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METHANE GAS: A RENEWABLE ENERGY SOURCE

A Thesis in

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by

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Abstract:

A qualitative analysis was made to ascertain what possibilities and prospects exist for generating energy from landfill methane. It was found that, while the general sensibility in channeling a greenhouse gas such as methane to productive use was extremely logical, certain cautionary measures would have to be adopted to safeguard against possible negative side-effects. The analysis was made solely on landfills that were devoted to municipal solid wastes; or at most, agricultural wastes. Landfills with hazardous and toxic waste profiles were not considered. An extensive literature review was conducted and the following was revealed that,

i. It was much better to recycle materials that either did not biodegrade easily or that, upon biodegradation, yielded toxic and other hazardous chemicals that threatened landfill sites with pollution.

ii. It was also revealed that old landfill sites, even if they produced economically viable quantities of methane, must be adequately safeguarded against possible pollution from by-products of anaerobic fermentation; the principal process that generates methane.

iii. It was also determined that new sites must strictly adhere to certain rules and regulations promulgated by local authorities. It was believed that such adherence would ensure that the site accepted only safe waste that broke down into methane gas without complication from toxic and hazardous by-products. Such adherence would also ensure that these future landfills would be adequately insulated against any manner of possible pollution of the environment via air, water and soil media.

iv. It was also ascertained that methane produced at landfills should be monitored for toxic and harmful content and accordingly purified to ensure against pollution and damage

in the course of utilization. The gas must also be purified of inert components that tend to reduce thermal energy content.

v. Small landfills that were considered incapable of producing economically viable quantities of methane must be equipped with methanotrophic bacteria in well-aerated topsoil so that the methane produced in the underlayers would be broken down into harmless components.

vi. Lastly, among certain models that could predict methane generation potentials of landfills with specific characteristics, the IPCC (International Panel for Climate Change) 2006, model was proposed as an international tool that could be used in countries where local models were unavailable as it had within its range of defaults that fitted many regions of the world.

In all, it is believed that an adequate generalized concept of landfill site safeguarding, collecting of gas, its purification, conveyance to utilities and utilization have been made available. Very few quantitative parameters have been used as these were found too specific for the purpose of the thesis; but again, it is believed that the novelty of the proposed generalized concept adequately made up for the loss of any specificities as these later could be handled at the deployment stage. It is noted though that all specificities that could be made to support the generalized concept, including the process via which anaerobic methanogenic microbials produced methane and the optimal conditions under which they did so, were adequately explored. Methane as a major environmental pollutant can be channeled into productive usage after employment of a few cautionary measures that have been discussed.

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Acknowledgments:

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Chapter 1. Introduction:

It may be that the technology that enables collection and usage of methane from sources such as landfills is old, but prospects of large-scale deployments in the future also raises prospects of newer techniques being developed to aid this technology and make it more efficient. While this paper will initially review prospects of collecting and utilizing methane from conventional sources, such as municipal septic tanks and landfills in addition to industrial and agricultural landfills, more unconventional sources utilizing anaerobic decomposition of organic carbon matter will also be discussed. The project intends to be responsible and therefore, all aspects of gas production from landfills have been discussed. Even those aspects such as alternate recycling mechanisms that can reduce waste dumping to landfills have been explored.

New legislation to ensure that landfills and other methane-generating sources are operated in compliance is being constantly proposed. This is because methane is potentially a dangerous emission, especially in and around inhabited areas. The gas is highly combustible with an extremely low boiling point of -161^{0}C at atmospheric pressure coupled with a comparatively low auto-ignition temperature of 580^{0}C, and its presence in ambient air in and around localities in any excessive quantity is a potential fire-hazard. Explosive capability of the gas is 5-15% by volume. Also, direct inhalation of the gas may cause asphyxia and death. As per a report from Ohio, and Michigan in 1989, seven farm workers in two separate incidents died from asphyxia after descending into a manure pit. Coal miners are especially susceptible to fire hazard and asphyxia from methane; therefore, special care is taken in mines to prevent disaster.

Methane from landfills can enter nearby buildings and structures and expose people to significant risks. Also, several researchers, including Chanton, 1999, and Scheutz, 2009, indicate emphatically that gas emissions from landfills are the primary anthropogenic sources of atmospheric methane, and since it is a greenhouse gas, it is environmentally source to contain emissions. Methane has a highly potent greenhouse effect; almost twenty-three times more than CO_2. Environmentalists would like to reduce emissions and have come up with the solution of using the gas as a renewable energy source. Since other toxic gases such as NO_x (nitrogen oxides) and H_2S (hydrogen sulfide) are associated with methane released at landfills, flaring the gases after collection but before purification is not a very good solution. After burning the other gases tend to produce toxic substances such as SO_2 (sulfur dioxide); a highly corrosive gas,.

Statutes included in the 1991 report "Air Emissions from Municipal Solid Waste Landfills" (Ewall, 2007), such as the one that requires that there can be no seepage of methane within 1000 feet of public buildings, are essential for public safety. In the US, typically, the 'California Environmental Protection Agency,' January, 2010, requires that owners and operators of uncontrolled landfills, within one year of finding breaches in the landfill, must ensure that methane leakage does not exceed 200 ppmv (parts per million by volume) pursuant to Section 95463(b)(2)(B)1 as an update to the 'California Global Warming Solutions Act' of 2006. The same update stipulates that owners and operators, instead of waiting for leakages, must monitor gas production within the landfill, and whenever the gas heat input capacity exceeds 3.0 MMBtu/hr, these owners and operators must immediately propose design plans for installing gas collection and control systems.

Ideally, all waste containing high organic carbon is a potential source for methane, and since the gas has a high heat capacity at 0.035 KJ/mol.K (1 bar and 25^0C), it is ideal for producing energy, whether for heating purposes or for electricity generation. Usually, waste from municipal sewage, industrial, or agricultural sources, is treated primarily to remove the solid content which is then either deposited into landfills or secondarily processed in digesters. In both processes, if the waste contains high levels of organic carbon, it becomes a potential producer of methane. Since there are very few potentially economical uses for this solid waste, it is recommended that it be used to produce methane and, thereafter, energy.

Methane produces energy when ignited through oxidative pyrolysis. It is conjectured that methane first oxidizes to form formaldehyde (HCHO). The formaldehyde oxidizes further to a formyl radical (HCO) and further oxidation of this produces carbon monoxide. Hydrogen gas is also released during the process. The formaldehyde forming process is so fast that very little physical evidence of it is available.

$CH_4 + O_2 \rightarrow CO + H_2 + H_2O$ (Oxidative Pyrolysis)

$2\ H_2 + O_2 \rightarrow 2\ H_2O$ + Energy (heat)

$2\ CO + O_2 \rightarrow 2\ CO_2$ + Energy (heat)

The result of the above is the following total equation**:**

$CH_4\ (g) + 2\ O_2\ (g) \rightarrow CO_2\ (g) + 2\ H_2O\ (l)$ + 891 kJ/mol (at standard conditions) (Methane, http://scifun.chem.wisc.edu/chemweek/methane/methane.html).

Of course, certain problems exist for landfills that are small or medium sized and cannot be expected to produce sufficient quantities of gas to meet minimum energy production requirements. In such cases, several researchers, including Scheutz, 2009, suggest that uneconomical landfills be supplied with soil that is conducive to microbial breakdown of methane to carbon dioxide and water. Methanogens are bacterial agents that produce the methane from waste carbonic matter. They do so because it is part of their mode of nutrition. The process by which they produce methane is anaerobic, but subsequently, there are other types of bacteria, the methanotrophs, which can oxidize methane to produce carbon dioxide and water.

Scheutz , 2009, proposed that, in the case of small and medium landfills that are considered uneconomical in respect to gas generation for energy purposes, operators and owners should ensure that their landfill soils be sufficiently oxygen-rich to promote growth of methanotrophs. These bacteria, unlike the anaerobic methanogens, operate best in oxygen-rich conditions. The researchers suggest that the methane from these small and uneconomical sources will be broken down by the methanotrophs into less harmful carbon dioxide. Since the purpose of this paper is to promote methane generation in all types of landfill, this issue of small and uneconomical landfills will be considered.

In the United Kingdom, landfill facilities are being lined with plastic films so that seepage of potentially polluting materials into the environment does not occur. If landfills all over the world are so insulated from the beginning, the task of collecting and controlling methane emissions from such sources could be rendered automatic and be stream-lined.

EPA is eager to consider the possibility of using methane in fuel cells. Potentially, the gas can be used to produce energy to run waste disposal systems. With increasing global human population and urbanization on the rise in almost all the continents, the disposal of waste generated by communities, whether large or small, is an acknowledged worldwide problem. One major solution can be conversion of all high organic carbon content waste into methane. It is notable that while large municipalities are capable of finding the means, both economic and technological, to process their waste into safe end-products, small isolated communities are more constrained (Smith in Hammer, p.3, 1989) by both economic and technological limits. Thus, one solution for these small and isolated communities can be conversion of high organic carbon waste to methane and conversion of methane to energy to run waste processing systems. “EPA describes the fuel cell as one of the cleanest energy conversions available to man today”(Ewall, 2007). The Food & Agricultural Organization, (FAO, 1992) recommended "Biogas processes for sustainable development." Marchaim, Uri, There are considerable numbers of biogas plants in developing countries such as India and China, especially in rural areas where high organic carbon content waste generated from farming activities is easily and cheaply available. Reliable literature indicates that methane constitutes almost 1000 ppm of biogas, together with other inflammable gases such as carbon monoxide (CO). One of the earliest examples of anaerobic digesters being used to provide for modern amenities was the one used in Exeter, England, 1896, that used gas from sewage to light streets (Marchaim, 1992). It is now relevant that developed countries in the west cannot afford to ignore these possibilities for more efficient waste processing even as communities are finding it difficult to fund their waste processing (Smith in Hammer, p.3, 1989). While innumerable technologies are available, they are relatively costly both economically and energy-wise. Today, communities in developed countries are looking more and more towards energy production and cost efficient means of waste disposal. The FAO initiated-means, such as biogas plants, that once were considered suitable for low-fund developing countries can today very well serve western communities that are as eager to conserve money and energy for sustainable development.

Chapter 2. Statement of Problem:

Complexity of life in the 21^{st} century has increased with increases in human technological capabilities. Humans use complexly-produced materials to cope with global problems. Where once very simple materials, close to natural substances, sufficed for human well-being, most everyday materials today in have such complex production and compositional characteristics that their counterparts can hardly be encountered in the natural world. The point is that humans today create substances that are far removed from substances that can be found in the ambient environment. On top of this is the huge human population increase. Almost every part of the Earth is inhabited, and wherever humans live, and work they generate waste. A UN document dated 2003, states that by 2030 AD almost 75% of all countries and areas will have almost half their populations living in urban conglomerates. The document also indicates that while developed countries such as the USA and others in the west have shown a low urban population growth rate (2%) in the period 1950-2000, lesser developed countries such as China, India, and Bangladesh have accumulated large masses of people in urban areas. For example, on the lower end of the scale, Argentina had a 2.2% urban population growth rate within this period while, on the higher end of the scale, Bangladesh had a 5.8% growth rate. The point is that the advantage humans had earlier in lieu of negligible waste generation from highly dispersed small communities has been lost forever. Earlier, small communities lived far away from each other dispersed throughout their countries, and the simple products they used to make life more comfortable hardly had any components that varied much from natural substances.

