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Methane Gas Emissions: Methods of Improving the Efficiency of the Biggest Landfill Gas Waste to Energy Project in the Middle East Installed in Amman, Jordan

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Abstract

In a world of increasing population and consumption, there is a pressing need to use our resources in the best possible way. This involves reducing the generation of waste, achieving high-quality recycling and efficient use of the residual waste for highly productive clean energy generation. A waste-to-energy facility may generate a range of energy outputs such as electricity, district heating, steam for industrial processes and many other energy outputs. In this way, residual waste, *i.e.* waste that cannot be recycled in an economic or environmentally beneficial way, can become a resource by turning it into energy for the benefit of people, countries and the environment. In the last 20 years, the main waste treatment facilities are landfills. However, during this time period, there has been a huge progress and more efficient and environmentally friendly methods of waste treatment as M.B.T. (mechanical biological treatment) plants, burners, medical sterilization plants etc. are constructed, but landfills still remain the main method of waste treatment. Landfills are commonly found in developing countries. These landfills are constructed following the latest construction methods that minimize the environmental problems and maximize the energy efficiency. This research deals with the energy production of the main landfill in Amman, Jordan. The biggest waste to energy facility in the Middle East is located in Amman, Jordan. This research paper emphasizes on the problems that can occur in a waste to energy project and introduces many unique techniques that were applied in the biggest waste to energy project in the Middle East to improve and maximize the landfill gas production in the most financially and environmentally friendly way as possible. These techniques have proved that they maximize the CH_4 concentration which increases the energy utilization of the landfill gas and

can, therefore, be applied in other similar projects. An image of the landfill area is shown in Figure 1.

Subject Areas

Atmospheric Sciences, Chemical Engineering & Technology, Environmental Sciences, Industrial Engineering, Mechanical Engineering

Keywords

Renewable Energy Sources, Waste to Energy, Biogas, Environment, Methane Gas, Engineering

1. Introduction

As a summer engineering intern, I had the chance to be part of a waste to energy project in Amman, Jordan. The scope of this project is to extract the landfill gas from Ghabawi landfill and produce 5 MW electrical power from it. By extracting and utilizing the landfill gas, we prevent its escape to the atmosphere, thus protecting the environment by reducing greenhouse effect due to methane (CH_4) that is the main component of landfill gas and the main gas responsible for the greenhouse phenomenon. Also, electricity is produced that helps the decrease of the consumption of conventional energy sources for electricity production.

In the Al Ghabawi dessert landfill, 40 km east of Amman, Jordan, an environmentally friendly project is taking place that involves the production of energy from waste. This landfill is the only landfill the city of Amman has. The total

Figure 1. Photo of the main project area.

amount of waste that has been deposited in the landfill since the landfill was created, in 2003, is more than 12,000,000 tons. Inside the waste mass in the landfill, a number of physical and chemical phenomena occur leading wastes to decomposition to their conversion in stable chemical compounds. Among others, the phenomenon of methane generation is observed, *i.e.* the creation and emission of biogas produced by the anaerobic degradation of the organic fraction of wastes which is mainly consisted of methane (CH_4) and carbon dioxide (CO_2). The proportion per volume of these ingredients varies between 45% - 60% for CH_4 and 40% - 60% for CO_2, while the entire process is completed through certain simultaneous stages that will be discussed later.

The project started in 2014 and it is currently in the biogas extraction phase. That means that the conversion of the biogas to electricity has not started yet and at the moment the biogas is burnt at a flare. It is very important that the Power Station starts producing electricity in 2018 as scheduled because of the energy needs the city of Amman has. The need for energy has encouraged people to find different and unique ways to supply the society with energy. This need has been more urgent for the city of Amman recently due to the increase of the population. The civil war in Syria has forced approximately 2,000,000 people to leave Syria and migrate in the capital of Jordan, in order to live a better life. This unexpected growth in the population has forced the city of Amman to find an alternative form of electricity production.

This waste to energy project is the largest project of its kind in the Middle East and the contractor is a joint-venture of two Greek construction Companies "Christopher D. Constantinidis S.A" and "HELECTOR S.A". The owner of the project is the Greater Amman Municipality (GAM) and the funding for this project came from the World Bank and the European Bank of Reconstruction and Development (EBRD). The landfill accepts only Municipal Solid Waste (MSW) which includes residential wastes, commercial wastes, and non-hazardous industrial wastes. The unacceptable wastes are hazardous-toxic waste in accordance with the reference regulatory definition in Jordan, infectious medical waste, construction and demolition debris, tires, water and wastewater treatment plant sludge dewatered to a minimum of 20 percent solids.

1.1. Location and Topography of the Landfill

Ghabawi landfill is located within Greater Amman Municipality in Jordan, in its Eastern part, near Jabal-Al-Ghabawi. Its distance from the center of Amman is 40 km, whereas from Amman ring road is 23 km. The nearest residential area is 8 km at the west of the landfill.

The location and the surrounding area were owned by the Jordanian military, without any residential, historical and cultural land use.

The Ghabawi landfill site is extended in an area of approximately 2,000,000 m^2. Its boundaries are presented in **Figure 2** and **Figure 3**. **Figure 3** depicts the division of the landfill in 9 cells.

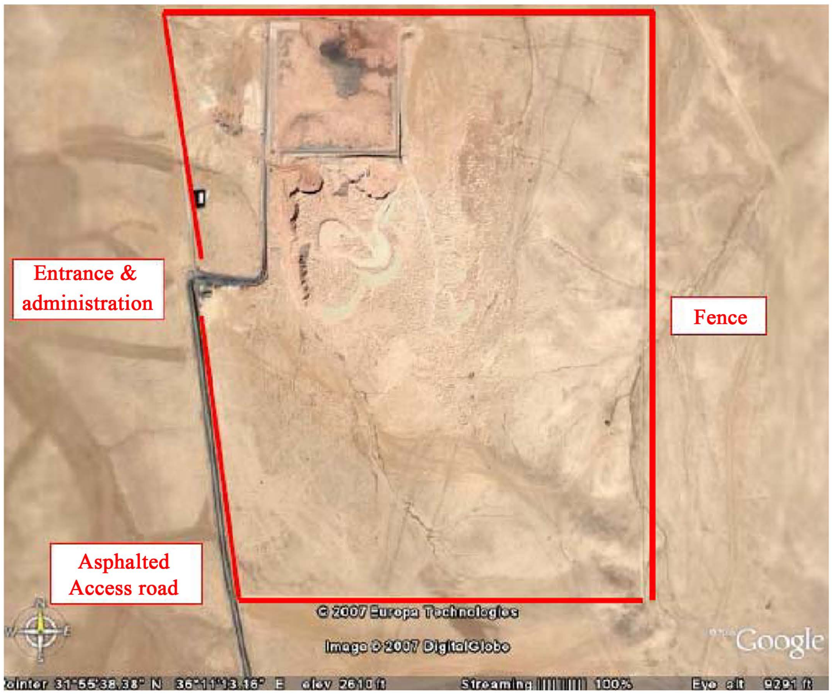

Figure 2. Boundary of the landfill.

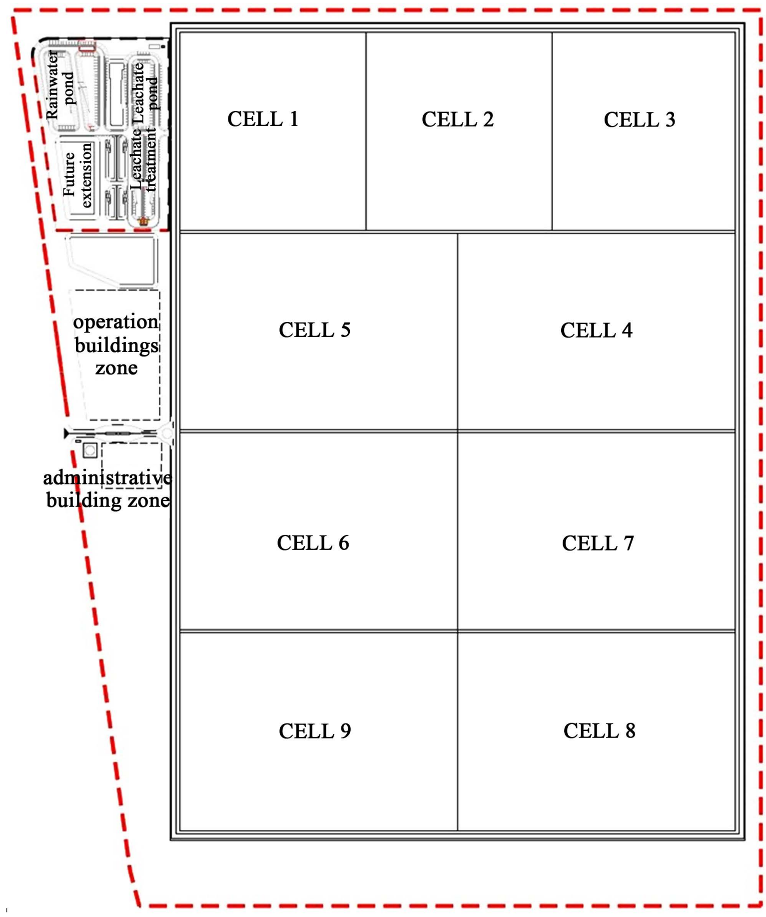

Figure 3. Depiction of the general layout of Al Ghabawi landfill [1].

The volumes of waste have been deposited in cells as depicted in **Figure 3** (above). So far Cells 1, 2, 3 have been filled with waste and the restoration works have been completed. Landfill gas is extracted from these three cells now. At the moment, cell 4 is the active cell and it is receiving all quantities of waste from Amman municipality greater area. In the following months, the construction of cell 5 will start. When the construction is completed in cell 5 the restoration and the landfill gas extraction works for cell 4 will start and cell 5 will be the active cell receiving the income waste. Gas extraction from Cell 4 is expected to start in the first months of 2019.

