Pertanika J. Sci. & Technol. 3(2): 311-323 (1995)

ISSN:0128-7680

Methane Gas Production from a Landfill Model under Saturated Conditions

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Received 30 March 1994

ABSTRAK

Satu eksperimen telah dijalankan di makmal bagi mengkaji penghasilan dan pengeluaran gas metana dari tapak pelupusan sisa secara perisian tanah yang tepu dengan air. Untuk kajian ini, satu silinder PVC berukuran 4 m panjang dan berdiameter 20 cm telah digunakan sebagai model untuk simulasi sel-sel perisian tanah setebal 2.5 m di tapak pelupusan bertanah berpasir. Tanah pasir yang sama juga telah digunakan sebagai bahan kambus. Operasi model tersebut dilakukan selama 30 bulan di mana pada 24 bulan yang pertama tiada mobilisasi cecair luluh lesap. Ini diikuti dengan mobilisasi cecair luluh lesap selama 6 bulan terakhir. Dalam tempoh ini, cecair luluh lesap dari lapisan sisa pepejal sebanyak 1.40 isipadu rongga telah dilalukan ke dalam lapisan pasir dan kelikir yang terdapat di bahagian bawah. Pengeluaran gas dari model tersebut dalam tempoh 24 bulan pertama ialah 22 ml/hari/kg berat basah sisa pepejal. Ia mengandungi 55% metana. Kadar purata pengeluaran gas tersebut meningkat kepada 77 ml/hari/kg berat basah sisa pepejal semasa mobilisasi cecair luluh lesap dilakukan dengan kadar aliran 1.6 cm/hari. Penapaian metana berlaku di dalam lapisan pasir tersebut tetapi ianya tidak berlaku di dalam lapisan sisa pepejal kerana pH yang rendah (5.3) disebabkan oleh nilai COD yang tinggi iaitu kira-kira 30,000 mg/l.

ABSTRACT

A laboratory experiment was conducted to examine methane gas production from landfills under saturated moisture conditions. A landfill model was constructed from a 4-m PVC cylinder of 20 cm internal diameter, to simulate municipal landfill cells of 2.5 m thickness on sandy soils. The same soil was used as the cover material. The landfill was operated over a period of 30 months, for the first 24 months without leachate mobilization and the last 6 months with leachate mobilization. A total of 1.40 pore volume of leachate from the solid waste layer was mobilized into the underlying sand and pebble layers during the last 6 months. Gas production from the landfill during the first 24 months was 22 ml/day/kg wet weight of solid waste. It contained 55% methane. The rate of production increased, to an average of 77 ml/day/kg wet weight of solid waste, during leachate mobilization operation at a flow rate of 1.6 cm/day. Methane fermentation took place in the underlying sand layer but not in the middle of the solid waste layer because the pH in the solid waste layer was too low (5.3) associated with a very high COD of about 30,000 mg/l.

Keywords: methane, landfill, lysimeter, leachate, solid waste

INTRODUCTION

Previous reported works on landfill simulation studies or lysimeter studies were primarily based on moisture contents which were at field capacity or below (Ham and Bookter 1982). In practice, however, many refuse disposal sites are situated below groundwater level and therefore it is necessary to examine processes under saturated moisture conditions.

This paper presents the findings of an experiment that was designed to study the characteristics of gas production by a laboratory landfill under saturated moisture conditions.

MATERIALS AND METHODS

A laboratory landfill model was constructed from a PVC column with dimensions 4 m in height and 20 cm in internal diameter (*Fig. 1*). In order to facilitate packing operations, the column was divided into four sections of 1 m each. These four sections were assembled after packing one by one from the bottom upwards by using flanges. Rubber gaskets were used for sealing the gaps between the flanges.

This landfill model was equipped with temperature probes and leachate sampling devices at different heights of the column, and facilities for measurement of pH, Eh, and gas production. One opening was also provided at the bottom of the model for the drainage and sampling of the leachate. Two openings were made in the top cover, one with a slightly lower projection tube for the input water, and the other one for a gas outlet. Two 31-litre water tanks, one at a level higher than the top of the landfill model and the other at lower level, were used for feeding water into the landfill model. Both were connected to a pump; the lower tank was used for feeding the higher tank, and the higher tank was used for feeding the landfill.