Today, this rusticated scene has changed. Much larger communities, even when dispersed in rural settings, use sophisticated substances that are composed of such artificial parts that these cannot be assimilated by the natural environment around such communities when these are discarded after use by human. In effect, it is not only the non-biodegradable material that causes harm. The biodegradable material, too, tends to pollute environments with its anthropogenic complexity. A careful study of literature will reveal how humans have been coping with the problem of safely disposing of the waste they, in the course of living in the 21st century, generate. There is little alternative, even for small rural communities, to throwing away everything that is unwanted on an everyday basis thereby risking the irrevocable pollution of the immediate environment.

Humans have taken to hiding their waste matter underground, that is, in landfills. These are extensive tracts of land earmarked for waste disposal near human habitation. For a few years, waste from the nearby human communities has been dumped in these large cavities in the ground. When it has been considered that the landfill was fully exploited, the cavities have been topped off with soil and other cover material, and the next land site was earmarked for future usage as a waste disposal dump. Unfortunately, soon it became evident that while the waste from the past remained unseen, it was not altogether undetectable. Foul odors emanated from underneath as various noxious gases, especially methane, found vents in the landfill covers and escaped over ground. Also, other highly toxic and pollutant materials such as arsenic and lead leached out of the landfill as rainwater and rising water tables dissolved some of the waste material and produced run-offs. There is increasing alarm at the possibilities of these landfills polluting, irrevocably again, the underground water resources. Also, methane and other gases such hydrogen sulfide were exuded from these underground waste dumps and caused health hazards.

Medically, a wide range of pollutant products are capable of being released from landfill sites, even long after stoppage of dumping waste there. Gaseous products include methane and carbon dioxide and a little of hydrogen sulfide and VOCs (volatile organic compounds) and metal vapors (Jarup et al, 2002). The 'International Agency for Research on Cancer (IARC) has further classified as dangerous the following substances: Benzene and Cadmium are acknowledged as carcinogenic (Group 1) to humans; formaldehyde (Group 2A) is probably also, as are styrene and lead (Group 2B), (Jarup, 2002). Also, Jarup, 2002, after review of previous researchers, warned that leaching and run-offs of waste decomposition products may occur while the site is being operated or after closure as waste products continue to decay. Human exposure to these pollutants occurs via inhalation of polluted air, ingestion of contaminated water, or skin contact with contaminated water and soil. Monitoring of these sites for detection of polluting substances indicated that exposure probabilities are confined to the immediate proximities of these sites, whether under current operation or under closure. A recent WHO, World Health Organization, report suggested that air pathways for exposure were restricted to 1 km from the sites while water pathways extended up to 2 km (Jarup, 2002).

The Jarup, 2002, study is on excess risks associated with leukemia and cancers of the bladder, brain and hepatobiliary systems in humans living near landfill sites in Great Britain. The study finds no extraordinary risks of these cancers and leukemia, but it does note that several other studies have found such associated risks. A recent US EPA release on procedures at the Dewey-Loeffel Landfill site in New York State can easily demonstrate the problem at hand.

2.1 The US EPA, Monitored Dewey-Loeffel Landfill, New York State:

As per a release dated 03/02/10, the US EPA, announced that it was adding the Dewy-Loeffel Landfill site in Southern Rensselaer County, New York State, to its Federal Superfund List as a measure against the extreme hazardousness of the site. The EPA measure assures the

American public that the agency will do everything in its powers to clean up the site and make the companies responsible to pay for the clean-up. The site had been operable from 1952 to 1968. More than 46,000 tons of industrial waste had been dumped into it.

The main contaminants, the agency release notes, are solvents, waste oils, potentially cancer-causing polychlorinated biphenyls (PCBs), scrap materials, sludge and solids. Some of these extremely hazardous materials, particularly the PCBs, had been found in nearby aquifers, streams and waterbodies, and several species of fish have been found contaminated with the PCBs. The Valatie Kill and Nassau Lake, including 1.7 miles of wetlands in the area, have been closed to fish-farming and have been subjected to monitoring since 1980 when they were found prone to PCB accumulation. As of October, 2009, fish from the area have been found contaminated from PCB, and authorities warn against consumption of these fish.

While the objective of this project is containing methane emissions from landfills, it still does good to understand that the entire business of dumping wastes into landfills is a dangerous one, both in the long and short term. This previous incident is a telling example of the predicament many governments around the world, together with the populations they govern, are facing because of unplanned disposal of waste. It is significant that though the Dewey-Loeffel landfill site has been closed as early as 1968, it continues to pose a health hazard for communities that live nearby. In addition, it is significant that the fish-farming water-bodies nearby are also closed to such activity probably affecting the livelihoods of several an entire community.

2.2 Some Global Statistics:

Before proceeding into the LFG production profiles of selected countries, it will be good to understand how such production on a global basis stands. The IPCC (Intergovernmental Panel on Climate Change), observes that total global anthropogenic methane emissions amounted to 300-400 million tons annually. Of this, 10% came from domestic and industrial wastewater, with industrial wastewater, principally from the paper and pulp and food processing industries accounting for 90% of this subtotal. Domestic and commercial wastewater produced 2 million tons annually. In contrast to methane emissions from solid waste, methane from wastewater was generated in non-Annex 1 countries, third world countries, which seldom treat wastewater and often store it under anaerobic conditions. Also, 10 Annex 1 countries, such as The EU, the US, and Japan, generate ~2/3 of all global anthropogenic CH_4 from solid waste. The USA alone generates 33% of CH_4, representing ~10 million tons.

Another study, conducted by Stern & Kanfinann, 1998, finds that, while estimated total anthropogenic methane emissions have increased from 79.3 million metric tons in 1860 to 371.0 million metric tons in 1994; the increase in landfill methane emissions for the same period had been from 1.6 million metric tons to 40.3 million metric tons.

The next observation available from these findings is that today landfill methane emissions roughly constitute 10% of all global annual anthropogenic methane emissions. This is substantial, as the tonnage signifies, and any efforts to diminish this dangerous trend substantially are worth making.

Also interestingly, the same study by Stern & Kanfinann, 1998, revealed that, for the period 1860-1994, while anthropogenic methane emissions from agricultural activities declined within the agricultural sector, the dominance in this aspect was by livestock farming activities whereas, earlier, rice farming activities had produced the most of agricultural methane emissions. This is very important to note as significant projections will be available later for the particular areas of agriculture that should be targeted when considering energy generation from methane.

Already, some case studies included later involve methane collection and utilization from landfill sites dedicated to manure disposal from livestock farming.

Landfill gas can be purified and injected into natural gas pipelines, as it is in several places in the USA. Also, as in Brazil, purified landfill gas is used to power a fleet of garbage trucks and taxicabs (IPCC, Section 8.2.2, Undated).

Section 8.3 of the IPCC document mentions some of the reasons why there has been some tardiness in the global response to processing of methane emitted from landfills or from solid waste. These reasons are:

- A lack of awareness of relative costs and alternate technical options;
- The more expensive aerobic wastewater treatment process is still promoted because there is lack of experience with the more recent but less expensive anaerobic processes for generating methane from such wastes;
- Methane generated by small landfills and dumps is ignored as it is not economical to recover it;
- Many countries and regions of the world are still not experienced enough in methane gas collection and utilization. Such countries and regions include Mexico City, New Delhi, Port-au-Prince, and much of sub-Saharan Africa;
- Existing systems may be unhygienic dumps or effluent streams where no treatment at all is available. Sudden investment may not be forthcoming for something as unpleasant as these;
- In both Annex 1 and non-Annex 1 countries, failure to reach agreement among the various stake-holders in the combined energy generation and waste management sectors has often aborted viable gas utilization projects.

2.3 Country Waste Profiles:

2.3.1 Australia:

The waste profile of a prominently developed country such as Australia features as follows. Waste was generated in three primary modern societal domains – municipal, commercial and industrial, and construction and demolition. In 2002-03, in the island continent, more than 54% of all solid waste generated was consigned to landfills. That is almost 17 million tons of waste per annum. This huge quantity was made up of 40% of municipal waste, 36% of industrial and commercial waste and 24% of demolition and construction waste (ABS, 2007). Waste composition was as formulated in table 1.

Table 1: Solid Waste Composition (2002-03): Australia

Waste Component	Municipal (%)	Commercial & Industrial (%)	Construction & Demolition (%)
Organics (Food & Garden)	47	13	1
Paper	23	20	-
Plastic	4	6	-
Glass	5	3	-
Metals	5	22	7
Concrete	3	3	82
Timber	1	9	4
Other	12	24	6

Adapted: ABS, 2007

It is observed that the Australian Bureau of Statistics (ABS) lists organics as that composed of food and garden waste, but it is often acceptable that organics will be meant as all waste that is primarily organic carbon matter. Component items such as paper, some types of plastic materials and timber can also be accepted as organic carbon waste, and, as it shall be explained later, these together are capable of being broken down by microbial agents for production of methane. It is nevertheless important to note that there is a high probability that such mixed organic carbon waste is likely to generate toxic pollutants such as PCBs (polychlorinated biphenyls) and dioxins (Cheremisinoff, p.119, 2003) as well as corrosive ones such as H_2S (hydrogen sulfide). These shall be considered at greater length later.

Nevertheless, in the interest of avoiding generation of impurities that may seriously pollute the soil, water ,and air around landfills, it is best to adopt the ABS' definition of organic carbonic waste as that comprised solely of garden and food waste as these are mainly composed of organic matter that is not only easily bio-degradable, but also produces much less toxic products.

Table 2 also contains interesting data on how the waste generated in the period 2002-2003 compared to that of 1996-1997 in the Australia.

Table 2: Waste Generation Indicators: Australia 1996-1997 and 2002-2003

Type of Treatment	1996-97 (tons)	2002-03 (tons)	Percentage Change (%)
Waste to Landfill	21,220,500	17,423,000	-19
Waste Recycled	1,528,000	14,959,000	825
Waste Generation	22,748,000	32,382,000	42
Waste to Landfill per Person	1.15	0.87	-24
Waste to Landfill per $m GDP	41.76	23.47	-44
Waste Generation per Person	1.23	1.62	32
Waste Generation per $m GDP	44.77	44.07	-2
Recycling per Person	0.08	0.75	812
Recycling per $m GDP	3	20.37	577

Adapted: ABS, 2007;

The above table is an interesting feature in the waste management profile of the island continent. It is immediately noticeable that waste generation per person has increased from 1996-1997 to 2002-2003 while waste generation per million $ GDP has declined slightly. The indication here is that the GDP growth has not been concomitant with population growth, but this is not germane to the issue at hand. Instead, it also becomes immediately noticeable that there is a striking improvement in environmental-consciousness; between the two periods – there has been 825% growth in overall waste recycling. The recycling per person improvement is also significant at 812%. Waste consigned to landfills has decreased by 19% overall and 24% on a per person basis. This is indicative of the consciousness Australians have gathered from the hazardous nature of waste fulminating unseen in landfills. In all, Australians have become environmentally-friendly to a large extent; but, unfortunately, there is still a long way to go before it can be said safely that the Australians have become fully environmentally-friendly. This is so because still a large amount of solid waste, almost 54% as per the previous estimates of the same later period by the Bureau, is being consigned to landfills, and, thus, still a large part of waste generated per annum remains unrecycled. It may be that more recent data will tell a less mournful tale, but this is doubtful as indicated from data available recently from other nations.