1.2. The Waste in the Landfill

The Ghabawi landfill serves the Greater Amman Municipality, Zarqa, and Ruseifeh Municipalities (mostly via a transfer station) and some private companies, hospitals, universities and the Army. The waste quantity received at the landfill on a daily basis is measured by a single weighbridge which was recently connected to a computerized management system. The landfill accepts only Municipal Solid Waste (MSW) which includes residential wastes, commercial wastes, and non- hazardous industrial wastes. The unacceptable wastes are hazardous-toxic waste in accordance with the reference regulatory definition in Jordan, infectious medical waste, construction and demolition debris, tires, water and wastewater treatment plant sludge dewatered to a minimum of 20 percent solids. More precisely, from August 2007, according to the internal regulation, the Solid Waste Materials that are banned from Ghabawi Landfill are: Chemical materials (Acids, Chlorine, etc.), Oils, Polyester, Alkaline materials, Liquid materials (shampoo, mineral water, etc.), Flammable and explosive materials, Iron, Wood, Tires and Nylon, Plastics, and Cardboard and Paper. Some of these materials are banned because of their hazardous properties, and others because they constitute recyclable materials and GAM intends to promote recycling. In that way, full loads of recyclable materials are refused to be dumped.

The daily waste quantity that is received in the landfill is about 3.500 tn/day. The annual quantities of waste received at Ghabawi landfill for the period from 2003 until today are presented in the following **Table 1**.

Table 1 serves to show the increasing waste the Ghabawi landfill receives each year. The Ghabawi landfill as mentioned above has 3 cells, full and closed. The restoration works (reshaping and final capping) of Cells No. 1, 2 and 3 were completed in March 2017 together with the gas extraction and leachate recirculation operations. Also, a flare system was installed in order to burn the extracted landfill gas. After that date, the operation period started. Regular measurements that are taking place daily are essential in order to make sure that the project is headed in the right direction and help the engineers figure out solutions for the problems that might occur. I worked during this period and I had the opportunity to take the necessary measurements, fill the reports and analyze these measurements.

Table 1. Amount of waste received in the landfill each year [2].

YEAR	AMOUNT OF WASTE (TN)
2003	447,945
2004	696,293
2005	752,688
2006	785,987
2007	795,188
2008	742,888
2009	892,464
2010	966,658
2011	937,645
2012	995,907
2013	1,048,612
2014	1,121,540
2015	1,172,980
2016	1,344,017
2017 (up to June 2017)	850.000

The next Phase of the project (3rd phase) is expected to start in August 2017. The 3rd phase consists of the procurement and installation of the electric Power Station (total capacity of approximately 5 MW) and their auxiliary equipment (chillers, transformers, middle voltage electric boards and equipment, blowers, etc.) as well as the permanent installation equipment necessary to transfer the produced electric energy to the supply grid. The electricity produced will be sold to the Jordanian Electric Power Company (JEPCO) which is in charge of supplying Jordan with electric energy.

2. Restoration of the Landfill

The restoration of the landfill is a very complicated process. The purpose of the restoration works is to insulate the landfill in order to avoid the escape of the landfill gas to the atmosphere. That is crucial for avoiding the environmental pollution from the landfill gas and increasing the quality and quantity of the extracted gas that is used for the producing electrical energy so is increasing the income from the sale of the electrical energy. The time needed for the execution of the restoration works depends on the size of the landfill. More specifically the restoration works, for the Ghabawi landfill needed approximately 6 months/cell for the first 3 cells. However, cell 4 is slightly bigger than the previous three cells so it is expected that the restoration time plan will exceed the 6 months.

The restoration works are divided into 4 stages with very important environmental results as shown in the following Table 2.

Table 2. The 4 stages of restoration and their results.

RESTORATION WORK	RESULT OF ACTION
1) Overlays-landscaping	New contour, aesthetic improvement, Covering of waste, Reshaping to maximum slopes of 1/3 (33%) for stabilization reasons and risk deduction for gas extraction
2) Final capping	Obstruction of water from entering the landfill Prevention of leaks of Landfill gas and odors to the atmosphere. Limiting of the potential for fires
3) Landfill gas extraction, collection, and transfer	Odour control, Reduction of CH_4 emissions Production of energy
4) Extraction and Recirculation of leachate	Control of water pollution, Improvement of CH_4 production with energy proposes.
5) Monitoring LFG migration and settlement measuring	Measuring of LFG migrations to areas outside the landfill and measuring of settlement in different areas of the landfill

In addition to the above environmental benefits, the production of electrical energy provides income for the Owner and makes the project financially feasible. Electricity is expected to be produced in 2018. An overall presentation of the procedure of how the gas is collected and how it is converted to electricity is depicted in Figure 4.

The restoration works that were executed in Ghabawi landfill and mentioned in Table 2 are described in detail in the following paragraphs:

2.1. Overlays-Landscaping

Before the construction of the works associated with Final Capping, LFG and Leachate Networks, it was required to execute earthworks with the necessary equipment in order to bring all cells to the appropriate condition that is:

- All waste must be covered with soil;
- The slopes should not exceed 33%.

Table 3 shows the materials and the operation of the layers.

2.2. Final Capping

The final capping of cells 1, 2, 3 was the main rehabilitation element and the main roles of the final capping are:

- Minimization of infiltration by surface water into wastes, in order to improve control over the produced leachate,
- Maximization of surface run-off and drainage of the final contour,
- Control over biogas leaks,
- Creation of a natural barrier between wastes and the environment.

In order to achieve the above objectives, it was customary, in accordance to the best engineering practices, to construct multi-layered final capping, which includes the following layers, starting from the wastes and moving upwards, with the respective functions:

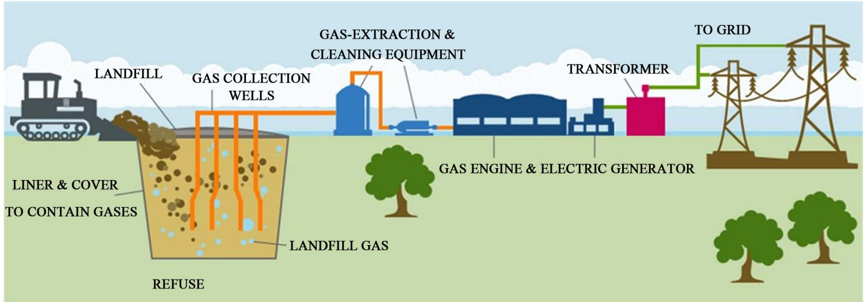

Figure 4. Process of converting biogas to electricity [3].

Table 3. Materials and operation of the layers.

Layer	Operation	Usual materials
Smoothing	Smoothing of waste contour in order to construct the final capping-provisional capping.	Soil materials of average permeability
Low permeability	Interruption of surface water ingress into wastes.	Geosynthetic Clay Liner (GCL).
Drainage	Controlled run-off of rainwater outside the final contour. Reduction of hydraulic elevation above the low permeability layer. Connected to respective works for arranging rainwater.	Draining material (gravel)
Protection	The barrier between the capping layers and the overlaying new uses (vegetation, etc). Protection of underlying from the root system of plants and from exposure.	Clean soil materials.

The layering of the final capping is shown in the drawing of the detailed design below. Specifically, all layers on the top of the cell are the same with the layers on the slopes and follow the same specifications (thickness, quality, water permeability etc.)

Description of **Figure 5**:

1) Above the soil material for the waste cover as well as the top formation layer a layer for smoothing the contour was placed, made from homogeneous materials of increased granulometry, with a diameter of 15 cm max, and of average 50 cm thickness.

2) The above is then followed by a barrier layer made of geosynthetic clay lining (GCL) of 7 mm thickness and of low water permeability, 5×10^{-11} m/sec.

3) Then, gravel material shall be layered (drainage layer) of granulometric class 20/40 and of 20 cm thickness, with water permeability rate between 1×10^{-2} - 1×10^{-3} m/sec.

4) This was followed by separating geotextile, weighing 200 gr/m^2, used for protecting the overlaying layer against the draining layer.

5) Afterwards, a protection layer was placed, made from uniformed materials of increased granulometry with 15 cm maximum diameter and 100 cm thickness.

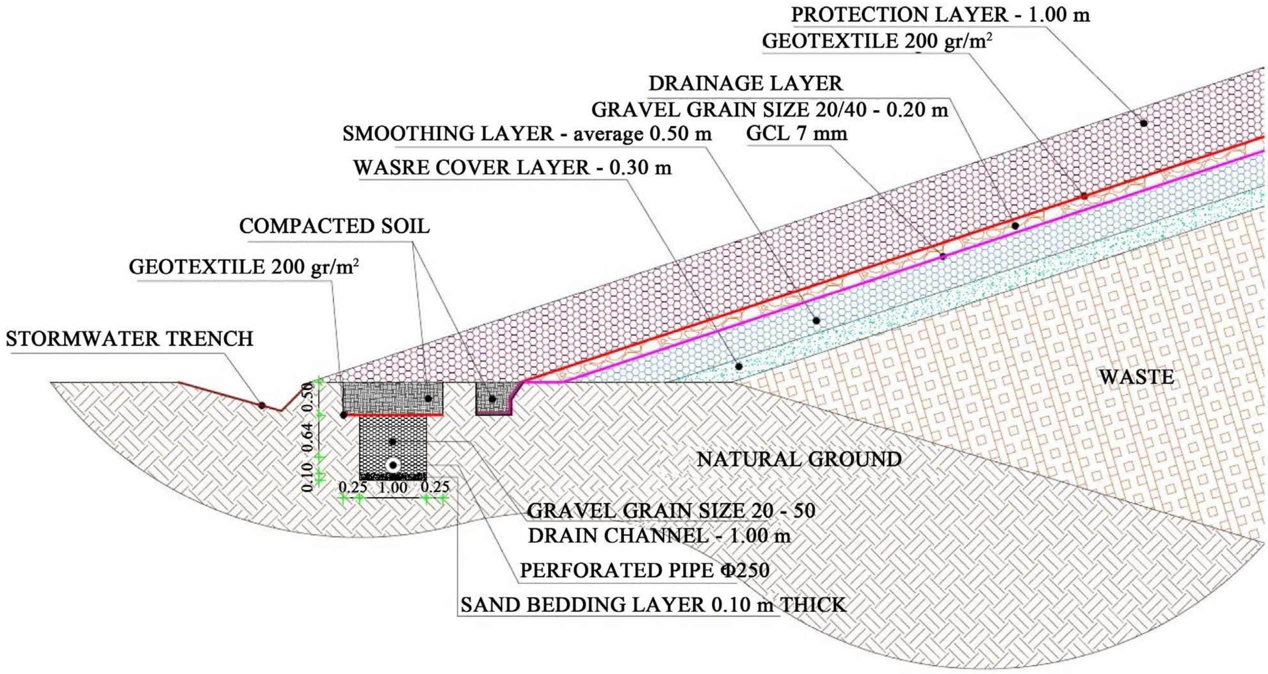

Figure 5. Layer of final capping [1].

