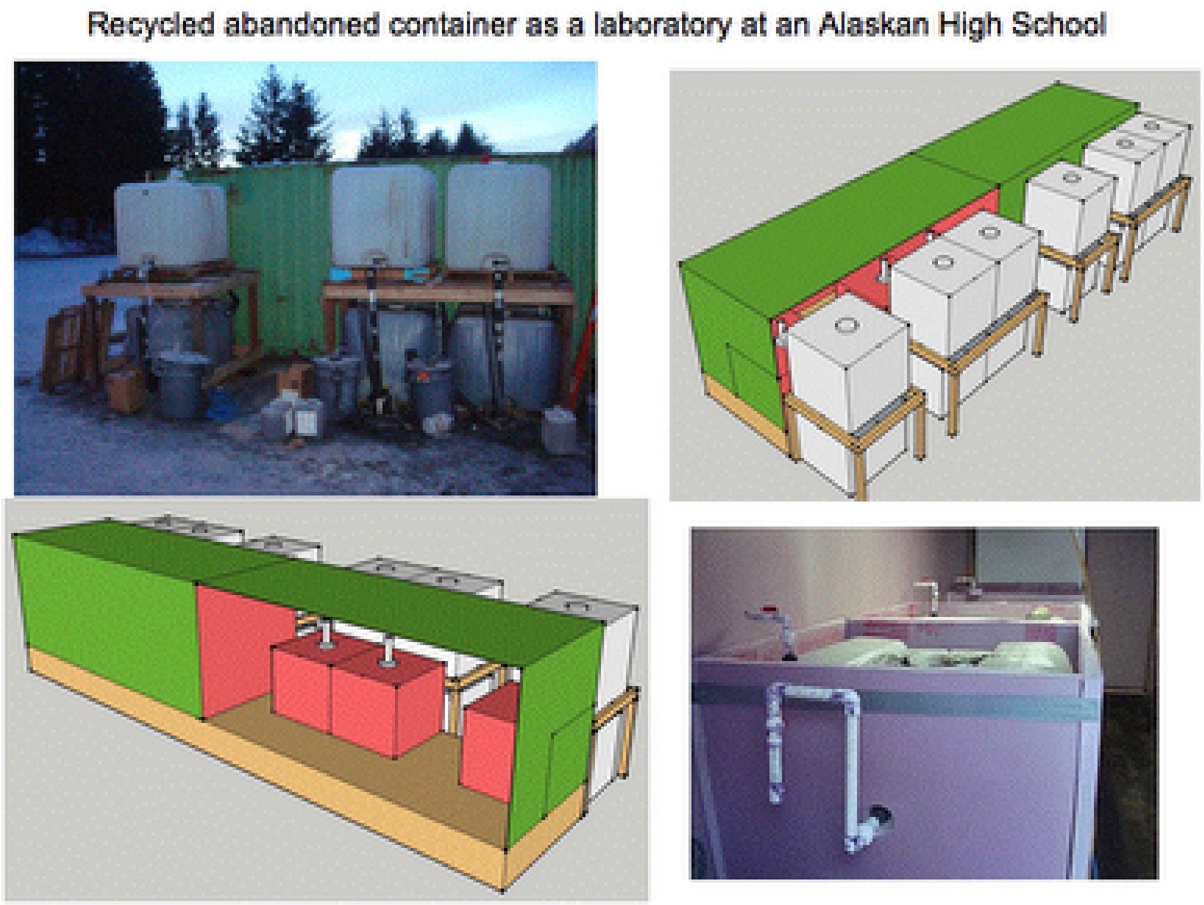

Figure 51. The six treatments at Cordova High School with mesophilic and psychrophilic bacteria.

A video flythrough of our Solar CITIES IBC tank system can be found at
http://www.youtube.com/watch?v=T5S9Cuhp04A

Acknowledgments

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Figure 52. The psychrophiles are producing abundant flammable methane under the ice of Alaskan and Siberian lakes.

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