The packing of the landfill was carried out in the following order:

Bottom Layer of Crushed Quartz

The bottom part of the landfill was packed with crushed quartz, of average 1-cm diameter, to a depth of approximately 10 cm. Above this, coarse sand (retained by sieves of 1.7 mm, 1.4 mm, 500 μm and 350 μm) was packed to another 8.5 cm thickness with the finest grain layer at the top.

The function of this quartz layer was to support the material above it so that it would elutriate through the bottom opening during sampling of leachate. Quartz was chosen because of its inert nature and therefore chemical reactions between this material and leachate could be avoided.

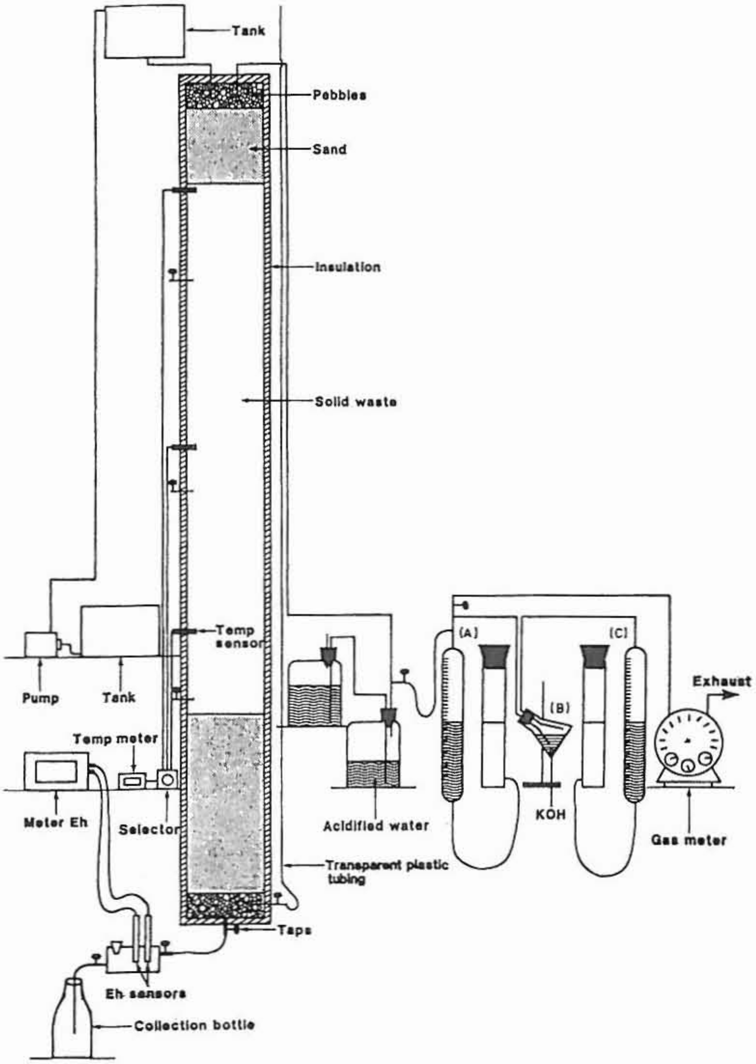

Fig. 1. Landfill model assembly

Underlying Sand Layer

A sand layer was packed on top of the crushed quartz layer. The packing was carried out at increments of 3.8 cm thickness with an average packing density of 1.58 g/cm^3. This value was based on the bulk density of the sandy soil in the field. Sand was packed to a depth of 79.2 cm in the bottom 1-m section of the landfill model. This sand layer was designed to simulate the placement of landfills on sandy soils, allowing study of leachate treatment and gas production as it moves through the sand, which is composed predominantly of quartz grains.

Solid Waste Layer

Solid waste with a composition similar to the average composition of municipal waste was packed inside the landfill model to a thickness of 2.5 m. The composition of the solid waste is shown in Table 1. A total of 43.775 kg solid waste was used for filling up the landfill model with a packing density of 0.52 g/cm^3.

The solid waste was processed by cutting it into small pieces (average size between 1 and 2 cm) and mixing it thoroughly before packing. Samples of vegetable waste, fruit waste, lawn clippings, plant clippings and food wastes were taken to determine the moisture content. The results are shown in Table 2. Moisture contents of the other components (metals, wood and rags) were not determined and are likely to be very low because these components were air dried before packing.