2.3. Landfill Gas Extraction, Collection, and Transfer

The landfill gas is extracted from the vertical wells that were drilled by a specialized drilling machine as is shown in the following picture. The gas wells are constructed using 600 mm diameter (nominal) boreholes. The whole landfill gas network is constructed by HDPE. (High-density polyethylene or polyethylene, it is a polyethylene thermoplastic made from petroleum).

Depicted in **Figure 6** an *HDPE pipe* having an outside diameter of 160 mm, drilled in a pattern designed to optimize methane recovery is inserted vertically in the borehole and surrounded by gravel that acts as a filter to prevent solids from being ingested. The gravel was 25/50 mm granulometry of non-carbonic origin (limestone less than 25%).

The annulus around the top of the well was backfilled and sealed with clay or bentonite (2.5 m thickness) starting 1.5 m below the GCL layer to prevent the escape of landfill gas. The last 20 cm until the top of the well is filled with compacted soil.

The top 4.2 m of the HDPE pipe is non-perforated to ensure the prevention of escape of landfill gas and also for safety reasons, preventing suction of atmospheric air, because the mixture of air and landfill gas at specific ratio can become explosive. The rest of the pipe is perforated with holes with diameter 12 - 14 mm. The Depth of the wells varies according to location and it must be always 2 - 3 meters above the bottom of the landfill. The project consists of 188 wells in cell 1, 157 wells in cell 2 and 192 wells in phase 3, for a total of 537 wells. A typical detail of the landfill gas well is shown in the following drawing. The vertical section of each well is made by HDPE PN10 DN160 pipe and of a galvanized

Figure 6. Machine used for drilling of the wella.

wellhead that permits the easy opening of the well in order to insert a submersible pneumatic pump to drain the leachate from flooded wells. Each wellhead has a sample point for the measuring of the landfill gas concentration as seen in **Figure 7**.

In order to simplify the operation Individual wells are grouped in well stations (manifolds) that are shown in **Figure 8**.

The maximum distance between a well and its associated well station is 85 m and the horizontal piping between wells and well stations is made by HDPE PN10 DN90 pipe. The well stations feature a dedicated gate valve for each well, for flow regulation purposes. They also include sampling points for the measuring of the landfill gas concentration and flow. Both wellheads and well stations are manufactured out of hot dip galvanized steel pipe with flanged connections between steel and plastic pipes. The above ground equipment (wellheads and manifolds) are not made of HDPE but of galvanized steel due to the fact that HDPE is not suitable for explosion to the sun for a long period and at this area the days of sunshine more than 300days/year. A typical manifold design is shown in **Figure 9**.

The horizontal piping between manifolds and the flare was manufactured of HDPE PN10 of various diameters (max. diameter DN 560). In the next face, a power station of approximately 5 MW will be installed for the landfill gas utilization.

2.4. Extraction and Recirculation of Leachate

2.4.1. Leachate Extraction

For the extraction of the leachate from the inside of the landfill 16 extraction

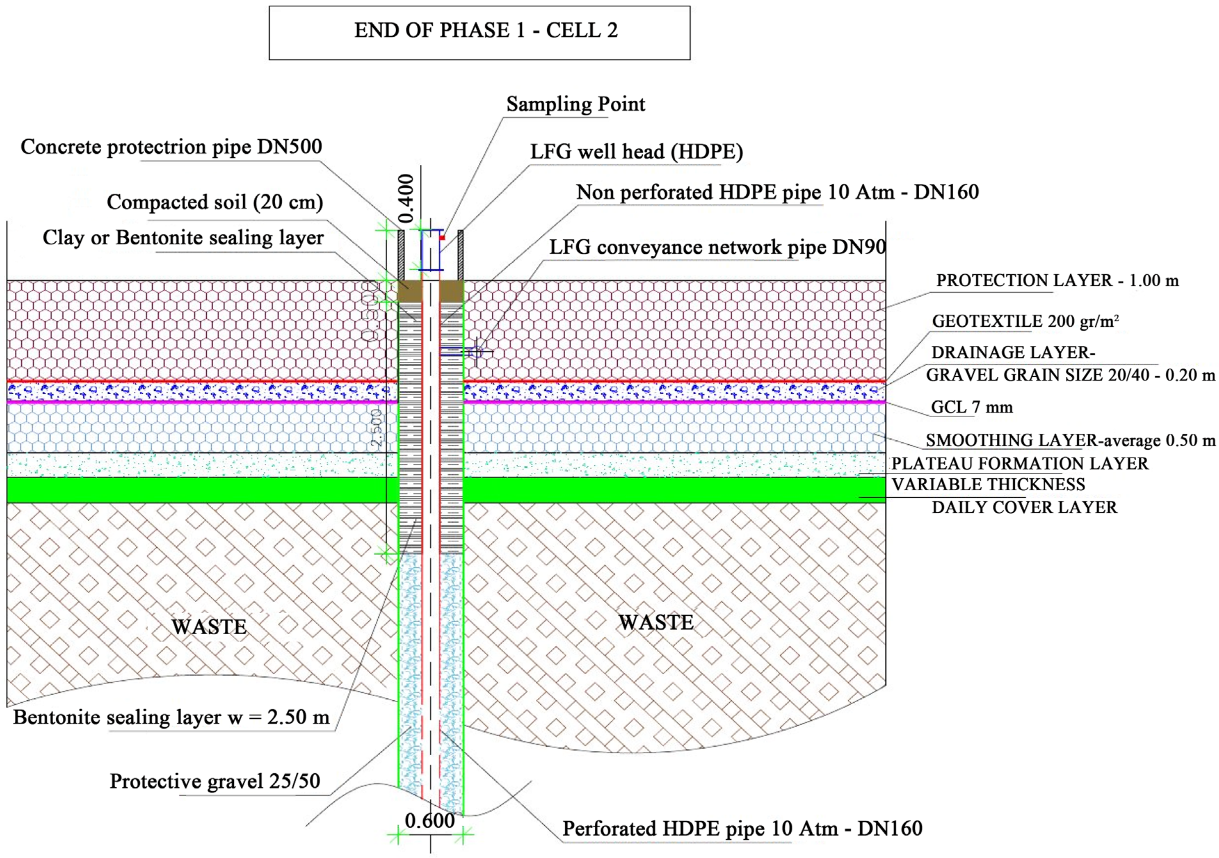

Figure 7. Parts of the well.

Figure 8. Measurement of gas concentration in the manifolds.

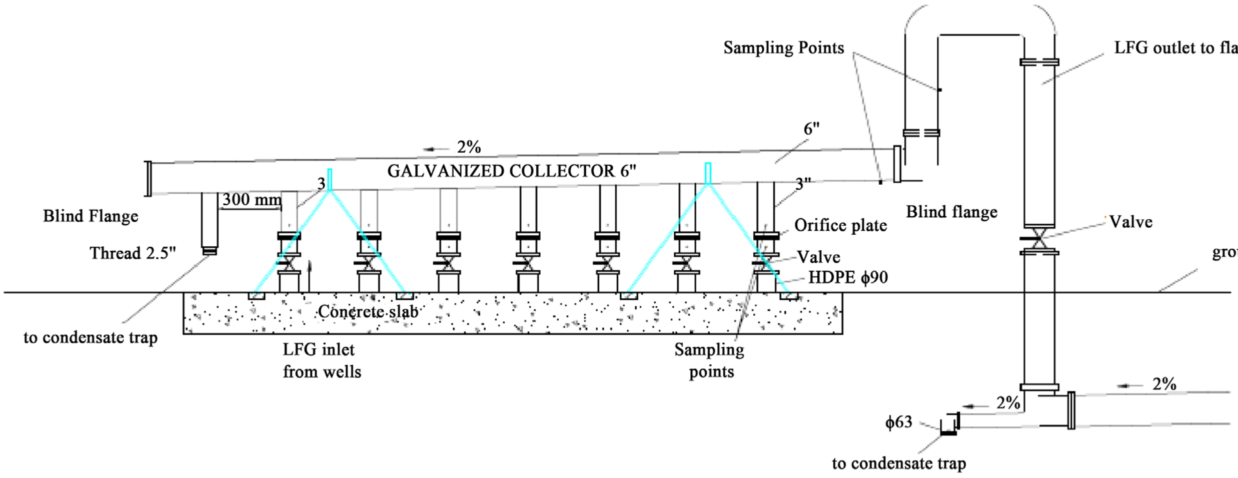

Figure 9. Typical drawing of manifold [1].

wells are installed in various positions. In each well, a pump is installed to pump the leachates from the bottom of the landfill to the surface. The position of all pumps was decided during the construction works and specifically during the drilling of the LFG wells. During the drilling of the LFG wells, the quantities of leachate in the wells were reported so the areas with larger amounts of leachate were identified and in these areas the leachate extraction wells were drilled.

2.4.2. Leachate Recirculation

In recent years, leachate recirculation has found widespread applications and continues to gain acceptance as a viable leachate treatment option. In fact, several full-scale recirculation sites throughout the world, presently are evaluating the performance of various recirculation systems.

These studies and research on leachate recirculation have generally reported benefits to landfill operations including an increased rate of refuse decomposition and landfill stabilization, reduction of leachate strength and associated leachate treatment cost, as well as increased methane gas production.

During the early stages of landfill operation, the leachate contained significant amounts of TDS (total dissolved solids), BOD5 (Biochemical Oxygen Demand), COD, nutrients and heavy metals. COD or Chemical Oxygen Demand is the total measurement of all chemicals (organics & in-organics) in the water and in the wastewater.

BOD is a measure of, the amount of oxygen that requires for the bacteria to degrade the organic components present in water/wastewater.

The ratio of BOD/COD is about; COD is higher than that of BOD; maximum of up to 4 times in medium scale industries; but it varies based on the industrial process and nature of the raw materials used.