2.3.2. Great Britain:

As part of sampling, domestic waste from another developed nation is profiled. A final report of a study of the disamenity costs of landfill in Great Britain (GB) conducted by the 'Department for Environment Food and Rural Affairs' (DEFRA), February, 2003, is utilized here to understand the impact of landfills on the British population. As per the report, 'disamenity costs' are termed as those local 'nuisance costs' that relate to such discomforts as odor, dust, litter, noise, vermin, and visual intrusion (DEFRA, 2003). The exact physiological nature of the disamenity is not defined. Together with disamenity to nearby populations, the country also lists emissions to air, water and soil, quite in line with other nations, as the second negative environmental impact of landfills. Interestingly, the singular study found that, as of 1994-95, a reduction of Sterling 5,500 which is 8710.3500 US dollars was observed in prices of housing located within 0.25 miles of an operational landfill site in GB while the reduction was lower at Sterling 1,600 which is 2533.9200 US dollars in prices of housing located within 0.25 to 0.5 miles of landfill sites. This does suggest that not only are nearby populations at health risk from landfills, but they also seem to suffer some financial loss from the proximity. Though not the whole of the report is germane here, parts have been utilized to get a better understanding of the problem.

According to the DEFRA, 2003, report, in 1998-99, Great Britain deposited almost 100 million tons of municipal, commercial and industrial controlled waste in landfills. The report also states that landfill waste disposal remained the most preferred system in the country. As per compliance to the EC (European Commission) Directive, 1999, a planned reduction of such waste being consigned to landfills is proposed. By 2010, the amount of biodegradable municipal waste (BMW) was to be reduced to ~75% of the 1995 levels; by 2013, to ~50% and, by 2035, to ~35%. While the 1995 waste disposal statistics remain slightly ambiguous in the report, the proposal for reduction at these percentages does demonstrate that GB, like other countries, is very serious about adopting waste recycling techniques that preempt the landfill disposal pathway.

The emission statistics revealed by the DEFRA, 2003, report also explains the country's urgent landfill waste disposal reduction plan. As of 1994, the GB's total methane emissions from landfills was an astounding 1,790 kt (kilotons) (25% of total EU15 methane emissions from landfills and 8% of the 21,930 kt total EU15 methane emissions, which is equivalent to 12% of total EU15 CO_2 emissions). This is a very quantitative estimate of how problematic methane emissions from landfills can be, and it will be used in the later parts of this project to clarify why urgent ways and means, such as diversion to energy production, have to be found to reduce such emissions from landfills.

Regulations in Great Britain:

Great Britain's DEFRA, 2003, as per EC Directive dated 1999, reports banning of co-disposal of hazardous and non-hazardous wastes, as well as banning landfill of liquid wastes, infectious clinical wastes and certain types of hazardous wastes such as explosive or highly inflammable ones. DEFRA, 2010, also reports that the same EC directive requires Great Britain to reduce gradually biodegradable municipal wastes (BMW) accepted at landfills. The same directive lists landfills as – 1) hazardous; 2) non-hazardous; and 3) inert (DEFRA, 2010).

2.3.3 The USA:

Literature review reveals that currently the USA, in like manner of other developed countries, consigns almost 70% of its solid municipal waste to landfills. Nevertheless, there are certain recent regulations that monitor and guide this country-wide waste management operation.

The US EPA, 20101, has posted a moderately definitive set of regulations for municipal solid waste landfills (MSWLs) as per federal regulations in 40 CFR Part 250 (Subtitle D of RCRA), or as per state regulations, whichever is applicable. These are as follows.

- Local restrictions ensure that landfills are built in geological locations that are suitably away from wetlands, flood plains, faults, or other defined restricted areas.
- To protect the groundwater and underlying soil from leachates, landfills must be lined along the bottom and sides with two feet of compacted clay soil upon which, additionally, flexible membranes (geomembranes) must be fixed.
- Leachate collection and removal systems to treat and dispose of the leachate must be adjusted above the composite layers lining the landfill.
- Proper operating practices must be adhered to and include frequent compaction and coverage of waste with several inches of soil to help reduce odors, control litter, insects and rodents and to generally protect public health.
- Periodic testing of groundwater wells must be conducted to assess whether contamination has occurred.

- Closure and post-closure measures must be undertaken to ensure that such landfills are well-covered and long-term care is established.
- Provisions for corrective actions must be established to ensure control and clean-up of landfill releases and protect groundwater resources.
- Financial assurance must be arranged to ensure closure and post-closure care for long-term environmental protection. (Adapted: Landfills, EPA, USA,2010).

2.4 General Trends:

In recent years, the growing concern for a clean and sustainable environment has greatly changed the goals of energy production, and the current focus worldwide has been the creation of energy-production systems that are environmentally conscious and sustainable. This concept is the basis for possibilities inherent in landfill gas capture. Landfill gas capture is a dual system of waste management for a clean environment dovetailing with energy-generation. Through the concept of capturing harmful landfill gases for conversion to energy, the needs for energy production and environmental relief would both be fulfilled.

The importance of the effect of gases released into the environment from energy conversion has been met with mixed opinions, but the unnecessary release of methane and carbon dioxide from landfills can have no counter opinion. This solution is now in sight; but it is necessary to make the solution feasible in an everyday manner. In other words, it is necessary to pinpoint cheap and sustainable technologies that can convert this concept into reality. This thesis will attempt to present a feasible and economic means of landfill gas capture, while explaining the environmental advantages of the process. The thesis will appeal to both the environment and business-conscious reader.

Chapter 3. Objective:

The objective of this thesis is to demonstrate that current landfill and future landfill technologies should include a methane capturing system to generate energy for local areas. Also, the information presented in this thesis will guide environmentalists and activists to convince politicians and businesses to set in motion landfill gas capture systems as alternative energy resources. Before it is said and done, this process may become a primary source for fuel rather than a secondary one depending upon the amount of waste produced at the landfill sites. We do not anticipate the amount of waste being deposited at landfills will decline in the future. A question is posed as to whether the quantity of fuel energy available from landfills and other similar waste dumping options will be enough to consider them primary sources of fuel or will they remain secondary ones while being considered primarily as aids to toxic gas release cleanup. Nevertheless, it has been emphatically suggested that more recycling of waste instead of deposition to landfills should be encouraged as wastes in landfills tend to produce dangerous chemicals that pollute the surrounding environment. Also, rigorous methods have been suggested to monitor all emissions from landfill methane gas utilization systems and to keep all such emissions within acceptable local regulation levels.

Chapter 4. Literature Review:

Solid wastes being dumped into landfills across America and other countries contain the potential to produce significant quantities of methane. Actually, the processes by which organic carbon matter in the waste is converted into methane gas are complex and is comprised of two primary sets of processes. The first set is aerobic, signifying presence of sufficient oxygen, while the second set is anaerobic signifying presence of little or no oxygen. By the first set of processes complex carbon matter such as carbohydrates, proteins, fats and cellulosic matter are broken down into low-molecular carbonic compounds such as monosaccarides, fatty and amino acids. This process of breakdown of complex carbonic matter into simpler ones is undertaken by heterotrophic bacteria that work best in oxygen-rich environments; since oxygen is a prime requirement for production of enzymes that allow these microbial agents to convert the complex matter into simpler ones (Vymazal & Kropfelova, 2008). The following equation illustrates this.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 + \text{energy}$$

Once the complex matter has been broken down, another set of microbial agents, this time anaerobic, begin to act on the simple carbonic compounds produced by the first set. The anaerobic processes have two parts. In the first part, the first fermentation step, the following occurs.

<u>1st Fermentation Step:</u>

1-$C_6H_{12}O_6 \longrightarrow 3CH_3COOH$ (acetic acid)

2-$C_6H_{12}O_6 \rightarrow 2CH_3CHOHCOOH$ (lactic acid)

3-$C_6H_{12}O_6 \longrightarrow 2CO_2 + 2CH_3CH_2OH$ (ethanol) (Vymazal & Kropfelova, 2008)

In all the above cases, any of which may be possible in an anaerobic situation, the first fermentation step products acetic or lactic acids or ethanol are further processed, now by a special set of anaerobic bacteria known as methanogens, or methane producers. The breakdown of acetic acid (CH_3COOH) in the second fermentation step is illustrated below.\

2nd Fermentation Step:

$CH_3COOH + 4H_2 \longrightarrow 2CH_4 + 2H_2O$ (Vymazal & Kropfelova, 2008)

In case hydrogen is also produced during the fermentation processes, it is also broken down into methane as follows.

$6H_2 + CO_2 \rightarrow 2CH_4 + 2H_2O + CO$ (Vymazal & Kropfelova, 2008)

In both the methane-forming equations, non-toxic water is produced. The formation of methane from hydrogen is known as hydrogenotrophy and most methanogens are capable of it (Vymazal & Kropfelova, 2008). There is one further process by which some methanogens are capable of producing methane from acetic acid directly.

$CH_3COOH \rightarrow CH_4 + CO_2$ (Vymazal & Kropfelova, 2008)

This is a rarer process and only two genera of methanogens – the Methanosarcina and the Methanosaeta – are capable of it. The two genera comprise about 10% of possible methanogens inhabiting an anaerobic site (Vymazal & Kropfelova, 2008).

It now becomes evident that, for the successful formation of methane from organic carbon waste, two sets of environments are required. In the first set, an oxygen-rich medium is essential for heterotrophic microbial agents to break down the initially high-molecular carbonic matter into the simpler compounds that can go into the first anaerobic fermentation step as reactants. It is also important to note that the production of lactic and acetic acids and ethanol via the first fermentation step is a crucial one as higher production levels can ensure higher production of methane in the second fermentation step. Nevertheless, there are certain singular characteristics that methanogenic microbials possess. It is necessary to know these as they germane to the microbial processes by which methane gas is produced in landfills.

4.1 <u>Methanogenesis, Specific Characteristics</u>:

As early as 1989, Barlaz et al, found four distinct phases in methane generation from refuse. These are as follows.

1. The aerobic phase during which the heterotrophs convert complex organic carbon molecules in the waste into low-molecular carbon compounds.
2. The anaerobic acid phase during which the anaerobic first fermentation step microbial agents convert the low-molecular carbon to polymeric acids.
3. The accelerated methane production phase during which the methanogens convert the polymeric carbon molecules of the second phase to methane by polymer hydrolysis.
4. The decelerated methane production phase during which the methanogenic activity is lowered.

Municipal waste has a unique composition – 40-50% cellulose; 10-15% lignin; 12% hemicelluloses and 4% protein. Three major groups of microbial agents are believed to assist in methane production from such waste – i) the hydrolytic and fermentative bacteria that convert biological polymers such as cellulose and hemicelluloses into sugars which, in turn, are again fermented to carboxylic acids, alcohols, carbon dioxide and hydrogen; ii) the obligate proton-reducing acetogenic bacteria that convert longer-chain carboxylic acids and alcohols to acetates, hydrogen and carbon dioxide; and iii) the methanogenic bacteria that primarily convert acetates and hydrogen with carbon dioxide to methane. (Barlaz, 1989). In the study in growth of the different bacterial populations, Barlaz et al, 1989, found that the rate was 2, 4, 5, 5 and 6 orders of magnitude between the fresh refuse and methane production phase for the hemicellulolytic bacteria, cellulolytic bacteria, butyrate-catabolizing acetogens, and acetate and H_2-CO_2-utilizing methanogens (Barlaz, 1989). Moreover Barlaz, 1989, found that the cellulolytic bacteria and the acetogens increased more slowly than the methanogens at first and accelerated growth only after methane production had begun. There was initial decrease in pH value from 7.5 to 5.7. Two reasons are put forward for this – i) the acidic end-products of sugar fermentation tended to accumulate because of the low acid-consuming capabilities of the acetogenic and methanogenic bacteria and ii) the levels of oxygen and nitrates in the fresh refuse was only sufficient for oxidation of 8% of the sugars to carbon dioxide and water. Also, only after the establishment of the acetogenic and methanogenic bacterial populations did the cellulolytic bacteria population take hold and cellulose and hemicelluloses decomposition accelerated (Barlaz, 1989). It seems that acid utilization by the acetogens and methanogens promoted cellulose and hemicelluloses decomposition, driving the cycle but polymer hydrolysis to methane, on the other hand, tended to limit methane production (Barlaz, 1989).