TABLE 1
Solid waste composition wet weight percentage

Composition	Landfill Model	Petaling Jaya
Paper products:		23.6
Corrugated card	12.6	
Newspaper	11.4	
Food waste:		48.32
Meat scraps and fats	11.4	
Seafood scraps	22.9	
Vegetable waste	13.4	
Fruit waste	0.9	
Metal:		5.93
Steel cans	4.1	
Aluminum	0.3	
Ferrous and other metals	1.7	
Wood	0.3	4.82
Rag	0.5	3.97
Others (glass, plastic and inert waste)	0.0	

Soil Cover

A covering layer of sand was placed on top of the solid waste to a thickness of 40 cm. Above this sand, a layer of 5-cm quartz pebbles was placed as a final cover. This pebble layer was used for reducing the scouring effects of water as it was introduced from the top of the column.

TABLE 2
Moisture content as percentage of wet weight from 5 samples

Component	Moisture Content
Vegetable waste	90
Fruit waste	88
Lawn clippings	60
Plant clippings	81
Meat scraps and fats	39
Seafood scraps	65

Landfill Model Initiation

Moisture was introduced into the landfill gradually from the bottom part by using plastic tubing connected to the higher tank through a control tap. A total of 49.9 l water was introduced into the landfill. The level of the water and the pressure inside the landfill were monitored by an open-ended plastic tube, connected to the lower part of the landfill, placed vertically at the side of the landfill to a level as high as the feed tank.

MONITORING AND ANALYSIS

The landfill was monitored over a period of two years. Gas production and temperature levels from four locations inside the column were monitored. A gas meter was connected to the gas outlet tubing for the measurement of total gas production. The ratio between carbon dioxide and the other gases (predominantly methane) was determined by collecting the gas in a combination of two 4-litre plastic containers above acidified water. Half-litre samples of the gas were taken from this container into a closed system cylinder, connected at one end to an open- ended cylinder half-filled with acidified water (A) and the other end to a stoppered conical flask (B) containing 45% by weight KOH (*Fig. 1*). Another set of cylinders (C) with a similar arrangement was connected to this conical flask. This arrangement of cylinders was used for bubbling the gas sample to and fro, for the removal of carbon dioxide by KOH, to a constant volume.

Leachate samples were collected from the bottom and middle taps of the landfill model for quality analysis. The middle tap provided leachate samples from the middle of the refuse layer while the bottom tap provided leachate which had passed through the 1-m layer of sand. The parameters measured were pH, Eh, BOD, COD, Ortho-P and ammonia.

Replacement water was introduced into the landfill model immediately after every sample collection through the opening at the top of the landfill. By this procedure, the landfill was maintained at saturated conditions with an approximately constant amount of moisture throughout the experimental period.

Test Load

The test load was introduced into the sand layer by draining 3.5 of leachate from the bottom drainage. Due to gravity flow a similar amount of leachate flowed from the refuse layer into the underlying sand layer. The quality of the leachate is presented in Table 3.

Leachate movement into the sand layer was calculated from the pore volume of the sand layer. From the calculations it was found that the total pore volume of the sand layer and the supporting pebble layer was 13.5. l It means that the 3.5 l of leachate from the refuse layer was equivalent to about 26% of the total liquid inside the sand and pebble layers.

A similar volume of water was introduced into the landfill model through the top. By this procedure, the amount of moisture inside the landfill model was considered to be approximately constant.

After draining the leachate the landfill model was monitored for another 2 months. The daily rate of gas production was monitored by using a gas meter connected through plastic tubing to the gas outlet at the top of the model. A ratio of carbon dioxide and the other gases (predominantly methane) of around 2:3 was consistently found.

Continuous Loading

After the test load and a rest period of about 8 weeks, a continuous loading experiment was carried out. Leachate generated by the solid waste layer was introduced into the underlying layer by weekly draining 1.5 l of leachate from the bottom drainage. At this draining rate it was calculated that the leachate would have an average detention time of 9 weeks and an infiltration rate of 1.6 cm/day. This calculation was based on the total pore volume of the sand and the supporting pebble layers divided by the volume of the leachate collected weekly. Obviously gas was developing inside the sand layer and the effective pore volume had become smaller; therefore the actual detention time could be shorter than the calculated value.