When the leachate is recirculated, the constituents are attenuated by the biological activity and by other chemical and physical reactions occurring within the landfill. For example, the simple organic acids present in the leachate are being converted to CH_4 and CO_2. Because of the rise in pH within the landfill when CH_4 is produced, metals are precipitated and retained within the landfill. An additional benefit of leachate recycling is the recovery of landfill gas that contains CH_4. Typically, the rate of gas production is greater in leachate recirculation systems. For the Al Ghabawi landfill, a vertical recirculation system consisted of a number (37 wells) was constructed for the 3 cells (Cell 1 = 11, Cell 2 = 12, Cell 3 = 15). The installation of the wells was conducted by excavating a hole 1.20 min diameter and 3.5 m (below the lowest layer of the top cover) deep in the refuse. A High-density polyethylene (HDPE) pipe of 110 mm was installed in the center of the excavated holes shown in Figure 10.

Gravel backfill is installed to ensure uniform distribution of leachate at the refuse surface. A bentonite seal is installed at the well top to seal the cap against any leachate backup. These vertical systems are connected with a horizontal piping installation, above the top cover ground, which transfers the recirculated leachate from the filtration pond of the leachate treatment plant to the wells. In order to provide the necessary pressure to guide the leachate to the wells, a pumping station was constructed where submersible pumps are installed. This design provides the ability to recirculate leachate to each cell independently (for example recirculate only to cell 1 and not to the other 2 cells) and to control the quantity of recirculated leachate in relation to the produced landfill gas.

2.5. Emergency Leachate Storage Ponds

In order to deal with leachate flowing from the cells on the western border, 4 emergency leachate storage ponds were constructed in the beginning of 2007.

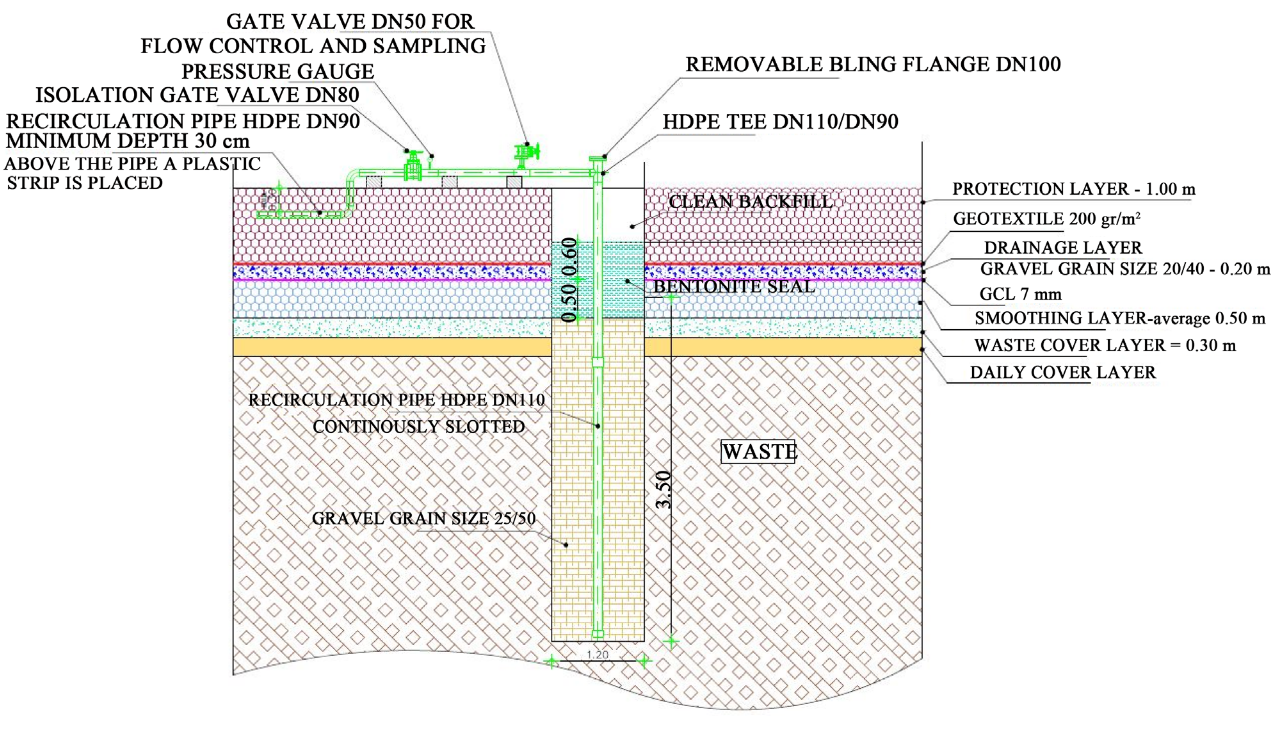

Figure 10. HDPE pipe [1].

For months, only about 60% - 70% of their storage capacity was used, but since December 2007, they are used to their maximum capacity.

Nevertheless, these ponds, shown in Figure 11, have not been constructed in a proper way: collapsing in some parts, one 1 mm HDPE geomembrane with nor GCL or protection geotextile.

Thus, these ponds should be considered only as temporary ponds. In the future, a new leachate treatment plan will be constructed in order to utilize the leachate and produce water for the landfill needs.

2.6. Monitoring LFG Migration and Settlement Measuring

Biogas production inspection is an indivisible section of the safe landfill operation. It must be continued until the produced gas is not a hazard for the surrounding area. For the proper environmental inspection of the landfill, 22 biogas monitoring (detection) boreholes are installed around the landfill outside the cell limits in order to identify the landfill gas migration outside the landfill by measuring the CH_4 concentration at the air inside those boreholes.

Furthermore, 132 settlement markers are installed in all cells in order to measure the settlement of different areas in the landfill on a regular basis. Important Settlements may cause damages at the underground LFG pipes so repair works should be performed

2.7. Production Stages of LFG

Biogas production in a landfill is performed through five more or less distinct stages:

Stage 1: Adjustment stage

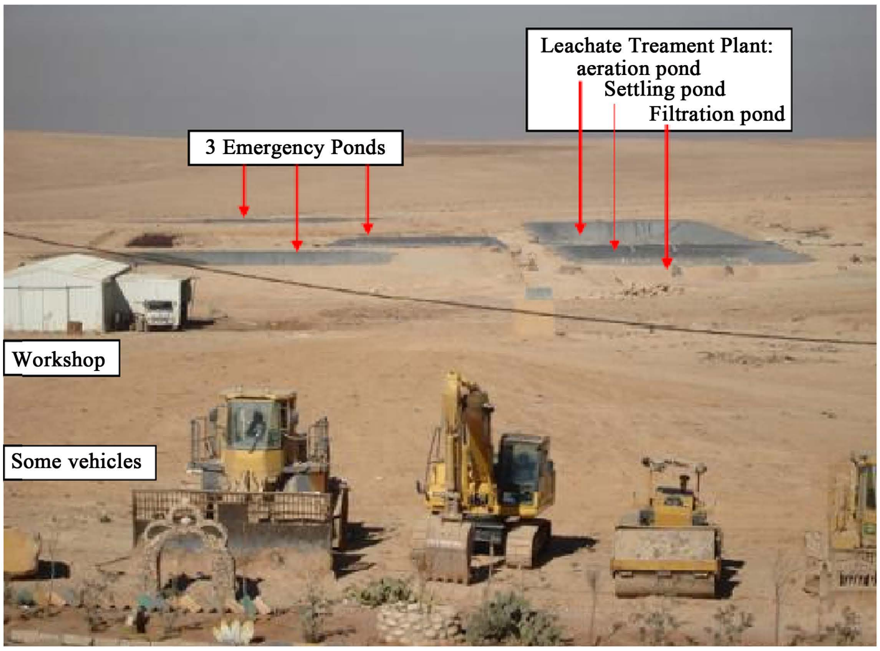

Figure 11. Emergency ponds.

The organic content of wastes is degraded under the effect of microorganisms immediately after being disposed of in the landfill. At this stage, the biological degradation is aerobic, due to the air captured inside the waste mass. The microorganisms causing the anaerobic or aerobic degradation come from the soil, which is used in order to cover the wastes on a daily basis, as well as from the biological sludge if this is made available along with the wastes and finally by the leachate when it re-circulates inside the waste mass.

Stage 2: transition stage

In the second stage, oxygen is consumed and the anaerobic process begins. During the anaerobic process, nitrogen and sulfur are converted to gaseous nitrogen and sulfuric hydrogen respectively by receiving electrons. At this stage, the redox potential is approx. −50 to −100 millivolts. Methane is produced when the redux potential lies between −150 and −300 millivolts. While the reduction of potential continues, the microorganisms responsible for producing methane and carbon dioxide start converting the organic material to organic acids, while reducing further pH.

Stage 3: Acid stage

This stage is characterized by the formation of organic acids and hydrogen gas. The first stage refers to the degradation of organic compounds of large molecular weight into simple ones, which shall be used as a source of energy and carbon for microorganisms. In the second stage, organic acids are formed and pH is significantly reduced. In this stage, carbon dioxide is produced, as well as hydrogen gas. The value of pH of the formed leachate is lower than 5 due to the presence of organic acids. In these conditions, lots of inorganic constituents, and mainly heavy metals are dissolved and removed through leachate, as well as nutrients.

Stage 4: Methane formation stage

This is the stage where methane is formed. Another group of microorganisms converts organic acids and hydrogen to methane and carbon dioxide. These microorganisms are strictly anaerobic (methanogens or methane formers). pH increases in neutral conditions (6.8 - 7); the same occurs in leachate.

Stage 5: Maturation stage

This stage begins when the entire biodegradable material has been converted to CH_4 and CO_2. As moisture enters the waste mass, the organic material that had remained stable starts dissolving. The biogas production rate is low and mainly CH_4 and CO_2, are formed, as well as small quantities of N_2 and O_2.

The duration of each separate stage varies and depends on the quantity of the organic materials disposed of in the landfill, the availability of nutrients, the moisture of the wastes and their compression level.

2.8. Produced Biogas Quantity

The chemical reaction describing biogas production during the anaerobic process can be noted as follows:

$$\text{Organic material} + H_2O \xrightarrow{\text{MICROORGANISMS}} \text{fixed organic material} + CH_4 + CO_2 + \text{other gases}$$

The organic material located in wastes can be divided into the following two categories:

- Material which is immediately degradable (three months to five years) and
- Material that is degraded at a very slow rate (from five to more than 50 years).