Many researchers have opined that the former microbial agents (acid-forming) for the two anaerobic fermentative steps are symbiotically associated with the acetogens and methanogens (acid-consuming). If the activities of the former are not complemented rate-wise by the latter, accumulation of acid in the medium decreases pH levels and inhibits the acid-producers. Thus, only when the acetogens and methanogens have begun work in earnest do the bacteria of the fermentative process grow fully and accelerate their acid-producing activities. Ultimately, methane generation plateaus off with a balance being established between acid production and acid consumption.

4.2 **Methanotrophs**:

Methanotrophs are types of bacteria that oxidize methane as part of their metabolic processes. These are major microbial agents for natural *in situ* methane suppression. Since methane is a greenhouse gas and a possible emission from several waste disposal systems, primarily landfills, much attention has been paid to these bacterial types to investigate how they oxidize the gas into more benevolent products. The methanotrophs use two enzymes, soluble methane monooxygenase (sMMO) and particulate methane monooxygenase (pMMO), to make methane oxidation work. The gene expression mechanism for release of pMMO is copper dependent in action (Knapp et al, 2007), and where there is deficit in the mineral, the methanotrophs use the alternate gene expression pathway to produce sMMO to activate their methane oxidation mechanism. Otherwise, under conditions where the metal ions are available in soluble form as in $CuCl_2$ (copper chloride salt), the pMMO transcripts increase (Knapp et al, 2007). Under conditions where the metal ions are compromised, as Cu^{++} doped iron oxide or Cu^{++} doped borosilicate glass, the pMMO transcription mechanism takes aid of Cu acquisition systems such as methanobactins (mb), and the transcription rate remains relatively stable with sufficient production of the pMMO enzyme for methane oxidation work (Knapp et al, 2007).

Methanotrophs are important microbials for a very specific reason. There are immense reserves of free methane on Earth, but there is no current technology available that can convert the gas to liquid fuel compounds such as methanol. Making the gas available in liquid reactant form has many advantages, but the technologies available are expensive and involve high costs as well as generation of wasteful by-products. Essentially, methanotrophs do the conversion, methane to methanol, naturally, but very little is still understood of these wonderful micro-organisms and their peculiar ability.

Methanotrophs have been considered because this project reserves the option for using these bacteria in small uneconomical landfills for dissimilating the methane produced there instead of allowing it to seep into the atmosphere. In this context also, the project shall first study potential optimal, maximal and minimal landfill sizes in consideration of methane generation for energy production. Only then will it be determinable if landfill sizes can be considered too small to sustain methane generation for energy production.

It is well-known that while methanogenesis is an anaerobic process as the methanogens operate best in oxygen-poor environments, methanotrophy is best conducted by the aerobic methanotrophs in oxygen-rich environments (Scheutz et a, 2009). In landfills, where both processes may occur at the same time, the methanogens work in the anaerobic lower layers, while the methanotrophs work in upper aerated layers. Both sets of bacteria thrive in mutually exclusive environments.

4.3 Certain Factors that may Affect Methane Production in Landfills:

Temperature:

The effects of temperature and pH are also considerable in the production of methane from organic carbon wastes. In a study in Sri Lanka, effluent from a palm oil mill was subjected to temperature changes. It was observed that at 37^0 C a loading (HLR) of 12.25 g[COD]/L/day for a hydraulic retention time (HRT) of 7 days was achievable with 71.10% reduction in COD (chemical oxygen demand) and a biogas production rate (BPR) of 3.73 L of gas/L[reactor]/day with 71.04% methane content (Choorit & Wisarnwan, 2007). In contrast, when the reactor was subjected to 55^0 C, with a higher HLR of 17.01 g[COD]/L/day for a shorter HRT of 5 days a 70.32% COD reduction was possible with biogas production at 4.66 L of gas/L[reactor]/day with 69.53% methane content (Choorit & Wisarnwan, 2007). It was observed that while the reactor subjected to the lower temperature demonstrated very little variation in efficiency when the temperature was varied from 37^0 C to 55^0 C, the reactor subjected to the higher temperature demonstrated a fall in efficiency when subjected to temperature reduction from 55^0 C to 37^0 C (Choorit & Wisarnwan, 2007). It can be concluded from this study that there is a particular range in temperature nearer the higher value 55^0 C at which the anaerobic microbial agents that produce methane work best. Any reduction in temperature from this range level affects microbial work and reduces methane production.

Effects of pH:

Research finds that the anaerobic microbial agents that produce methane from organic carbon-rich substrate operate best at a neutral pH centering at around 6.8 (Demirel & Scherer, 2008). When substrate such as sugar beet silage with low pH (3.3) is used, substantial addition of pH buffering agents such as sodium or potassium hydrogen carbonate is required (Demirel & Scherer, 2008). Additionally, Ahn, 2009, finds that when fatty acids such as acetic acid are allowed to accumulate inside reactors, they tend to bring down the pH levels, and this causes progressive reduction in gas production. This is because the microbial agents, in the lowering pH medium, become reduced in activity. Ahn, 2009, also recommend a dry manure load for reactors instead of wet loads as this reduces required reactor volumes though the dry medium and may be more difficult for the microbial agents, that require moisture, to work on.

Moisture Content:

It is essential that landfill mass has an optimal moisture content to enable biodegradation. In certain circumstances, where such landfills are designed with restrictions and kept intentionally dry, possibly to contain leachate production, degradation by microbial agents, which require some moisture to operate, is slow (Williams, p.205, 2005). It has been found that high moisture content landfills produce more gas. The quantity of moisture in landfills is a function of certain processes – the initial level of moisture in the waste mass, the level of precipitation, specifically rainfall, in the region, the percolation of outside moisture from surface and groundwater, and the rate of existent biodegradation, since moisture is a degradation product (Williams, p.205, 2005). Moisture in MSW ranges from 10-40% with typical averages at 30%. It is important that moisture in the landfill mass circulates to distribute microorganisms and nutrients and to flush away degradation products (Williams, p.205, 2005). In cases where such movement is artificially designed, caution may be taken to ensure that leachate formation is contained to prevent environmental pollution. Such artificial flushing will increase gas production by increasing pervasion by microorganisms and nutrients, but it will also increase leachate flows. Another point is that, as per present norms of enveloping the entire landfill mass insularly in geomembranes, there is little possibility of moisture percolating into landfill masses from groundwater and surface areas. Thus, modern landfills must be designed with moisture access and circulation in mind. One possible method will be insulated leachate recirculation with moisture addition. This must be done in an insulated manner so that leachate substances, including any emissions, do not infiltrate the environment.

Surface Area:

Before waste is dumped into landfills it may be pulverized or shredded to increase unit surface area available for bio-reactions (Williams, p.204, 2005). The density or compaction of the landfill mass is also influential in gas production as the density or compaction will produce a continuum in which bio-reactions can proceed easily. Nevertheless, if such density or compaction is too much, nutrient and moisture inflow and reaction product and moisture outflow will be inhibited. A depth of at least 5 m is recommended for the landfill mass at which oxygen availability is poor and anaerobic reactions can progress efficiently . Very great depths are not desirable as the enveloped mass within the landfill will be deprived of any precipitation it may need for proper bio-reaction processes (Williams, p.204, 2005).

Nutrients:

Table 3 lists the macronutrients and micronutrients necessary for methanogenesis by anaerobic microbial agents in landfills.

Table 3: Methanogenesis: Macro- & Micronutrients

Macronutrients		**Micronutrients**	
Element	**Concentration (g/kg TSS)**	**Element**	**Concentration (mg/kg TSS)**
Nitrogen	65	Iron	1,800
Phosphorus	15	Nickel	100
Potassium	10	Cobalt	75
Sulfur	10	Molybdenum	60
Calcium	4	Zinc	60
Magnesium	3	Manganese	20
		Copper	10

Adapted: Ghasimi et al, Table 4, p.4575, 2009;

Ghasimi et al, 2009, found that the macronutrients and micronutrients in Table 3 are necessary in the mentioned concentrations in landfills for optimum performance of anaerobic methanogens. Nevertheless, since nitrogen is also a major nutrient in the process, its ratio with organic carbon is accepted as the most important factor in nutrient analysis. The C:N ratio for easily degradable OCs is in the range of 20:1 to 25:1 while semi-degradable and recalcitrant OCs will require a C:N ratio as high as 40:1. An excessively high C:N ratio will produce an acid environment while a low one will allow conversion of nitrogenous matter to NH_4^- faster than the methanogens can assimilate the ammonium-N. Since most landfill waste masses contain nitrogenous waste, anaerobic digestion can reduce these to ammonium-N, through mechanisms such as de-amination of proteins and amino-acids 9. The researchers found that, as pH increased with formation of acids from the OC breakdown, the NH_3-N increased. This is possibly because, as Barlaz et al, 1989, point out, acetogens and methanogens activate after acid formation and the possible delay in this initiation may increase pH. Since methanogens assimilate the NH_3-N their low activity at this stage will tend not only to increase pH but also the NH_3-N. Nevertheless, toxicity from ammonium-N can be restrained if pH levels are maintained at this high concentration point to 6.8-7.5 (Ghasimi et al, 2009).

Other Factors:

There are some other factors that influence methanogenesis via anaerobic microbial agents significantly, but the major ones that require mention have been included. Others such as waste composition are identified in Section 5.1. Still other factors such as inhibitors $SO_2^{--}$and PO_3^{--} ions and pre-composting have not been treated at length. These are important on a site characteristic basis.

By-Products:

The carbon dioxide produced during the last fermentation processes is “likely to leach out into the soil and water because it is soluble in the water” (Mayes 2006). The methane will escape from the landfill because it is a gas and is lighter than the air. The US EPA (Environmental Protection Agency), has already introduced the “Landfill Methane Outreach Program” that seeks to bring assistance to operators and owners of landfills in controlling and collecting methane. The agency acknowledges that methane is a potentially dangerous emission and a notified greenhouse gas. Its safe collection and utilization in producing energy is an aim that not only directly removes a hazard from the immediate environment but also assists in producing a sustainable larger environment, while eliminating a highly polluting greenhouse emission, in the future. The Database of State Incentives for Renewable Energy further promotes the use of renewable energy by offering state, local and federal incentives for those landfills that promote technology for producing renewable energy from CH_4.

Food in Waste:

Leftover food in daily waste contributes to about "40 percent of the methane waste to landfills" (Wallace 2010). Reducing the gas emission by recycling can lead to conserving valuable "organic resources and returning them to the soils, reducing climate warming gases by reducing water pollution, extending the life of landfills and saving money by lowering consumer garbage waste bills" (Wallace 2010). It is notable that if all edible products are eaten without being thrown away, a large portion of daily waste, especially in developed countries, will be reduced and a large part of the worrisome problem of waste disposal will be solved. One possible use of leftover food is to convert it into compost instead of dumping it with the daily waste. This will promote the usage of organic fertilizers and minimize the production of dangerous pollutants such as methane.

4.4 General Information:

It has already been mentioned that there are three major waste generation segments in modern society with large potential for producing methane. These are municipal waste treatment systems, agricultural activates, and industrial activities. In the following section, a project for generating energy from methane produced by agricultural wastes is discussed.