The continuous loading experiment lasted for about 3 months. During the period, samples of leachate from the bottom drainage, the base of the solid waste layer and the middle of the solid waste layer were collected every week. The samples were analysed for pH, COD and BOD. Nutrient levels, namely Ortho-P and Ammonia-N, were also determined. Redox conditions (Eh) were also determined during the collection of samples.

Before collection of the leachate, approximately 3 l gas was collected from the model landfill in 4-litre plastic containers. This was done by closing the outlet taps. In this way, a positive pressure was always maintained inside the landfill model even during the draining of leachate through the bottom drainage. The temporary gas storage chamber also provided gas samples for the determination of the methane and carbon dioxide ratio (percentage of other gases was considered small). A sample of 0.5 l gas was used for each determination by bubbling through 45% potassium hydroxide solution to a constant volume. Two samples of gas were determined every week.

The volume of the leachate samples collected every week from the bottom drainage, the base of the solid waste layer and the middle of the solid waste layers were measured separately and recorded. Replacement water of similar volume was then introduced into the landfill model through the top water inlet.

A total of 18.7 litres of leachate was collected from the bottom drainage over the period of the continuous loading experiment. The total amount of leachate collected was equivalent to about 1.4 pore volumes of the underlying sand and pebble layers.

RESULTS AND DISCUSSION

The total gas production for a period of two years is depicted in *Fig. 2*. A steady rate of gas production was achieved approximately 4 months after complete saturation. At that stage, a maximum gas production of 3.65 l/kg refuse per week was generated.

The ratio between carbon dioxide and other gases is presented in *Fig. 3*. The first two months represented the early phase of gas production where the peak may indicate the presence of other gases such as nitrogen and hydrogen. Comparing this graph with the study by Farquhar and Rovers (1973), this period may be interpreted as the acid-producing stage. The two-month period after this represents the beginning of the methanogenic stage.

After six months, a steady methane content of approximately 55% (with variation around 3%) was achieved. Further determinations of the methane content indicated a gradual increase from 55% to about 65% after one year (*Fig. 3*). The Eh level of the leachate dropped very rapidly to below -250 mV. This Eh level was found to be consistently low through out the study period. The pH of the leachate sample from the middle of the landfill model was always low with an average of 5.3. However, very slow release of leachate from the bottom tap was found to increase the pH from levels of around 5.5 to above 7 after six months' operation. The increase in pH was obviously due to an increase in methanogenic activity within the underlying sand layer.

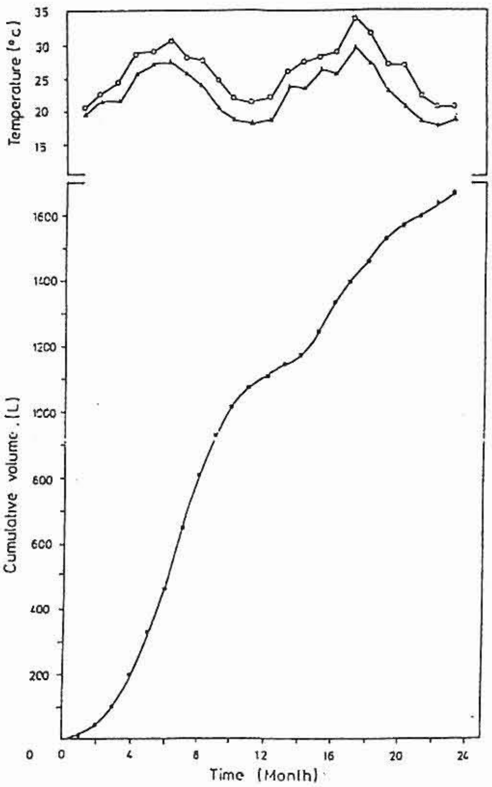

Fig. 2. Cumulative gas production (•) in the landfill model containing 43.8 kg Perth refuse under ambient temperatures (x) and landfill model temperature (0)