The chemical equation describing the degradation of the organic material in order to produce methane and carbon dioxide is the following: Based on the above equation, and by using a different chemical formula for the fast and for the slow biodegrading material, we can calculate through stoichiometry the produced biogas quantity.

Under normal conditions, the degradation rate of wastes, measured by the produced biogas quantity, presents a maximum value in the first two years and then gradually is reduced, continuing, for certain gases, for a time period exceeding 25 years. If moisture does not enter the wastes, in regard to properly compressed wastes, it is not rare to locate materials at their initial condition several years after they have been disposed of.

As mentioned above, a section of the wastes shall be subjected to anaerobic degradation immediately after being disposed of in the landfill, while another section shall start degrading after several years. A similar progress is presented by the biogas production rate, as noted in the following **Figure 12**.

As presented in **Figure 13**, biogas production starts on the second year after disposing of the wastes. It is estimated that biogas production starts approximately at the end of the first year of a landfill's operation and continues for several years after being filled; small quantities can be traced even 20 years after.

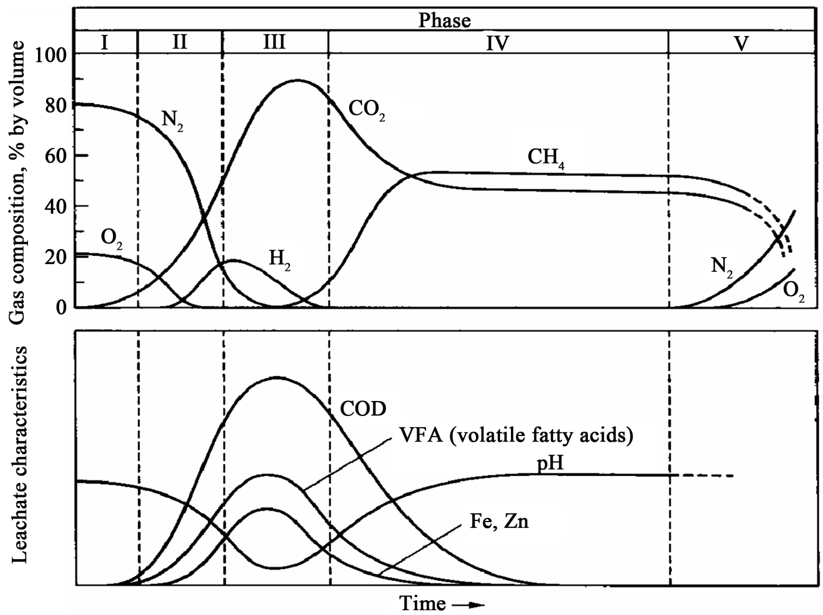

Figure 12. Schematic presentation of biogas production stages. Source: "Integrated Solid Waste Management" G. Tchobanoglous, H. Theisen, S. Vigil [4].

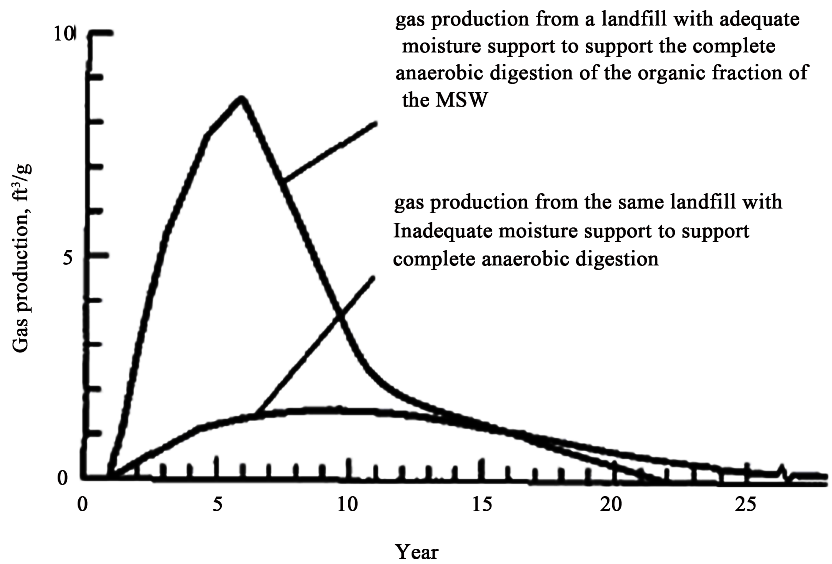

Figure 13. Effect of reduced moisture content of the production of landfill gas. Source: "Integrated Solid Waste Management" G. Tchobanoglous, H. Theisen, S. Vigil [4].

In several cases, waste moisture is not enough in order to complete their anaerobic degradation. The best moisture rate is 50% - 60%. In case of insufficient moisture, the production rate is reduced, resulting in a flatter biogas production curve, expanding to a large time period.

2.9. Landfill Gas Production

The production of LFG is determined from the mass of available carbon (1 mole of carbon produces 1 mole of carbon dioxide or methane). The proportion of carbon dioxide to methane for methanogenic degradation is determined using the ratio of 1%, as described above. The quantity of carbon dioxide and hydrogen generated acetogenically is determined by the equation below.

$$C_6H_{12}O_6 \rightarrow 2CH_3COOH + 4H_2 + 2CO_2$$

Table 4 demonstrates the amount of the LFG produced as well as the projected amount up to the year 2028, from cell 1, 2 and 3. The LFG recovered quantity is the 75% of the estimated produced quantities and it is the amount that is expected to be utilized. This 75% is a correction factor based on the experience of the contractor.

3. Measurements

During my time in the project, I cooperated with two local site engineers. We were in charge of measuring the following parameters:

1) Landfill gas composition, flow, and suction at the flare (completion of Form 1)

These measurements show the quality and quantity of landfill gas that enters the flare. This form is completed daily in order to check if the landfill gas extraction in according to our expectations.

Table 4. Landfill gas produced from cells 1, 2, 3.

	Phase 2 (Cells 1, 2 & 3)				lfg Produced total (m^3/hr)	lfg recovered total (m^3/hr)
	End of year	lfg Produced cell 1 (m^3/hr)	lfg Produced cell 2 (m^3/hr)	lfg Produced cell 3 (m^3/hr)		
1	2011	2333	2091	1120	5544	4158
2	2012	2116	1894	2148	6158	4619
3	2013	1948	1742	2830	6520	4890
4	2014	1779	1593	3285	6657	4993
5	2015	1624	1451	3021	6096	4572
6	2016	1486	1322	2763	5571	4178
7	2017	1344	1208	2516	5068	3801
8	2018	1247	1108	2293	4648	3486
9	2019	1142	1015	2095	4252	3189
10	2020	1044	935	1922	3901	2925
11	2021	955	844	1760	3559	2669
12	2022	892	779	1622	3293	2469
13	2023	845	706	1464	3015	2261
14	2024	797	654	1351	2802	2102
15	2025	735	606	1224	2565	1924
16	2026	710	554	1134	2398	1799
17	2027	669	530	1051	2250	1687
18	2028	635	507	961	2103	1577

2) Landfill gas composition and suction at each manifold (completion of Form 2)

These measurements show the efficient operation of each manifold and we can identify if any problem exists at the manifold.

3) Landfill gas composition, flow, and suction of each well (completion of Form 3)

These measurements show the efficient operation of each well and we can identify if any problem exists at the well.

4) Landfill gas composition, flow, and suction of each well at the well and at the manifold (completion of Form 4).

These measurements allowed us to check everything as in form 3 but also to identify if there is a problem at the horizontal or the vertical LFG network.

5) Leachate level inside the LFG wells (completion of Form 5)

These measurements allow us to measure the leachate level inside the wells in order to decide to pump the leachate with a portable pump or not.

6) Air composition at the monitoring wells (completion of Form 6) in order to identify if any LFG migration exists outside the cell area

7) Elevation of settlement markers (completion of Form 7) in order to check

the settlement of the landfill periodically.

A portable gas analyzer was used for these measurements and also a portable digital manometer that measures suction and differential pressure. From the differential pressure, we were able to calculate the landfill gas flow. Monitoring events should be paired with balancing activities to optimize LFG composition at individual wells and at the manifolds as relevant.

3.1. Collection Field Monitoring and Adjustment

The LFG collection field must be routinely monitored and adjusted to optimize the effectiveness of the collection system. The adjustment of valve settings to reduce or increase LFG flows from low or high generation areas of the landfill is required to maximize LFG collection without overdrawing from those areas of the site that may be susceptible to air intrusion. It should be noted that collection field adjustments must be made based upon a review of history of well or trench performance considered within the context of the overall field operation. Even relatively minor changes to a particular collection point will influence flow and vacuum at other locations within the collection system.

A certain amount of judgment gained from site-specific experience is required when making adjustments to the collection field. If combustible gas readings at a specific well or trench are found to be substantially below the plant gas concentration, then the flow from that well or trench should be reduced. Changes in the valve position (*i.e.*, going from fully open to fully closed) are often counter-productive, as a given well may demonstrate high oxygen/low methane at full vacuum exertion, but reasonable gas quality at some reduced level; this reflects the purpose of well control valves. Smaller changes in valve position are more conducive to effective operations and are most useful when the history of a well relative to LFG quality and valve position are recorded and utilized to guide future balancing activities.

The above mentioned routine inspections are also conducted to characterize the condition of the closure facilities and the LFG collection network to be more precise.

Personnel of the contractor is responsible for conducting the inspection of a list of items and the suggested frequency of the inspections. Typical problems that might be observed are (**Table 5**):

- Odors: blower inoperable, broken gas well pipes;
- High gas readings in monitoring boreholes: failure of impermeable liners/barriers.

Provision for the insertion of a hot-wire anemometer is likely sufficient to yield velocity data if required. Generally, this information is used in field diagnostics if the conventional well field data is not able to identify the cause of an issue. Water/leachate levels in vertical gas extraction wells may also be obtained and can be important where there is a known or suspected perched leachate or leachate mound condition. Interpretation of LFG data must be undertaken with caution where water level readings indicate that the well screen is flooded, as this

Table 5. Accepted operation limits for the major LFG parameters [2].