A report from Stege, 2007, for SCS Engineers, Phoenix, Arizona, USA, contains the findings of the company under commission from the World Bank to evaluate significant under-delivery of actual emission reductions achieved by waste management carbon finance projects for LFG (landfill gas) recovery. The commission is in response to the Bank's needs to assess the degree of under-performance of such projects undertaken in developing countries in lieu of CDM (Clean Development Mechanism). Accruable financial benefits under CDM is assessable primarily via the claimable Certified Emission Reductions (CERs). The Bank wanted SCS to assess the extent of CERs that are viable. For this project, similar benefit can be accrued from the report as estimates of current recovery models can be made.

Feedlot biomass gives off methane gas (CH_4). Particularly, dry and liquid manure from cattle, hogs and poultry farms are presently being used to produce biogas, a large component of which is methane, in energy production. How feasible and productive this process is? depends "on the amount of moisture and non-biodegradable solid materials that are contained in the manure product." (Texas A & M 2010). While moisture promotes methane formation as presence of water assists in anaerobic fermentation, presence of non-biodegradable materials such as metals and certain types of plastics inhibits the process. In many countries, such as India, dry manure (moisture content >20%) is burned directly to produce heat and light. This is an age-old practice. Nevertheless, in other countries, including regions in India, where this practice is not acceptable, for whatever reason, converting moist manure into methane gas for energy production is considered.

Creating Energy through Anaerobic Digestion

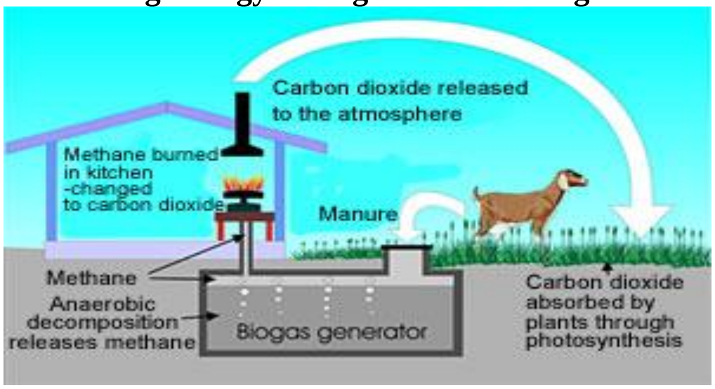

Figure: 1 Copyright© The Pembina Institute 2006
Illustrator: David Mussell
This photo represents how famers convert methane gas into heat energy used in the kitchen for preparing food.

COVERED ANAEROBIC DIGESTER

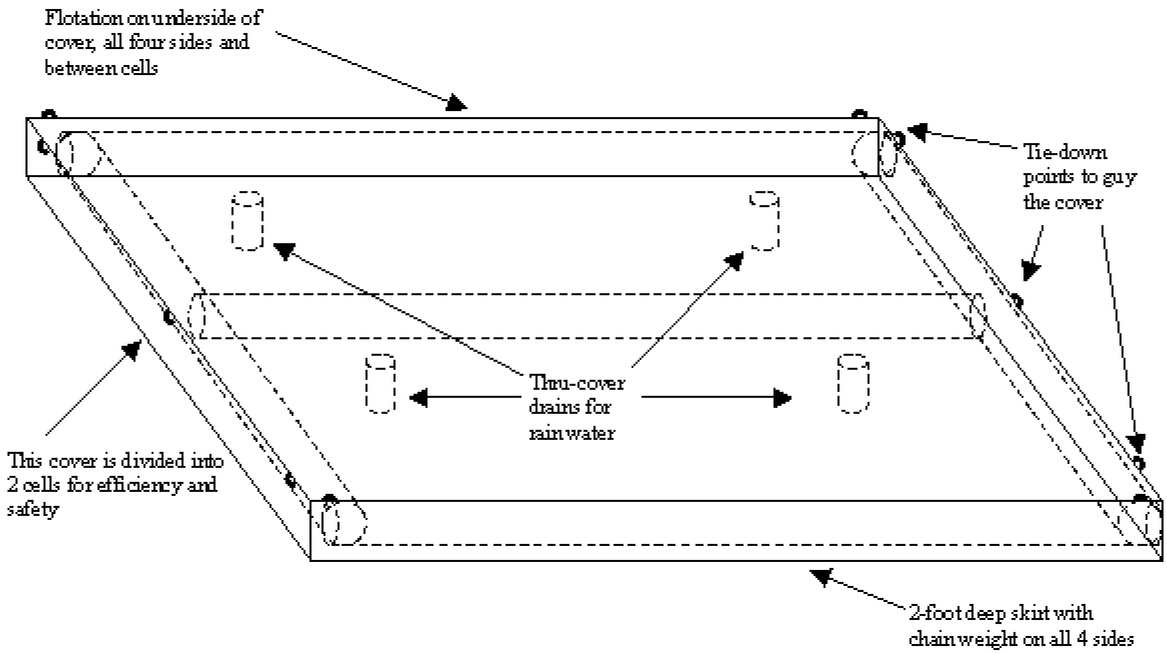

Figure: 2 http://www.methanetomarkets.org/expo/docs/postexpo/landfill_augenstein.pdf

ANAEROBIC DIGESTER TANK

Figure: 3 ANAEROBIC DIGESTER TANK
DOE

Figures 1-3 demonstrate equipment necessary to produce methane-rich biogas from wet manure. Biogas from the wet manure can be captured and purified as a means to yield pipeline grade natural-gas grade methane. Though the equipment above, especially in Figure 1, is a basic type used by farmers in China and India, the principle for utilization of biogas is amply illustrated. Clean biogas can be used in natural boilers and furnaces including household kitchens for heating and lighting purposes. The digester unit illustrated in Figure 3 uses the anaerobic fermentation processes mentioned earlier to produce biogas. Farmers in developing countries, capable of utilizing only rudimentary technology, can use such digesters as they are simple to operate. Similarly, farmers in the west can also do this on an individual basis as the technology level is low and capable of being utilized by anyone with some basic understanding. The Environmental Protection Agency (EPA) has enabled an AgStar Program to aid in voluntary commitment and participation in digestion and utilization of liquid manure on the farm. Current production varies in cost and efficiency “It takes 2.4 kilowatt-hours (kWh) of electricity to burn a 100-watt light bulb for a day. The electrical energy available in one cow's daily manure contribution can produce 3.0 kwh of ‘cow power.’” (Texas A& M 2010). A more schematic representation of the process is available in Figure 4 that follows.

Exactly how much energy, while eliminating environmental pollution, is produced at landfills and agricultural sites? It is estimated landfills in a large city such as Chicago, Illinois or Los Angeles, California can bring electricity to approximately 5,000-10,000 homes. Power utilities serving such large urban conglomerates can use secondary sources to augment their supplies. Most large farms in states such as Texas produce enough manure for operation without the need of purchasing electricity from an outside power source.

4.5 Methane Collections:

Though more technical details will be available later, exactly how it works is detailed here.

Methane is collected through piping systems by wells drilled into the landfills. It is then combusted and used to run turbine engines and simple cycle turbines. When the methane is burned in incinerators, its chemical bond energy is converted to heat energy, and this energy is used to generate steam that is used, in turn, to produce mechanical energy under pressure to turn turbines and produce electrical energy. The electrical energy is supplied to a local area distributor. As methane, the feedstock which would otherwise be waste is produced by an anaerobic digester; the landfill and energy source operator gets credits for emission control and electricity generation from unconventional sources. This credit system is introduced in more detail later. Roughly 60% of the landfill waste gas is comprised of methane gas and 40% is comprised of CO_2 gas. It is suggested the methane gas can and will be a source of up to 2% of global energy requirements in the near future. Since the gas, in effect, is considered a by-product of waste, it is highly efficient and economical in the sense of recycling materials to conserve precious resources as a source of electricity. It is cheaper and cleaner and much easier on the environment!

Power from LFG, Landfill Gas, burning units tends to produce in the range of 3 to 8 megawatts. A six megawatt plant will produce 47 million kilowatt hours of energy, enough to supply over 32,000 homes with electricity. Sometimes it may take years until a landfill has built up enough methane gas to produce that much electricity. This all depends on the size of the landfill and the rate at which waste is dumped there. The costs to produce electricity at landfills is much cheaper than at power plants but are still much more expensive than producing electricity or heat energy from coal. As per a general literature review, the cost ranges from 8 and 14 cents per kilowatt hour.

In the Montlake Landfill area in the City of Seattle, Washington, there were caps put on about 3 feet of landfill from 1926 to 1971. In the fall of 2004, the nearby university tested the area wells on and around the perimeter in accordance with the Department of Ecology's Solid Waste Landfill Design Manual. There was a rise in the amount of methane gas. This was surprising because the site was expected to be sufficiently capped. What had caused the gas production? This is not exactly determinable, but the purpose of the study to determine if the closed landfills could affect the surrounding buildings did show that this was possible even from closed landfills. The results showed the lower explosive limits were met and the upper explosive limits were not exceeded. This was with regard to comparison of 1000 feet of abandoned landfill area under protocol Section 10.09.060 which states the government has a mandate to protect structures within 1000 feet of a landfill from potential landfill migration. Table contains data on details of permissible methane emission levels in regards to building distances. This is applicable to the US.

Table 4: Permissible Methane Emissions Levels

Methane Action Level Monitoring Area	**Action Level**
Perimeter Wall – at boundary of landfill or within 1000 feet of perimeter	5% methane by volume (50,000 ppm)
Off-site UW structures within 1000 feet of the perimeter including Laurel Village, Plant Services Building, Conibear Shell House and the Center for Urban Horticulture	0.01% methane by volume (100 PPM)
On-site UW structures including Ceramic and Metal Arts Building , Environmental Safety Storage Building, Environmental Safety Office Building, Baseball Batting Cage, Golf Driving Range Building, and the Intramural Activities Building	1.25% methane by volume (12,500 PPM)

Some case studies are presented to demonstrate how LFG has been utilized in some countries, both in the developing and developed worlds.

4.6 Case Studies:

4.6.1 Case Study 1, The Huckaby Ridge Facility, Texas:

COMPLETE MIX AND DIGESTER FOR METHANE RECOVERY

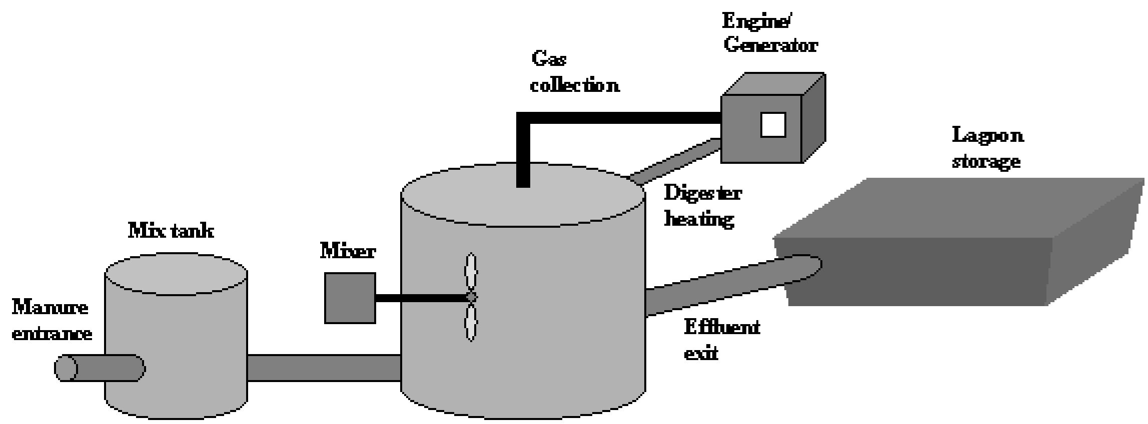

Figure: 4 http://www.methanetomarkets.org/expo/docs/postexpo/landfill_augenstein.pdf

The material drawn from the anaerobic digester is called sludge, or effluent. "It is rich in nutrients (ammonia, phosphorus, potassium, and more than a dozen trace elements) and is an excellent soil conditioner. It can also be used as a livestock feed additive when dried." (Texas A & M 2010). Currently the Huckabay Ridge facility in Texas uses a digester combine such as in Figure 4 to produce 650 million Btu of natural gas per year, a quantity sufficient for lighting 10,000 homes. The gas is produced from manure available locally. Manure from approximately 10,000 cows is put through eight anaerobic digester tanks. Each tank has a total capacity of 916,000 gallons. The digesters produce pipeline grade methane that is supplied to Austin, Texas, and also pipelined to the lower Colorado River Authority to be used for electricity generation by the Pacific Gas and Electric Company in lieu of a 10 year contract struck between the digester operator and the electricity company. This is a prime example of a simple technology that is utilizable not only by individual farmers in developing countries, such as India and China, but also by businesses in developed countries.