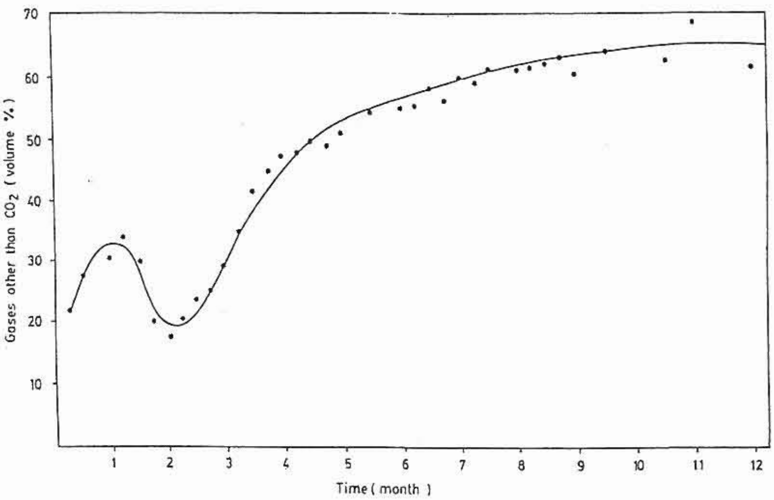

Fig. 3. Volume percentage of gases other than CO_2

The leachate from the middle tap (the middle of refuse layer) contained very high levels of ammonia and COD. With minimal water circulation the levles remain very high even after 22 months' operation (Table 3). Under complete saturation conditions and slow mobilization of moisture, as in this study, the methane fermentation process in the middle of the landfill is likely to be inhibited by the very high ammonia level (>1500 mg/1) and low pH. The high level of COD in the leachate is evidence of this phenomenon.

Mobilization of leachate through leachate recirculation has been shown capable of stabilizing landfills in less than two years (Titlebaum 1982).

TABLE 3
The characteristics of leachate from the middle of the refuse layer

Parameter	Concentration
COD	36,100 mg/1
BOD	22,500 mg/1
Ammonia-N	1,700 mg/1
Ortho-P	12 mg/1
pH	5.3

Results of Leachate Mobilization

Anaerobic fermentation of leachate inside the underlying sand and pebble layers resulted in the production of methane and carbon dioxide gases. In the process, COD was removed. The rate of the fermentation process was influenced by the conditions inside the sand and pebble layers, namely temperature, pH, Eh and the concentration of nutrients.

The ratio between organic materials and nutrient elements (BOD:N:P) was found to range between 1000:100:1 in the leachate samples from the middle of the solid waste layer to 400:100:1 in the leachate from the base of the solid waste layer. This ratio was smaller than the recommended optimum ratio of 100:5:1 for the treatment of organic waste water by aerobic processes (Boyle and Ham 1974). However, despite the low levels of soluble phosphate, methane fermentation was taking place normally inside the underlying sand layer. This situation was clearly indicated by the rapid rate of gas production and good COD reduction.

Results of gas production, maximum daily laboratory temperatures and the landfill model temperature are presented in *Fig. 4.* The graph shows the average daily gas production calculated every week over a seven-month period. The daily average temperature was calculated weekly and found to be fluctuating between 21°C and 34°C. Results of the temperature monitoring inside the model landfill indicated that, in general, the average landfill model temperature was slightly higher than the average daily maximum laboratory temperature.

Laboratory temperatures were found to have influence on the rate of gas production. The average daily gas production rates during the hotter weeks were higher than the rates in the cooler weeks (*Fig. 4*).

The general pattern of gas production indicated a strong correlation with the movement of leachate from the solid waste layer into the underlying sand layer. Before the leachate was mobilized, gas production ranged between 0.85 and 1.1 l/day. Based on the total weight of the solid waste inside the landfill model (43.8 kg), it was calculated that this gas production is equivalent to 19.4 ml/kg/day to 25 ml/kg/day of solid waste. The average production rate was around 22 ml/kg/day.