Parameter	ACCEPTED LFG VALUES		
	Flare	Manifold	Well[1]
CH_4	>40%	>40%	>35%
O_2	<3%	<3%	<7%
Suction Pressure	>-60 mbar	>-100 mbar	>-70 mbar
Recording Form type	1	2	3
Frequency of Measurements	Daily	Weekly[2]	Monthly[3]

suggests that none of the vacuum exerted on the well is being transmitted into the waste to draw LFG (*i.e.*, no variance in pressure on either side of the control valve). This condition is often difficult to correct, as it requires an evaluation of the leachate and surface water control systems. In some cases, inserting pumps into LFG extraction wells can reduce liquid levels, but if the liquid is associated with a leachate mound, it is unlikely that single pumps will influence the liquid profile. In addition, biogas shall be measured in the manifolds of the collection - transfer network, placed inside the wastes.

The following measurements are going to be performed on the manifolds:

- Pressure (suction) measurement;
- detection of concentrations of methane, carbon dioxide, and oxygen.

3.2. Limit Levels and Action Plan for LFG Network

The above performance standard is not meant to be restrictive. In some cases, especially where a utilization system is in place, it may be necessary to monitor and balance on a much more frequent basis, particularly if the LFG management system is large. Daily monitoring and balancing are not uncommon at large landfills. Additionally, LFG quality and flow can be subject to a number of meteorological conditions, one of which is atmospheric pressure. It has been observed that rapid changes in atmospheric pressure can affect LFG composition and flow. For utilization systems, however, monitoring and balancing may need to respond to changes in atmospheric pressure, or even anticipate such changes by providing adjustments to well field valve settings before the pressure front arrives. There are a number of additional reasons for monitoring and balancing on a more frequent basis, and thus the performance standard for monitoring frequency should be seen as a minimum requirement. Monitoring at each collection point should begin with the measurement of vacuum pressure. A portable gas meter is then used to measure methane and oxygen composition. As good monitoring practice, combustible gas readings should not be taken until after the pressure measurements, due to the possibility of interference with pressures by the action of extracting the gas sample. If required, water/leachate levels should be taken after all gas measurements are completed, as this monitoring may require opening the LFG extraction well cap. The following Table presents a simple diagnostic tool to highlight some common problems in the operation of the LFG collection and utilization facilities and their recommended actions. Table 6

Table 6. Non accepted measurements and how to treat them.

Non accepted measured parameter		$CH_4 < 35\%$
Checked Values	**Diagnosis**	**Recommended Actions**
Same recorded values of CH_4, O_2 and suction pressure for both well and manifold	There is none problem with the LFG horizontal network. The problem is identified on LFG well	• STEP 1: Measurement of the leachate level at the LFG Well and check if the level is high (<15 m). • STEP 2: Isolation of the well from the LFG system in the case of high leachate level • STEP 3: Extract the leachate through a portable pump. The pumped leachate is transported to the wastewater treatment plant by a tanker truck. • STEP 4: This procedure of above step should be repeated until the successful leachate level drop • STEP 5: Measure the leachate level from the isolated well after three days • STEP 6: If the leachate level is accepted, the isolated well is connected again to the LFG system (through the valve at the manifold). We repeat the level measure after three days • STEP 7a: if the CH_4 is lower than 35% and leachate level is rising up again (<15 m) then we repeat the above-mentioned steps as many times as required • STEP 7b: if the CH_4 is lower than 35% and leachate level is accepted then we isolate again the well from the LFG network and repeat the measure after 15 days
• The CH_4 concentration at well is higher than to the manifold • The O_2 concentration at well is lower than to the manifold • The suction pressure at manifold is lower than to the well	The horizontal LFG network either is blocked by condensate or is partly damaged	• STEP 1: Blowing air to the network after wellhead opened • STEP 2: Repeat the suction pressure measurement after few minutes. If the problem continues to exist then we proceed to the horizontal LFG network problematic branch repair
• The CH_4 concentration at well is higher than to the manifold • The O_2 concentration at well is lower than to the manifold • The suction pressure at manifold is equal with this at the well	The problem is on horizontal LFG network	Repair the problematic branch of the horizontal LFG network
• The CH_4 concentration at manifold is equal with this at the well • The O_2 concentration at manifold is equal with this at the well • The suction pressure at manifold is different to this at the well	The problem is on horizontal LFG network	• STEP 1: Blowing air to the network after wellhead opened • STEP 2: Repeat the suction pressure measurement after few minutes. If the problem continues to exist then we proceed to the horizontal LFG network problematic branch repair
Non accepted measured parameter		**$O_2 > 7\%$**
Checked Values	**Diagnosis**	**Recommended Actions**
Same recorded values of CH_4, O_2 and suction pressure for both well and manifold	There is none problem with the LFG horizontal network. The problem is identified on LFG well	• STEP 1: Measurement of the leachate level at the LFG Well and check if the level is high (<15 m). • STEP 2: Isolation of the well from the LFG system in the case of high leachate level • STEP 3: Extract the leachate through a portable pump. The pumped leachate is transported to the wastewater treatment plant by a tanker truck. • STEP 4: This procedure of above step should be repeated until the successful leachate level drop • STEP 5: Measure the leachate level from the isolated well after three days • STEP 6: If the leachate level is accepted, the isolated well is connected again to the LFG system (through the valve at the manifold). We repeat the level measure after three days • STEP 7a: if the O_2 is higher than 7% and leachate level is rising up again (<15 m) then we repeat the above-mentioned steps as many times as required • STEP 7b: if the O_2 is higher than 7% and leachate level is accepted then we isolate again the well from the LFG network and repeat the measure after 15 days

Continued

• The O_2 concentration at well is higher than to the manifold • The CH_4 concentration at well is lower than to the manifold • The suction pressure at manifold is lower than to the well	The horizontal LFG network either is blocked by condensate or is partly damaged	• STEP 1: Blowing air to the network after wellhead opened • STEP 2: Repeat the suction pressure measurement after few minutes. If the problem continues to exist then we proceed to the horizontal LFG network problematic branch repair
• The O_2 concentration at well is higher than to the manifold • The CH_4 concentration at well is lower than to the manifold • The suction pressure at manifold is equal with this at the well	The problem is on horizontal LFG network	Repair the problematic branch of the horizontal LFG network
• The O_2 concentration at manifold is equal with this at the well • The CH_4 concentration at manifold is equal with this at the well • The suction pressure at manifold is different to this at the well	The problem is on horizontal LFG network	• STEP 1: Blowing air to the network after wellhead opened • STEP 2: Repeat the suction pressure measurement after few minutes. If the problem continues to exist then we proceed to the horizontal LFG network problematic branch repair

Non accepted measured parameter		Different measured Suction Pressure
Checked Values	**Diagnosis**	**Recommended Actions**
The suction pressure at manifold is lower than to the well	The horizontal LFG network either is blocked by condensate or is partly damaged	• STEP 1: Blowing air to the network after wellhead opened • STEP 2: Repeat the suction pressure measurement after few minutes. If the problem continues to exist then we proceed to the horizontal LFG network problematic branch repair

below describes some common LFG issues that occur in a landfill and how they can be repaired.

3.3. LFG Migration Assessment and Control

It is expected that the implementation of efficient, well-operated LFG management systems will in many cases address concerns regarding LFG migration through subsurface soils. Nevertheless, it is important to evaluate potential for migration through completion of a migration assessment and then to provide adequate controls if the LFG management system is not sufficiently protective of on or off-site migration issues. Field activities for migration assessments typically include the installation of gas probes along the perimeter of the landfill. Perimeter gas probes are used to monitor LFG migration beyond the waste discharge area typically at or near the property line or nearby structures.

These perimeter probes mentioned in Table 7 are usually permanent installations for ongoing monitoring. Field activities for migration assessments typically include the installation of gas probes along the perimeter of the landfill. Perimeter gas probes are used to monitor LFG migration beyond the waste discharge area typically at or near the property line or nearby structures. These perimeter probes are usually permanent installations for ongoing monitoring. An LFG

Table 7. Dangerous gas percentage and actions to prevent consequences.

Parameter	Limit Level	Action
Methane (CH_4)	>0.5% v/v (or >10% LEL)	1) Prohibit smoking, all fires, and naked flames. 2) Post warning signs. 3) Increase ventilation to lower the methane to less than 0.5% v/v.
	>1% v/v (or >20% LEL)	1) Stop all the construction activities in the affected area. 2) Evacuate personnel who are working in the affected area. 3) Prohibit entry to the affected area. 4) Increase ventilation to lower the methane level to less than 0.5% v/v
Carbon Dioxide (CO_2)	>0.5% v/v	1) Increase ventilation to lower the CO_2 level to less than 0.5% v/v
	>1.5%	1) Extinguish all fires and naked flames. 2) Stop all the construction works in the affected are. 3) Evacuate personnel in the affected area 4) Prohibit entry to the affected area 5) Increase ventilation to lower the CO_2 level to less than 0.5% v/v
Oxygen (O_2)	≤18% v/v	1) Stop all the construction activities in the affected area. 2) Evacuate personnel in the affected area. 3) Prohibit entry to affected area. 4) Increase ventilation to increase the oxygen level to above 18% v/v

migration assessment should be completed by a Qualified Professional to identify potential risk and pathways of the LFG prior to installation of any monitoring probes. The perimeter gas probes should be monitored for combustible gas content and probe gauge pressure on a regular basis. Water levels within probes installed near the water table or in areas of perched water tables should be monitored to determine seasonal fluctuations in the water table at each location. It is expected that correctly installed gas probes should generally remain dry, but a varying water table surrounding the site may cause periodic flooding of some probes. Interpretation of soil gas data from flooded probes must be undertaken with great care, as LFG composition data is generally meaningless if the soil probe screen does not have access to soil gas. Immediately following each monitoring event, the data collected should be reviewed. The objectives of the review are:

- Verify unusual and/or erroneous readings,
- Identify problems and, if necessary, initiate remedial action (*i.e.*, repair damaged,
- Probes, calibrate or repair equipment, etc.),
- Bring to the attention of the individuals responsible for detailed assessment and,
- Contingency plans, those readings that may indicate gas presence,
- Identify the occurrence of LFG migration,
- Develop any remedial actions that are warranted,
- Assess the effectiveness of any actions that may have been taken.