Case Study 2; Montauk Energy Capital, LLC, Ohio:

Montauk Energy Capital, LLC, operates one of the largest landfill gas recovery plants in the world. The Rumpke Sanitary Landfill near Cincinnati, Ohio: the 230 acres landfill site receives 2 million tons of waste per annum, and 15 million cubic feet of gas per day is produced. Biogas containing methane, carbon dioxide (CO_2), water and hydrogen sulfide (H_2S) is transported from the site through a 24 in pipe to a pretreatment plant that removes H_2S and volatile organics from the gas. The purified gas is then piped to 25,000 local area residential and commercial customers being served by Duke Energy Co. Montauk Energy also uses PSA (pressure swing adsorption) systems to purify the gas of CO_2. The incentive is available under the 'Carbon Trading Renewable Energy Credit (REC)' program. (Xebec Adsorption Inc. Publicity Material, Undated Document)

The East Kentucky Power Cooperative operates a methane gas recovery facility to produce renewable electricity. "They produce enough electricity for about 5,000 homes." (Rumpke recycling 2010).

Case Study 3, Jatibarang, Indonesia:

The Jatibarang landfill waste disposal site is near Semarang, the capital city of Central Java province in Indonesia, Landfill gas (LFG) will be produced by fermenting organic waste from the city. The gas will be collected and supplied as fuel to electric power generators. This will not only suppress the release of methane gas into the atmosphere and preempt the gas's known greenhouse effects, but it will also assist a developing nation with a supply of cheap electric power. Indonesia is a country poor in natural fossil fuels, and this renewable energy sourced on something as common as municipal waste will certainly assist the nation immensely. Semarang, a city of 1.45 millions as of 2005, produces approximately 120,000 tons of solid waste annually. The Jatibarang site opened in 1992 and, since, has received ~1.5 million tons of waste. As of March, 2007, the site has been emitting methane into the atmosphere. Venting wells will be dug into the landfill to extract the gas, and pipes will carry it away to thermal generators to produce electricity. The Chugoku Electric Power Co., Inc. has been put in charge of project study and consultation. The site covers a total area of 46 ha and, of this, 25.6 ha has been specifically dedicated to the burial of waste. The site will be closed at the latter part of 2010 because it will have reached its maximum capacity.

The system will collect the gas in vertical extraction wells, treat the gas, store the gas and provide for engine power generation and power transmission and flares. The total power generated will be equal to 400 kWh from two different generation facilities. A part of the generated output will be consumed internally to run the blower and other allied systems required for gas extraction and collection. The rest of the generated capacity will be sold to the local power grids. There will be a complementary flare system to burn off any excess gas that cannot be utilized for power generation. Also, in case of emergency shutdown of the power generation facilities, the excess gas, which cannot be stored indefinitely, will be flared to preempt costly and potentially hazardous storage problems. It is estimated that a savings of 605,729 tons equivalent of CO_2 will be available during the estimated project period 2008-2017. (Feasibility Study of the Landfill Methane Gas Utilization Project in Semarang, Indonesia 2007).

Chapter 5. Technical Aspects of the Landfill Gas Generation Process:

5.1 Classes of Substrates:

Essentially, for wastes rich in organic carbon, there are three classes of substrates – carbohydrates, proteins and fats. The biogas yield per kg of volatile solid (VS) substrate and the methane percentage available are presented below.

Table 5: Substrate Type with Biogas and Methane Yields

Substrate Type	Biogas Yield (L/kg of VS)	Methane Content (%)
Fat	1000-1250	70-75
Protein	600-700	68-73
Carbohydrate	700-800	50-55

Table adapted from Tab. 1, Petersson & Wellinger, 2009.

It is obvious from Table 5 that fatty compounds produce the most biogas with the highest methane content. Nevertheless, it is more probable that landfill waste consists mainly of cellulose and hemicellulose material. As per Section 4.1, municipal waste is more likely to have a composition – 40-50% cellulose; 10-15% lignin; 12% hemicelluloses and 4% protein. As per Pelt et al, 1998, in explaining the development of a 'Landfill Gas Generation Model,' the methane generation potential L_0 of any particular waste mass is highly dependent upon the percentage of cellulose present in the waste. The higher the cellulose content, the higher the value of L_0 (Pelt et al, 1998).

According to Ritzkowski & Stegmann, 2007, the easily degradable organic carbon matter in municipal solid waste (MSW) is mainly carbohydrates, cellulose and proteins while semi-degradable and recalcitrant organic carbon (OC) matter tends to be hemicelluloses and lignin. Even with the relatively large presence of these latter semi-degradable and recalcitrant

OCs, it is likely that degradation rates tend to depend upon the factors that affect methanogenesis. If ambient conditions – aeration, presence of nutrients for the microbial agents, temperature, moisture content, pH, etc. – are favorable for both the aerobic and anaerobic agents, it is likely that more percentages of both easily degradable and semi-degradable and recalcitrant OCs will be converted (Ritzkowski & Stegmann, 2007). As per Section 4.1 on methanogenesis, the aerobic bacteria work best in the upper layers where aeration rates are higher while the anaerobic agents inhabit the lower regions of the waste mass in landfills where aeration rates are very low. Also, as per Section 4.1, the aerobic agents convert the complex macromolecules present in the initial mass of waste to simpler low-mass molecules which are then degraded by the anaerobic agents in the lower regions. Thus, it is essential that two sets of conditions, mostly based on aeration rates, co-exist in upper and lower layers of the same landfill to enable better production of methane. Also, while the degradation abilities of the aerobic bacteria are much stronger than those of the anaerobic ones, it is more likely that the semi-degradable and recalcitrant OCs will be broken down in the upper layers even in poor conditions when there is at least better availability of oxygen. In the same upper layers, it is also likely that the poor conditions will affect the work of the anaerobic bacteria in the lower layer, and the broken down molecules in the upper layer will only be treated partially in the lower layers. It seems that anaerobic bacteria tend to be affected to a greater degree by ambient conditions than aerobic ones (Ritzkowski & Stegmann, 2007).

As per literature review, untreated MSW may have an initial biodegradable TOC (total organic carbon) content of 170-220 kg/ton fresh waste on an average with a half life of 5 years (Ritzkowski & Stegmann, 2007). Nevertheless, it is advisable, for any entity expecting to utilize LFG from any site, first to test the waste content ratios and the prevailing ambient conditions so that better estimates can be made of the methane generating potential (L_0) and the degradation rate (k) available at the site.

5.2 <u>Pollutants in LFG</u>:

There is also a necessity to understand the various compositions of biogas, landfill gas and natural gas so that differences can be easily demarcated between useful and harmful emissions. While methane is a useful component of landfill gas, other gases that tend to be included in the same emissions are not, and often, gases such as H_2S and NMOC (non-methane organic compounds) are considered as major hazardous pollutants with capabilities to compromise health of those under influence. As per a report from the 'National Library of Medicine' (NLM), USA, dioxins, possible part of the NMOC in LFG emissions, are highly toxic, persistent and tend to accumulate as they move up food chains in local areas. As per Section 2.1, it has already been shown that PCBs (polychlorinated biphenyls) have infiltrated the immediate environment of the EPA monitored Dewey-Loeffel landfill site in New York state and have entered the food chain there. Fish from waters in the area have been taken off the dibbles list by environmental protection authorities, including the EPA, as the aquatic animals have been found contaminated. Dioxins include some PCBs (NLM, 2009).

Dioxin is the common name for the 2, 3, 7, 8-tetrachlorodibenzo-p-dioxin, or TCDD. NLM, 2009, lists incineration of wastes as one of the major sources of dioxin emissions. The chemical is often the ingredient in daily-use substances such as pesticides and preservatives though it is not accurately known if the practice of such inclusion persists to the present. The degree of toxic potency of these stubborn pollutants can be assessed from the fact that fetuses are affected by the chemicals via their mother's blood while babies are similarly affected via breast milk, cow's milk and infant formula (NLM, 2009). Even landfilling of PVC (polyvinyl chloride), a common plastic material in many parts of the world, can produce dioxins in substantial amounts in the gas emissions and other polluting mechanisms such as leachates (NLM, 2009).

Other sources, Cheremisinoff, p.119, 2003, find that LFG flaring can produce substantial CO (carbon monoxide), a toxic gas, and NO_x emissions. There are two types of flaring equipment available. These are the candle flares with open air flames and no easy means of monitoring for either dioxins or any other toxic emissions and the shrouded flares with the flames enclosed within insulated shrouds between 16-60 feet tall. A limited EPA 1995 report found that such emissions are most likely from internal combustion engines and least likely from boilers, while flares and gas turbines are somewhere in the middle (Cheremisinoff, p.119, 2003). Dioxin emissions are also more likely from flaring of LFG. There are variations in emission amounts according to waste compositions by sites though data is sparse. Dioxin formation is restricted to temperatures ~752^0 F. While candle flares have no means of monitoring toxic emissions, shrouded flares produce flames at ~1400^0 F, much above the dioxins production range. When these flames emerge from the shroud to meet cooler air outside, the sudden drop in temperature often enters the dioxin production range and substantial potential for the toxins' production remains (Cheremisinoff, p.119, 2003).

Table 6 compares the different compositions of bio-, landfill and natural gas.

Table 6: Comparative Compositions of Bio-, Landfill and Natural Gases

Component	Biogas	Landfill Gas	Natural Gas (Dutch)
Methane (vol-%)	60-70	35-65	81
Other hydrocarbons (vol-%)	0	0	3.5
Hydrogen (vol-%)	0	0-3	-
Carbon Dioxide (vol-%)	30-40	15-50	1
Nitrogen (vol-%)	-0.2	5-40	14
Oxygen (vol-%)	0	0-5	0
Hydrogen Sulfide (ppm)	0-4000	0-100	-
Ammonia (ppm)	-100	-5	-
Lower heating value (kWh/Nm^3)	6.5	4.4	8.8

Adapted from Tab.2, Petersson & Wellinger, 2009.