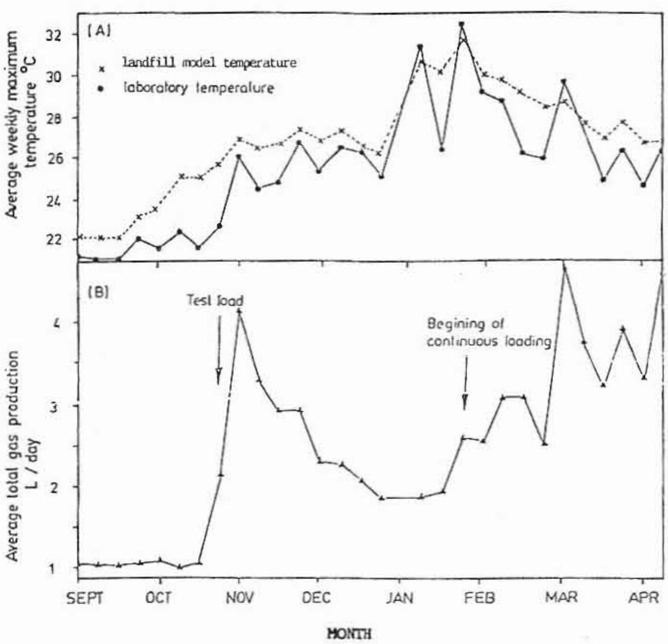

Fig. 4. Rate of gas production from the landfill model (l/day), average weekly maximum laboratory temperature and landfill model temperature (°C)

Results from the test load were associated with a marked increase in gas production. The daily gas production increased from about 22 ml/kg/day to about 47.9 ml/kg/day. In the following week, the production increased again to around 94 ml/kg/day.

The test load was followed by a rest period of about two months. During the rest period, the average maximum laboratory temperature fluctuated between 24°C and 26°C. The daily rate of gas production during the rest period decreased gradually from 94 ml/kg/day to an average of 43.8 ml/kg/day.

Gas production in the underlying sand layer could only take place when there was organic material to be fermented. The increase in gas production immediately after the test load indicated that the process of gas production predominantly took place inside the underlying sand layer, or at the base of the solid waste layer, but not in the middle of the solid waste layer.

The increase in gas production suggested that rapid methane fermentation took place as a result of the introduction of degradable organic materials in leachate into the sand layer. The gradual decrease in gas production during the rest period indicated that the amount of degradable organic material ever was decreasing gradually with time as the process of fermentation continued. Nevertheless, the production rate was maintained at a certain minimal level. This minimal rate was probably due to the presence or movement of organic materials from the base of the solid waste layer through diffusion.

Results of gas monitoring during the continuous loading experiment indicated that the gas production rate increased to a maximum of 106 ml/kg/day with an average of 77 ml/kg/day. Comparison of the rate of gas production from the model landfill with reported works elsewhere (Table 4), it can be seen that the landfill model shows a significantly higher rate of production. This was probably due to the high moisture (completely saturated) and temperature conditions in the landfill model.

CONCLUSION

Mobilization of concentrated leachate through the underlying sand and pebble layers by controlled flow could increase methane production and reduce COD of the leachate. The COD of the leachate after methane fermentation was maintained at about 2,000 mg/l during loading of 50.7 g COD/week.

Rapid breakdown of organic materials by anaerobic fermentation resulted in a high rate of gas production. The average gas production during the continuous loading was 77 ml/day/kg wet weight of solid wastes. Under saturated conditions, rapid methane fermentation could take place inside the underlying sand layer or at the base of the solid waste layer but was not likely to occur inside the middle of the solid waste layer. This was because of the low pH (around 5) inside the solid waste layer associated with the very high COD.

TABLE 4
Rate of gas production from landfills and landfill simulation studies*

Researcher	Source of Gas	Rate of Production (ml/kg/day) Average	Maximum	Temperature (°C)
Schuler (1973)	30-m deep recovery well at Palos Verdes Landfill, California.	30	56	NA (field conditions)
	30-m deep recovery well at Sheldon Arleta Landfill, Los Angeles.	22		NA (field conditions)
Colona (1976)	12-m deep recovery well at Mountain View Landfill, California.	45		NA (field conditions)
DeWalle and Chian (1978)	208-litre laboratory landfill cell operated at 99% moisture content.	3.5 (with buffer)	7	17
Walsh and Kinman(1979)	Test cell after 2.5 years operation with annual infiltration of 406 mm.	0.5	1	NA (outdoor temperature at Cincinnati, Ohio)
this study*	Model landfill after 2 years under complete saturation:			
	1. Before test load (no leachate mobilization)	22	21	
	2. One week after test load	94	24	
	3. Continuous loading (leachate movement at 1.6 cm/day)	77	106	27

* based on the weight of solid waste; NA = Not available

The high rate of gas production suggests that gas recovery may be economical. The gas would be best abstracted from a gas well which penetrates the base of the solid waste layer into the top of the underlying sand layer.

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