A more detailed evaluation of the data should be performed on an annual basis and should include an analysis of all prior readings for trends. This analysis is an important tool in anticipating the occurrence of migration and assessing the effectiveness of any remedial measures taken. Where an active LFG management system is present in the landfill, the performance of this system should be evaluated against monitoring data related to probe data. Optimization of the LFG management system may be required to address ongoing migration concerns. Note that analysis of monitoring data from perimeter probes is complex and must consider not only the monitoring results but also must take into account the following:

- Barometric pressure (may be incorporated into routine LFG collection field
- monitoring and/or tracked daily),
- Frost conditions,
- Soil stratigraphy,
- Hydrogeology,
- Status of LFG controls (if applicable).

The detection of combustible gas in the soil constitutes evidence of migration; the confluence of combustible gas with high-pressure readings indicates a situation where this combustible gas is migrating with a driving force beyond that of simple diffusion. Gauge pressures that are consistently positive in probes where combustible gas is detected give an indication of the magnitude of the force behind the migration. Gradients of combustible gas concentrations may be helpful in indicating the extent, range, and direction of migration. However, interpretation of concentration gradients may be complicated by physical and/or chemical processes acting upon the gases as they move through the soil. As indicated previously in this Guideline, such processes may have a preferential effect on some LFG constituents over others; specifically, the carbon dioxide component of LFG may be stripped into soil water over extended migration lengths, resulting in a proportionately-higher concentration of methane per unit volume. Soil gas concentrations at the property boundary should not exceed the lower explosive limit of methane (5 percent by volume). If greater than 5 percent by volume of methane is measured at the property boundary, an additional assessment must be conducted as soon as possible to assess the potential issues that may arise from LFG migration. Additional monitoring of the probes may be warranted, as well as residential monitoring if LFG migration is suspected in residential areas around the landfill.

The measurements of LFG migration are executed one per month and the following table shows the analysis of the measurements and the necessary actions that need to take place.

3.4. Measurement Process and Results

As it was mentioned before, the LFG measurements reveal to us whether the project is efficient or not. The contractor has given to us, the engineers, certain forms that we have to fill during the measurements. These forms are in excel format after they are filled with the collected data they are sent to the project manager in order to be analyzed that will reveal what the future actions for the project will be. The forms are seven and are completed for each cell. The measurements for each cell indicate whether there is an issue with the wells and the manifolds. The accepted measurements for methane and oxygen percentages have been mentioned Table 5 and Table 6. In case the measurements reveal a problem with the wells/manifolds the engineers will proceed to solve the problem using certain techniques.

Below is a sample of each form (**Appendix**).

4. Conclusions

Waste to energy facilities has been increasing in number throughout the world as a solution to the problems societies have trying to manage enormous amounts of waste in the most environmentally friendly way possible. Although landfills are not the most effective and environmentally friendly method of waste treatment, many landfills exist around the world. These existing landfills give us the opportunity to take advantage of huge amounts of methane gas with high energy potential. The energy utilization of the landfill gas is crucial for the environment and for the society and as a result, the contractors try to ensure that the efficiency of the project is the highest possible. This can be achieved through many techniques that target to minimize the existence of leachate. These techniques have various benefits to landfill operations including an increased rate of refuse decomposition and landfill stabilization, reduction of leachate strength and associated leachate treatment cost, as well as increased methane gas production. Maximizing the production of biogas, we increase the potential energy that can be produced to provide the community with electricity and other forms of energy that improve the well-being of the people. In a world that the population keeps increasing along with the energy demands, finding new energy sources that serve the needs of the people and are also environmentally friendly, is something crucial.

It is certain that the more popular the method of producing energy from landfill gas gets, more research will be conducted on the subject and waste to energy projects will become even more efficient.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Form 1. Daily report of boosting and flaring system.

Day	Time	Blower	CH_4 (%)	O_2 (%)	Wells in Operation	Suction (-mbar)	Flow (m^3/hr)
1/6	7:00	2	56	0.5	492	10	1341
2/6	7:00	2	55	0.6	492	15	1557
3/6	9:10	2	58	0.3	492	11	1548
4/6	7:00	2	55	0.6	492	13	1569
5/6	7:00	2	55	0.6	492	13	1558
6/6	7:00	2	55	0.6	492	13	1554
7/6	10:00	2	58	0.4	492	11	1534
8/6	7:00	2	55	0.6	492	13	1505
9/6	7:00	2	55	0.6	492	13	1519
10/6	7:00	2	55	0.6	492	13	1497
11/6	7:00	2	55	0.5	492	13	1503
12/6	7:30	2	55	0.6	492	14	1523
13/6	7:00	2	55	0.5	492	14	1503
14/6	7:30	2	55	0.6	492	14	1523
15/6	9:00	2	55	0.6	492	13	1516
16/6	7:30	2	55	0.6	492	14	1528
17/6	8:00	2	55	0.6	492	13	1559
18/6	7:00	2	55	0.7	492	13	1511
19/6	7:30	2	55	0.7	492	13	1508
20/6	7:30	2	54	0.7	492	13	1521
21/6	7:30	2	54	0.7	492	13	1520
22/6	8:30	2	54	0.7	492	14	1546
23/6	7:00	2	55	0.6	492	13	1566
24/6	7:30	2	54	0.7	492	14	1547
25/6	7:00	2	54	0.7	492	14	1546
26/6	7:00	2	54	0.7	492	13	1533
27/6	7:00	2	54	0.7	492	13	1546
28/6	7:00	2	54	0.7	492	14	1531
29/6	7:00	2	54	0.7	492	14	1550
30/6	7:00	2	54	0.7	492	14	1624

Form 2. All cells manifold collector gas report.

MANIFOLD	DATE: 12/6/2017		SUCTION (-mbar)	WELLS IN OPERATION	TOTAL WELLS
	CH_4 (%)	O_2 (%)			
			CELL 1		
PH2M1	47.6	0.9	−4.2	15	16
PH2M2	54.9	0.7	−4.9	16	16
PH2M3	48.7	1.6	−5.1	16	16
PH2M4	55.0	0.2	−5.5	11	11
PH2M5	55.0	0.4	−5.4	15	16
PH2M6	45.6	1.8	−5.5	10	14
PH2M7	55.6	0.4	−5.4	16	16
PH2M8	49.2	1.6	−5.2	12	12
PH2M9	54.1	0.3	−5.3	12	12
PH2M10	54.5	0.5	−5.5	16	16
PH2M11	52.9	0.9	−5.6	11	16
PH2M12	53.4	0.8	−5.3	14	14
PH2M13	54.8	0.3	−5.3	13	13
			CELL 2		
PH1M1	54.2	0.5	−4.6	12	17
PH1M2	57.5	0.2	−4.7	15	16
PH1M3	53.4	0.7	−4.6	11	14
PH1M4	55.1	0.3	−4.7	13	14
PH1M5	55.2	0.4	−4.7	15	16
PH1M6	55.1	0.4	−4.7	12	17
PH1M7	55.5	0.5	−4.5	15	18
PH1M8	58.2	0.3	−4.8	9	10
PH1M9	54.1	0.9	−4.6	12	14
PH1M10	61.2	0.0	−5.1	13	15
PH1M11	58.9	0.0	−4.7	3	12
			CELL 3		
PH3M1	53.6	0.5	−4.2	13	13
PH3M2	55.3	0.1	−4.0	9	9
PH3M3	54.7	0.2	−4.3	9	9
PH3M4	52.5	1.4	−4.3	11	14
PH3M5	53.4	0.2	−4.7	11	12
PH3M6	56.1	0.8	−4.4	16	16
PH3M7	55.1	0.6	−4.6	8	9
PH3M8	55.6	0.5	−4.5	9	9
PH3M9	55.4	0.5	−4.0	16	16
PH3M10	54.6	0.8	−4.6	13	14
PH3M11	55.6	0.4	−4.5	15	15
PH3M12	55.8	0.2	−4.4	12	13
PH3M13	55.1	0.4	−4.5	14	14
PH3M14	54.2	0.8	−4.4	17	17
PH3M17	53.4	0.7	−4.6	12	12
TOTAL				**492**	**543**

Form 3. Cell 1: Manifold lines gas report.

MANIFOLD: M 12					
DATE: 21/6/2017					
WELL	**CH_4 %(MAN)**	**O_2% (MAN)**	**DP**	**FLOW**	**COMMENTS**
168	53.2	0.3	0.1	2.5	
157	54.8	0.0	1.9	11.0	
169	54.5	0.0	0.2	3.6	
182	54.6	0.0	0.2	3.6	
170	54.5	0.0	0.1	2.5	
183	54.3	0.9	0.1	2.5	
158	55.1	0.0	1.1	8.4	
171	53.1	0.3	0.1	2.5	
184	50.6	1.1	0.3	4.4	
172	54.8	0.4	0.2	3.6	
159	54.6	0.0	1.9	11.0	
160	46.4	2.8	4.4	16.8	High O_2 to be checked
147	52.8	0.8	0.9	7.6	
146	47.8	2.7	4.2	16.4	High O_2 to be checked
TOTAL	53.4	0.8	−9.9	96.4	

SUMMARISED TABLE CELL 1						
MANIFOLD	**CH_4**	**O_2**	**SUCTION**	**TOTAL**	**OPERATION**	**FLOW**
M1	47.6	0.9	−6.4	16	15	121.50
M2	54.9	0.7	−9.1	16	16	133.32
M3	48.7	1.6	−9.3	16	16	91.48
M4	55.0	0.2	−9.1	11	11	50.10
M5	55.0	0.4	−9.8	16	15	77.74
M6	45.6	1.8	−6.7	14	10	62.61
M7	55.6	0.4	−9.6	16	16	162.15
M8	49.2	1.6	−9.9	12	12	89.49
M9	54.1	0.3	−9.9	12	12	57.14
M10	54.5	0.5	−9.8	16	16	56.70
M11	52.9	0.9	−9.9	16	11	50.78
M12	53.4	0.8	−9.9	14	14	96.44
M13	54.8	0.3	−9.9	13	13	43.56
TOTAL				**188**	**177**	**1093.02**

Form 4. Cell 2: Manifold lines and wells gas report.