It is observable from the Table 6 that LFG has a higher heating value than biogas though this is much lower than that of natural gas. Inert gases such as nitrogen, carbon dioxide and water vapor (Reinhart, 1994), when present in significant amounts, do tend to reduce heating values. This is more so in the case of carbon dioxide, which has a high value for LFG while it is almost absent in natural gas. This is one reason why natural gas tends to have the higher heating value. Natural gas, which is almost pure methane, is a much better energy production per unit volume than LFG because the latter is infiltrated with many kinds of impurities.

Table 7 has been adapted from Cheremisinoff and contains an exclusive components list of LFG and their possible range of occurrence and averages. While the previous Table 6 has posted a comparative componential breakdown of LFG, biogas and natural gas, this Table 7 posts only the LFG data, and it is immediately observable that when values of individual components in both tables are compared, there is slight variation. For example, while Cheremisinoff, 2003, posts values for NMOCs at average 2,700 ppmv Petersson & Wellinger, 2009, Table 7 does not post a significant amount. While Table 6 shall be utilized for comparative study , Table 7 shall be used to understand the composition of LFG.

Table 7: Landfill Gas Composition

Component Gas	**Concentration in LFG (%)**	
	Range	**Average**
Methane (CH_4)	35-60	50
Carbon dioxide (CO_2)	35-55	45
Nitrogen (N_2)	0-20	5
Oxygen (O_2)	0-2.5	<1
Hydrogen sulfide (H_2S)	1-1,700 ppmv	21 ppmv
Halides	NA	132 ppmv
Water vapor (H_2O)	1-10	NA
Non-methanic organic compounds (NMOC)	237-14,294 ppmv	2,700 ppmv

Adapted: Cheremisinoff, Table 1, p.101, 2003

Author's Notes:

1. *NA – Not available; ppmv - parts per million by volume;*
2. *The highest amounts of the components occur in perimeter wells.*

It is observable from the Table 7 that CO_2 has an almost 45% presence in LFG. Since it is an inert gas, LFG has to be purged of this gas before it is used for energy production purposes. This increases the heating value of LFG (Reinhart, 1994). The specific techniques available for this purpose are explained in the next section on process equipment. Water vapor also is a heating value reducer, and there are ways and means to reduce its presence in LFG when, for a particular site, it is present in significant percentage by volume (Reinhart, 1994).

5.3 Process Equipment:

Before proceeding to the process equipment required utilizing LFG from landfills, it is necessary to mention a few points.

Considering the possibilities of (Table 7) impurities in LFG polluting the surroundings of landfills, it is in the best interest of humanity that, everywhere in the world, most of the MSW (municipal solid waste) generated by humans be segregated into parts capable of being recycled. Products such as paper, plastics, timber and others that are often accepted into these wastes as part of organic carbon components can easily be recycled without being consigned to landfills. This greatly reduces possibilities of impurities such as H_2S (produced from paper and gypsum waste) and PCBs, dioxins and other NMOCs (produced from plastic and other chemical wastes) infiltrating environments around landfills. The Australian Bureau of Statistics' (ABS) (as per Section 2.3.1) definition of organic carbon waste as that comprised solely of garden and food waste is a relatively secure one as this type of waste is less likely to produce harmful pollutants in the resultant landfill gas. Also, as per Section 2.3.1, in the island continent, there has been 825% growth in overall waste recycling in the period 2002-03 compared to the 1996-97 period. The per person improvement is also significant at 812%. Waste consigned to landfills has decreased by 19% overall and 24% on a per person basis. Though more recent data is not available, this demonstrates that Australia is serious about conserving its pristine environment and other nations should follow. It is much better to recycle than consign waste, even MSW, to landfills with possibilities of harmful substances being emitted from these sites for years to come. It is best to inculcate habits that recycle everything possible rather than consign everything that is considered useless to landfills.

The dissertation still has its use since recycling all the solid municipal waste generated everywhere in the world is still a long way away, and there are existing and proposed landfills that are highly likely to impose problems of pollution from methane and other impurities.

Going back to Section 2.3.3, the US EPA, 2010, regulations for municipal solid waste landfills (MSWLs) as per federal regulations in 40 CFR Part 250 (Subtitle D of RCRA), or as per state regulations, whichever is applicable, is a definitive set of directives that can be used to govern landfill operations.

Also, if the landfill is considered as too small to generate commercially applicable quantities of gas, it is advisable that methanotrophs that are capable of oxidizing the methane produced during methanogenesis are cultured. Methanotrophs, as per Section 4.2, are aerobic bacteria and aeration of the entire landfill mass or substantial parts of it will reduce methane emissions as much of the gas produced will be consumed by the methanotrophs.

For the purpose of inclusion of process equipment for landfill gas recovery, this project uses, in parts only, the Onyx Landfill Gas Recovery Project at the SASA landfill site located near the city of Tremembe in Sao Paolo district, Brazil. The project is being implemented as part of the Clean Development Mechanism (CDM) promoted by the World Bank in association with other bodies such as the IPCC (Intergovernmental Panel on Climate Change). The Onyx project uses two separate locations within the same landfill site – Aterro 1, an existing area of 850,000

m^3 capacity where waste disposal is not prevalent anymore; and Aterro 3, a new area of 1,700,000 m^3 capacity where 1,80,000 tons/per annum of municipal and commercial waste will continue to be deposited in 4 phases untill 2012. The project will use the following process equipment, considered here quite adequate.

Progressive Vertical Wells: These are vertically lowered wells that are fitted into disposal areas even before the area has been notified as full. The wells are constructed of perforated concrete pipes with a central high density perforated pipe to descend into the waste and collect the gas as it is produced by means of anaerobic degradation. As the waste continues to be disposed into the area, the wells are progressively raised above the upper surface of the waste. The high density perforated pipe is backfilled with gravel.

Vertical Wells; In areas that are considered full and no more disposed waste is accepted, vertical wells with perforated bottom ends are inserted into the waste along drilled bores. The waste is topped off in these areas and covered with suitable material. The vertical wells are backfilled with gravel and sealed. Both the progressive and vertical wells have wellheads that monitor gas quantity and quality. Also, there are fitted valves to manipulate well vacuums.

Horizontal Drains: These drains are fitted into the waste mass at intervals of 60 m horizontally and 5 m vertically. They are perforated and surrounded with gravel or any other suitable material that will allow the gas to collect into the drains. The purpose of the drains is to collect the gas at horizontal levels and bring it to the vertical well system, with which the drain system will be connected.

Collection Piping: A network of high density polyethylene piping is used to carry the gas away from the drain-and-well system to the blower/flare/evaporator apparatus.

The four sets of equipment above are those that comprise the gas collection and delivery system. The system is an active gas collection one with valves and monitoring units at the well heads to assist in regulating gas flow and gas composition. Passive systems only assist in collecting the gas and conveying it to the next process unit. They do not regulate gas flow or indicate gas characteristics. They be helpful for very small units that may not require much sophistication.

LFG Purification: Since landfill gas (LFG) is a biodegraded product of waste materials consisting of many chemicals, there are several impurities in LFG. This has already been mentioned at some length, especially in Section 5.2. Impurities such as halocarbons, halides such as those of chlorides and fluorides, hydrogen sulfide, siloxanes and water vapor can be corrosive, and the LFG has to be purified before it can be used. There are several clean-up technologies available in the market, and these are used to clean up the gas when end-applications require. Also, all toxic and other applicable emissions such as dioxins should be monitored to ensure conformance to local regulations. Specific purification techniques involve adsorption, absorption and membranes. Appropriate techniques for purification must be applied for specific potential chemical production in the landfill.

Also, LFG contains a number of chemicals that are inert and reduce the power available from the energy content of the gas. This also has been mentioned at length in Section 5.2. Impurities such as CO_2, oxides of nitrogen, and water vapor are the main inert substances LFG contains. These have to be removed before the energy available from the gas is up to the mark (Reinhart, 1994). Again, end-applications determine the level of purification required. The highest level of purification is required when the methane is being made available to pipelines serving natural gas customers (Reinhart, 1994). In applications such as burning methane to evaporate landfill leachate, very little purification is undertaken, as in the Onyx project at Tremembe, Brazil. Actually, the more delicate the process apparatus of the end-application is, the more the level of purification required. Else, impurities in the gas tend to damage the equipment early and this will require costly replacements. Nevertheless, gas impurity levels should be monitored to conform to all local regulations. This should be made applicable to all such emissions including CO_2, which is a less potent greenhouse gas but levels of which have to be monitored for overall environmental safety. Also, CO_2, when available in large volumes, has some industrial applications such as in refrigeration, and purification processes such as pressure swing adsorption (PSA) can substantially separate the gas from LFG after the LFG has been purified of other such gaseous impurities as H_2S.

End-Applications: Landfill gas, or the purified methane content, can be used directly as combustible fuel for boilers, space heating, cement and brick kilns, sludge drying and leachate evaporation and incineration (Reinhart, 1994). In the Onyx project, Brazil, the gas is being used initially to evaporate the leachate being produced by the landfill. This is an effective use as the gas, generated by the waste, is being used in other areas of the waste management process there. Part of the gas is flared, in the absence of any other usage options, but the Onyx project managers plan to install electricity generation turbines soon for better utilization of the gas, part of which is as much as wasted as it is flared off. In the case of flaring, as per Section 5.2, Cheremisinoff, p.205, 2003, warns of the toxic and other emissions that can result. It is necessary to monitor such emissions.

As already mentioned, one end-application is gaining ground in energy conscious countries such as Brazil. LFG, after stringent purification, is being converted to LNG (Liquid Natural Gas) status and being used as fuel in vehicles. Also, since LFG is largely made up of methane, it can be used for conversion to costly hydrocarbons. LFG is also planned for usage in internal combustion engines, as in the vehicles, and in steam turbines for generation of electricity (Reinhart, 1994).

Developing countries such as India and China have small biogas plants that fuel kitchens in nearby family units. This same singular application can be proposed in more developed countries where the cost of preparing food is gradually being considered as a burden. Small landfills adjacent to farming communities can very well produce moderate volumes of gas that can be put to this domestic use.

In effect, the range of equipment available for the collection-to-applications processes for LFG is so diverse that the project has refrained from mentioning any specificities. Instead, general process systems have been included. Nevertheless, the process descriptions themselves are interesting enough to attract progressive people eager to choose cutting edge technology that is clean but efficient.

5.4 Landfill Gas Production Rate Models:

It is necessary for landfill operators, energy recovery project owners, regulators and energy users to predict with some degree of accuracy the quantity of usable gas recoverable from a particular landfill given the rate of waste deposit within a particular time period is made available. Such gas production is predictable in two types of models – one that projects potential production and one that projects actual production.

The US EPA has developed a predictive gas generation rate model that the agency opines is fairly accurate. The generation rate is based on a first-order degradation model with certain default parametric input values, the last also developed by the agency. The model fits conventional landfills while, for more efficiently designed landfills operated as bioreactors, rate constants and methane generation potentials will have to be redesigned to fit in with the higher production rates (Reinhart et al, 2005).

The model is termed the US EPA LandGEM model, and it is operated on the basis of a 1.5 year lag phase on average.

$Q_M = \sum_{i=1}^{n} kM_i(L_0 - V_{lp})e^{-k(t_1 - t_0)}$ …….(1) (Reinhart et al, 2005)

In this particular model, Q_M = Rate of methane generation in m^3 in a year; t_i = i^{th} year; t_0 = lag period, 1.5 year on average; M_i = mass of waste accepted into the landfill in the i^{th} year; and V_{lp} = the volume of methane generated in m^3 per megagram (Mg) during the lag period.

Reinhart , 2005, on behalf of the agency defines conventional landfills for which the model was developed as short-term waste depositories with long-term gas production potentials. Thus, both k (the rate constant) and L_0 (the methane generation potential) are designed for these conventional landfills, as stated earlier.