MANIFOLD: M 3									
DATE: 14/6/2017									
Well	Ch_4 % (man)	O_2 % (man)	Ch_4 % (well)	O_2 % (well)	Suction (man)	Suction (well)	Dp	Flow (m^3/hr)	Comments
55	58.1	0.0	61.7	0.0	−19.3	−1.0	0.2	3.6	
47	55.8	0.4	64.0	0.0	−19.5	−2.0	0.3	4.4	
46	58.7	0.5	58.8	0.0	−19.5	−0.5	0.1	2.5	
38	56.7	0.5	57.7	0.0	−19.1	−6.0	0.1	2.5	
37	61.1	0.0	61.7	0.0	−19.4	−4.0	0.2	3.6	
36	56.6	0.3	57.8	0.0	−10.2	−3.4	9.7	24.9	
35	56.9	0.3	55.1	0.4	−1.5	0.0	18.9	34.8	A lot of leachate. To be pumped
45	46.1	1.5	51.4	0.8	−19.6	−18.6	0.2	3.6	
34	49.7	1.1	52.0	0.7	−19.7	−16.0	0.1	2.5	
23	60.8	0.5	59.5	0.3	−19.2	−18.7	0.2	3.6	
44	56.7	0.0	56.2	0.0	−6.6	positive	0.0	0.0	No flow. Blow horizontal network
33	32.6	7.5	53.8	0.0	−18.8	positive	0.0	0.0	Damaged pipe. To be repaired
43	60.5	0.0	63.9	0.0	−18.8	0.0	0.0	0.0	A lot of leachate. To be pumped
54	60.7	0.0	60.0	0.0	−18.7	−16.6	0.1	2.5	
TOTAL	53.4	0.7			−11.0			88.5	

SUMMARIZED TABLE						
Manifold	Ch_4	O_2	Suction	Wells		Flow
				Total	Operation	
M1	54.2	0.5	−11.1	16	12	101.38
M2	57.5	0.2	−11.9	16	15	68.21
M3	53.4	0.7	−11.0	14	11	88.51
M4	55.1	0.3	−10.5	14	13	128.63
M5	55.2	0.4	−8.1	17	15	98.51
M6	55.1	0.4	−7.9	13	12	142.82
M7	55.5	0.5	−10.7	17	15	219.45
M8	58.2	0.3	−9.3	9	9	29.99
M9	54.1	0.9	−10.7	14	12	67.20
M10	61.2	0.0	−17.0	15	13	63.53
M11	58.9	0.0	−11.3	12	3	15.10
TOTAL				**157**	**130**	**1023.32**

Form 5. Cell 2: Leachate level measurements into lfg wells (measures from ground).

DATE: MARCH 2017					
Well	**Final well depth**	**Leachate level (m)**	**Well (w)**	**Final well depth**	**Leachate level (m)**
1	15.10	5	81	29.90	11.0
2	13.90	full leachate	82	30.10	11.0
3	13.90	full leachate	83	30.10	12.0
3A		6	84	30.10	11.0
4	15.20	2	85	30.10	10.0
5	17.10	full leachate	86	30.10	4.0
6	18.00	5	86A	30.00	14.0
7	18.00	full leachate	87	30.10	13.0
8	18.00	5(MUD)	88	30.10	13.0
9	17.50	6	89	30.10	9.0
10	16.30	6	90	29.90	13.0
11	16.30	full leachate	91	29.90	12.0
12	17.00	4	92	29.80	12.0
13	21.40	4	93	29.90	6.0
13A	21.00	5	93A	30.00	11.0
14	20.60	7	94	30.10	11.0
15	20.70	3	95	30.10	11.0
16	21.60	6	96	30.10	11.0
17	23.60	9	97	30.00	13.0
18	24.20	9	98	29.90	7.0
19	24.00	9	98A	30.00	15.0
20	23.80	7	99	29.80	13.0
21	22.60	3	100	29.80	13.0
22	22.70	3	101	30.00	11.0
23	28.00	12	102	29.00	11.0
24	26.80	12	103	30.00	11.0
25	26.30	12	104	29.90	11.0
26	26.30	12	105	29.80	11.0
26A	26.00	12	106	29.90	11.0
27	27.70	13	106	29.80	11.0
28	29.30	14	107	30.10	12.0
29	29.20	14	108	30.00	11.0
30	29.30	14	109	29.70	13.0
31	28.90	14	110	29.00	14.0
32	29.30	14	111	23.70	full leachate

Continued

33	27.00	3	112	28.00	8.0
33A	27.00	7	113	27.90	8.0
34	27.80	12	114	27.30	9.0
35	29.50	13	115	28.70	9.0
36	29.40	5	116	29.00	9.0
36A	30.00	14	117	29.30	9.0
37	29.20	14	118	30.00	10.0
38	29.30	12	119	29.10	11.0
39	29.50	12	120	29.90	10.0
40	27.50	10	121	29.10	11.0
41	29.20	13	122	23.20	full leachate
42	29.30	12	123	22.80	full leachate
43	29.50	2	124	22.30	full leachate
44	29.20	5	125	22.30	full leachate
44A	29.00	13	126	25.20	full leachate
45	26.90	9	127	26.40	full leachate
46	29.70	9	128	27.00	full leachate
47	29.60	9	129	27.50	full leachate
48	29.70	9	130	27.00	3.0
49	29.40	9	130A	27.00	9.0
50	30.00	9	131	26.80	7.0
51	29.80	10	132	25.50	4.0
52	30.00	16	133	13.10	full leachate
53	30.10	2	134	17.70	full leachate
54	22.50	5	135	16.50	3.0
55	30.10	12	136	17.90	full leachate
56	30.20	6	137	19.00	full leachate
56A	30.00	14	138	20.20	full leachate
57	30.10	6	139	21.00	full leachate
58	30.00	5	140	21.70	full leachate
58A	30.00	13	141	21.40	6.0
59	30.10	10	142	21.10	6.0
60	30.10	10	143	20.50	6.0
61	29.60	10	144	19.00	full leachate
62	30.10	10	145	14.50	full leachate
63	30.10	4	146	12.80	full leachate
63A	30.00	13	147	12.40	full leachate

Continued

64	30.00	13	148	11.80	full leachate
65	30.10	13	149	12.60	full leachate
66	30.10	13	150	13.50	full leachate
67	30.10	13	151	14.80	full leachate
68	30.10	5	152	14.30	borders 2 & 4
68A	30.00	12	153	14.50	borders 2 & 4
69	30.10	9	154	15.00	borders 2 & 4
70	30.10	8	155	15.60	borders 2 & 4
71	29.40	8	156	16.00	borders 2 & 4
72	29.00	9			
73	27.00	8			
74	25.60	9			
75	29.60	7			
76	29.70	13			
77	29.40	7			
77A	29.00	15			
78	29.50	5			
79	30.00	5			
80	29.90	5			
80A	30.00	11			

Form 6. Cell 2: Settlement markers coordinates.

Cell 2	Marker		Northing (y)	DECEMBER 2016	MARCH 2017	JUNE 2017
				Elevation(z)	Elevation(z)	Elevation(z)
PH1M	1	262,296.4919	149,556.1337	797.35	799.50	799.454
PH1M	2	262,333.8712	149,556.1347	796.93	796.78	796.75
PH1M	3	262,383.8534	149,556.1328	796.93	796.74	796.722
PH1M	4	262,433.8627	149,556.1319	799.46	799.27	799.219
PH1M	5	262,483.8767	149,556.1337	800.20	800.02	800.004
PH1M	6	262,533.8718	149,556.1397	800.09	799.93	799.902
PH1M	7	262,581.6487	149,556.1346	798.47	800.10	800.015
PH1M	8	262,298.9330	149,506.8580	809.45	809.25	809.176
PH1M	9	262,333.8620	149,505.3370	808.86	808.63	808.563
PH1M	10	262,384.1490	149,506.1240	810.13	809.90	809.834
PH1M	11	262,433.7740	149,506.1890	812.48	812.26	812.161
PH1M	12	262,482.5820	149,506.1930	813.80	813.54	813.444
PH1M	13	262,533.5350	149,506.4400	812.77	812.54	812.455
PH1M	14	262,298.2400	149,454.8810	815.54	815.28	815.162

Continued

PH1M	15	262,333.8380	149,456.4190	815.86	815.58	815.47
PH1M	16	262,384.0470	149,454.9830	817.19	816.94	816.834
PH1M	17	262,433.8700	149,456.4430	818.43	818.20	818.112
PH1M	18	262,484.0200	149,456.3170	818.22	817.98	817.874
PH1M	19	262,533.8770	149,456.1621	816.77	816.52	816.517,,
PH1M	20	262,297.8220	149,406.9580	817.28	817.19	817.111
PH1M	21	262,333.7800	149,406.4090	816.97	816.81	816.684
PH1M	22	262,383.8450	149,406.3490	818.75	818.66	818.572
PH1M	23	262,433.8810	149,405.7540	819.73	819.62	819.563
PH1M	24	262,484.0470	149,406.2910	819.38	819.29	819.243
PH1M	25	262,533.7670	149,406.0870	818.32	818.21	818.157
PH1M	26	262,294.3660	149,355.6820	817.00	816.40	816.299
PH1M	27	262,334.0770	149,356.0550	816.53	816.45	816.343
PH1M	28	262,383.9060	149,356.3680	817.95	817.86	817.748
PH1M	29	262,433.7780	149,356.3260	818.80	818.77	818.644
PH1M	30	262,484.1810	149,356.0420	818.54	818.46	818.363
PH1M	31	262,533.9570	149,356.0050	818.29	818.22	818.158
PH1M	32	262,296.2570	149,306.2000	811.82	811.76	811.703
PH1M	33	262,333.8170	149,306.0580	811.93	811.86	811.804
PH1M	34	262,383.9240	149,305.7380	812.37	812.32	812.245
PH1M	35	262,433.7510	149,306.2580	815.97	815.88	815.814
PH1M	36	262,483.7650	149,306.1010	816.60	816.52	816.446
PH1M	37	262,533.8490	149,305.7790	816.79	816.73	816.654
PH1M	38	262,295.8080	149,255.8590	803.44	803.66	803.578
PH1M	39	262,334.1190	149,256.2070	803.30	803.26	803.203
PH1M	40	262,383.6720	149,256.0760	803.73	803.72	803.654
PH1M	41	262,433.7010	149,256.0670	805.52	805.48	805.438
PH1M	42	262,483.9150	149,255.8330	806.95	806.93	806.846
PH1M	43	262,533.5050	149,255.6670	806.45	806.42	REMOVED
PH1M	44	262,584.2240	149,256.1500	805.02	BROKEN	REMOVED