A mixed-effects model regression analysis yielded means and confidence intervals from which the following prime values emerged - V_{lp} = 33 m^3/Mg; L_0 = 76 m^3/Mg; and k = 0.28 yr^{-1} (Reinhart et al, 2005). When the model was put to test on three wet landfills with waste intake over several years, the following k and L_0 values emerged – i) 0.21 yr^{-1} and 115 m^3/Mg; 0.11 yr^{-1} and 95 m^3/Mg; and 0.12 yr^{-1} and 87 m^3/Mg. Based on the upper 95 confidence limits, the agency has put forward the following estimates – <u>k = 0.3 yr^{-1} and L_0 = 100 m^3/Mg</u>. It is noted that the exponential effect tends to decrease the gas generation potential of a particular mass of waste accepted into the landfill in the earlier years when the L_0 is considered in the current year. The kM_1 segment in the first part of the generating equation preempts the waste mass accepted in the calculation year from this decreasing tendency.

The above model is a wet cell one, Reinhart et al, 2005, signifying that, for individual projects on landfills where moisture conditions are less optimal, appropriate changes to the rate constant k and the gas generation potential L_0 be made. The project notes that these parametric constants are not likely to fit all landfill conditions existent everywhere, and appropriate condition- based constants be chosen for specific projects where, it seems, conditions vary. The agency believes that gas generation tends to increase with full-scale wet landfills, but there can be variations in derived parametric values unless the specifics of gas collection systems, gas quality and quantity, waste input rates and moisture conditions are made available (Reinhart et al, 2005).

The Intergovernmental Panel on Climate Change (IPCC) (2006) Model:

The IPCC (2006) model developed to estimate the quantity of methane recoverable from solid waste disposal systems such as landfills is a capable one (Weitz et al, Undated). The initial default model had the following form:

$$Q_M = [(MSWT \times MSWR \times L_0) - R] \times (1 - OX)$$

This equation, as observable from Table 8, required total national municipal solid waste, fraction of such solid waste disposed in landfills, CH_4 recovered (if any), oxidation factor (if appropriate), and a CH_4 generation potential (the quantity of CH_4 capable of being emitted by unit mass of waste) (Weitz et al, Undated). L_0, the CH_4 generation potential, is dependent upon the MCF (methane correction factor or the degree to which the waste is capable of degrading anaerobically), the DOC and the DOC_F, and F (Weitz et al, Undated).

The first order decay (FOD) model uses the 'bulk waste' and a time delay factor. The form is as follows:

$Q_M = [\sum_{x=S}^{T-1}\{MSWT_x.MSWF_x L_{0,x}(e^{-k(T-x-1)} - e^{-k(T-x)})\} - R] \times (1 - OX)$

The dimensions are as follows:

x = year in which waste was disposed;

S = start year of inventory calculations;

T = inventory year of emissions calculations;

k = reaction constant (yr^{-1}).

There are certain advantages to this FOD model. The same oxidation and recovery calculations are inherent but, now, CH_4 generated in the current inventory year from waste deposited in previous years (R) becomes accountable. The time delay in CH_4 generation is also inherent, and both the CH_4 generated from waste of previous years and time delay factor are available from the exponential parts of the model. In the same manner as the US LandGem model, the exponential part tends to decrease the gas generation potential over years. The same technique of preempting the waste mass being deposited in the current year from this exponential effect is available here. The methane generation potential depends upon the composition of waste while the rate constant and the oxidation factor tend to depend upon the conditions prevalent in the site in conjunction with microbial activity, both aerobic and anaerobic for both methanogens (for k) and methanotrophs (for OX).

The IPCC 2006 model can be adapted for individual landfills where the MSWT (Total MSW generated) product can simply be converted to the amount of waste existent in the landfill in the current year. There are defaults suggested by the IPCC 2006 model for regions on a world-wide basis. This makes it more appropriate for applications, in areas where the EPA USLandGem model may not become applicable. For individual projects, these defaults with net values can be used. The defaults for the specific region in which such a project is located should be used. These defaults are not included here. Also, the updated EPA LandGem model features emissions production modules that can be used to predict emission levels of particular chemicals given some initial composition data. These also have not been included. Both the EAP, USA, LandGem and IPCC 2006 models seem appropriate, but it may be that more recent default figures and parametric constants may become available as research proceeds in this direction. There are several private researchers who have proposed several models which are worthy of notice, but the project has chosen to incorporate only these two models as above since they seem adequate enough. It is necessary to note that model-fitting for individual projects should be a hands-on measure, and actual performance must be monitored with real quantitative data collection accompanying model application.

The existing composition of the landfill as well as future deposit composition must be ascertained fairly accurately so that, in case there are possibilities of harmful emissions, appropriate models that can incorporate prediction of these additional harmful emissions are chosen.

It is noted that the project has only proposed models for no co-disposal landfills wherein only municipal waste is dumped. Landfills that take in industrial and other wastes have not been treated at length though agricultural waste such as that from dairy farming treated earlier in the project is sufficiently covered.

Table 8: Dimensions (IPCC Methane Recovery Model, 2006)

Symbols	Descriptions	Units
Q_M	Amount of methane generated	Gg/yr
MSWT	Total municipal solid waste (MSW)	Gg/yr
MSWF	Fraction of MSW deposited in SWDS (Solid waste disposal system)	Gg/yr
R	Recovered methane	Gg/yr
OX	Oxidation factor	Dimensionless fraction
L_0	CH_4 generation potential	CH_4(Gg)/Waste(Gg)
MCF	Methane correction factor	Dimensionless
DOC	Degradable organic carbon	C(Gg)/Waste(Gg)
DOC_F	Fraction of DOC dissimilated	Dimensionless
F	Fraction by volume of CH_4 in landfill gas	Dimensionless

5.5 Methane Recovery Costs:

Section 8.2.2, of the IPCC technical paper used earlier, mentions some interesting cost analyses of methane recovery from solid waste, as in landfills. The costs vary according to the technology used and the site characteristics. A 1-million ton landfill site serving a population of 50,000-100,000 will need ~$630,000 for collection and flare capital. A 10-million ton site would require $3.6 million. Obviously, there is some cost advantage in large-scale projects, if the site characteristics permit. The 1-million ton site would require ~$100,000-200,000 to operate. Energy recovery costs, including purification, will be ~$1,000-1,300 per net kW per year generated.

Actually, direct use, as mentioned earlier, in developing countries such as India and China, can be less expensive. In this case, users such as farmers consume the gas directly, possibly as biogas, to fire their home furnaces and to prepare food. This project can note that, in more developed countries such as those in North America and Europe, direct use can be for small farm businesses that require heat energy. In such direct use, pipeline costs are the principal capital employable. Typical electricity generation costs, as per US equipment and labor costs, can range from 0.14-0.35 cents per kW. This can be substantially less, as in developing countries where labor is especially cheaper. In sites where the gas is vented, collected and flared, electricity generation costs will substantially lower already existing costs of treating the emissions, since the extra income from such energy generation will help make up part of such treatment costs. It is notable that these costs are as on a historical basis as per IPCC calculations but the general trend in costing is available and considered sufficient in estimations for this project.

6 Conclusion:

The project has amply demonstrated that it is highly germane in the modern context of a beleaguered environment to use landfill gas for energy production – whether energy in the form of electricity or heat. Not only will this reduce methane emissions from landfills, when it is well-known that the gas is one of the most influential greenhouse perpetrators, but it will also assist in producing a cheap alternate source of energy in a world struggling to find such cheap energy sources. The project has shown that producing such energy from an otherwise useless venture in which landfills only continue to pollute the environment will only convert such uselessness into one of utility. Some novel elements have been incorporated in this project making it a singular one of its kind. While a number of these new proposals have been mentioned by several researchers in numerous publications, no existing one publication such as this project incorporates all of them. The last point, the seventh, is entirely new and suggested only in this project. These novel elements are listed below to enable the reader to find, in a gist, what is unique.

1. Small landfills may not be economical for harvesting the small volumes of methane gas they generate. The project proposes, together with some other researchers, that such non-remunerative small landfills be equipped with upper layers of soil where oxygen levels and other soil content factors allow methanotrophic bacteria to thrive and convert methane produced in the lower anaerobic layers into less harmful products.
2. In Section 5.3, the project has shown that existing landfills, when applicable, and proposed ones should adopt the US EAP, 2010. Also in Section 2.3.3, there are recommended regulations for insulating such landfills from polluting the environment

via methane emissions and via generation of other degraded products. Not only emissions of methane and harmful gases but also other polluting mechanisms such as leachates must be avoided. In localities where other such regulations become applicable, those, too, should be adopted.

3. The project has also shown that it is important to inculcate methanogenic bacteria in landfills that are expected to produce significant quantities of methane for commercial exploitation. Several research projects, already some have been cited in this paper, are investigating ways and means via which these methanogenic bacteria are supplied with the most optimal conditions for maximum activity in methane production.
4. As per current international efforts, this research study supports that economic viability incorporated in methane-from-landfill utilization projects will only encourage such projects. The IPCC 2006 FOD model is an adequate one. The US EPA model is also fairly efficient with appropriate default values already provided. Its current update also contains modules that can assist in estimating production and emission values of various possible chemicals that may or may not be considered dangerous. The default values for the IPCC 2006 model are not provided here but are available from the institute's website. Also, the project has thoughtfully suggested how the IPCC 2006 model, instead of being used only in the context of national waste, can also be used for individual landfill sites.
5. In the interest of health, only those waste materials that are fully biodegradable to relatively safe end-products should be deposited in current landfills. The Australian Bureau of Statistics', Section 2.3.1, suggested that only garden and kitchen waste composed of fully bio-degradable materials that are least likely to produce harmful by-

products be deposited in current and proposed landfills. Both government and private sources have been discussed at length to demonstrate how this may be possible.

6. This paper has also suggested, preempting production of dangerous substances from landfills, that waste be recycled to minimize landfill deposition as much as possible in the future. Nevertheless, in cases of existing landfills and those that are proposed in the near future, this paper has suggested a sufficiently secure deposition, in cases of new landfills, recovery, collection and utilization mechanism with strict adherence to local regulations for emissions and with efficient purification processes. Purification processes must be aligned to specific end-use characteristics, Section 5.3. Nevertheless, purification must be accompanied with sufficient emission monitoring at all stages of the use profile, Section 5.3, such as waste deposition with composition, gas generation and recovery, collection, storage, purification and usage. If harmful emissions occur at any stage sufficient, measures can be adopted to preempt them.
7. This papre suggested, in Section 5.4, how that the IPCC 2006 model can be utilized for individual projects in specific regions of the world. Though this is a very tiny part it is significant to users in regions of the world where no nationally available models such as the EPA USLandGem prevail. The model can be used in conjunction with more location-appropriate regional defaults available with the IPCC.

It is important to emphasize in the conclusions that greater accuracy is wanted in the oxidation factors and rate constants, as well as any other applicable parametric constants, that mark influences on aerobic and anaerobic microbial action on waste types. Thus, the DOC product in waste types and types of microbial present in particular landfill sites together with prevailing conditions that influence the potential of these microbials in producing methane, as well as other toxic and non-toxic products, must be accurately assessable. This is the most crucial part of methane recovery projects at landfill sites since more accurate oxidation factor values as well as rate constants, both of which inherently influence the gas generation potential, will enable better deployment of methane production models with more precise and real results emerging.

Landfill gas, with a few precautionary measures, is possible as an energy contributor. This paper has sufficiently shown this conclusion.

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