12 BIOGAS ASSESSMENT

12.1 INTRODUCTION

This *Section* provides an assessment of the potential hazards associated with biogas generation from the marine sediment to be left in place under the proposed Sham Tseng Development (STD). Where potential hazards are identified, monitoring requirements and mitigation measures will be recommended.

12.2 POTENTIAL SOURCES OF BIOGAS

In terms of general engineering practice on construction of reclamation, in areas of the reclamation where either settlement effects, construction programme constraints or foundation stability are critical, these areas should be dredged to remove the marine sediment. However, it is also recognised that there is a need to minimise the volume of sediment to be dredged and disposed of in accordance with EPD's policy directive to reduce disposal of dredged materials, wherever possible. In this regard, it was recommended that for the construction of STD, dredging should be assumed only along the seawalls. The remainder of STD sediments will be left in place. A combination of ground improvement techniques have been assumed, including wick drains and surcharging would be used to accelerate the reclamation settlements. The geological site investigation revealed that within the STD, sediment is concentrated in the centre of the reclamation, varying from 0 m to approximately 8.7 m in depth.

If dredging only at seawall is adopted, when marine sediments rich in organic matter left within the reclamation are covered with reclamation fill and the *in situ* oxygen is used up, anaerobic degradation of the organic matter in the sediments may occur and generate biogas (comprising mainly methane and carbon dioxide). Biogas may, thus, be generated from the in-place sediment underneath the STD and hence the potential risk of methane to subsequent developments at the reclamation must be assessed in this EIA. The following sections, therefore, assess the potential risks associated with biogas arising from the sediment within the proposed STD.

12.3 BIOGAS RISK ASSESSMENT CRITERIA

12.3.1 *Introduction*

There is no primary legislation in Hong Kong covering hazards to development caused by landfill gas or methane gas generated from anthropogenic organic deposits. The most relevant guidance is the *Landfill Gas Hazard Assessment Guidance Note* (1) issued by the EPD. The guidance note recommends that methane gas should be monitored periodically in all excavations, manholes and chambers and any confined spaces during construction. No works and no entry to the excavation areas or confined

(1) Environmental Protection Department (1997). Landfill Gas Hazard Assessment Guidance Note.

spaces should be allowed and the personnel on-site should be evacuated if the methane concentration measured during the monitoring exceeds 20% lower explosive limit (LEL) (or 1.0% gas).

In assessing the risks relating to the generation and emission of biogas, there are two aspects which need to be considered as follows:

- the likely rate of gas emission; and

- the maximum rate of gas emission which is acceptable.

A potential hazard will exist, and therefore mitigation measures will be required, if the likely rate of gas emission exceeds the maximum acceptable level. Thus, assessment of the risks relating to the generation and emission of biogas entails determination of the above two parameters.

12.3.2 *Maximum Safe Level of Methane Ingress / Emission*

Ideally, in order to determine the potential risks involved, specific details about the particular 'targets' which are at risk should be taken into account. This would include the following information about each of the rooms or confined spaces in the development which are at or below ground level, and would include the following:

- size of room;
- rate of ventilation (number of air changes per hour);
- occupancy (nature and frequency of use of the room); and
- presence of any sources of ignition.

With this information it is possible to calculate the maximum safe rate for which gas could enter any of the particular void spaces (rooms). Allowance could then be made for potential variations in the rate of gas ingress or rate of ventilation, by application of a suitable margin of safety, to derive an acceptable average rate of gas ingress.

For the proposed future development at the STD, it is difficult to specify all the potential 'at risk' areas (rooms or voids) or to know the specific details (size, rate of ventilation etc) of such rooms or voids, as such information is not yet available at this stage of the Project. However, various assumptions and approximations can be made based on the type of development which is proposed and the likely features of such developments.

A literature search revealed no references relating specifically to the estimation of the potential risks due to biogas from marine sediments. The most comprehensive report on the assessment of the hazards due to methane from the ground is provided in a report by the Construction Industry Research and Information Association (CIRIA) on the potential hazards and risks from all sources of methane from the ground(2), which includes a review of the approach adopted in several countries. In general, there is little or no guidance as to how to determine whether or not special building measures are required to protect against potential dangers from methane. Where guidance has been identified, this tends to be based on measurements of methane concentrations within the ground.

(2) Report 152: Risk Assessment for Methane and Other Gases from the Ground, CIRIA, 1995.

However, the process of estimating safe rates of biogas emission for reclaimed land which is to be developed is very similar to estimating safe emission rates of landfill gas when deciding whether or not an old landfill site can be regarded as being sufficiently stabilised so that it no longer poses a landfill gas emission danger. The assessment of a safe rate of landfill gas emission is necessary for determining when a site no longer needs to be monitored and when it can be used for unrestricted development. The assumption in this case is that any type of building could be safely constructed on top of the landfill and therefore requires the adoption of a universally applicable safe rate of methane emission.

A criterion for deciding when the rate of landfill gas emissions have dropped sufficiently that they no longer pose a danger is specified in the UK Department of the Environment's *Waste Management Paper No. 26A: Landfill Completion* (WMP26A) as follows:

"*Methane emission rate from any boreholes drilled into the waste to be less than 0.015 m^3 per hour* "

This figure was derived based on assumptions about the area of influence of a freely venting borehole on a restored landfill (assumed to be 100 m^2) and based on assumptions about the maximum acceptable rate of ingress of methane into any building constructed on the landfill. In *WMP26A*, the following assumptions were made about the most sensitive 'at risk' room or void in which gas might accumulate:

- height of void space = 2.5 m (based on a standard room); and
- rate of natural ventilation = 1 air change per week.

In the case of developments at the STD, we consider that it would be more appropriate to use the following assumptions about the most sensitive void spaces:

- height of void space = 1 m (to allow for smaller void space such as cable pits); and
- rate of natural ventilation = 1 air change per day (in line with commonly assumed rates of natural ventilation for closed rooms(3)).

The maximum safe rate of methane ingress was then defined as that at which it would take 1 day for the methane concentration to reach 1%. This is 20% of the lower explosive limit (LEL) for methane and therefore provides a safety factor of 5 to allow for variations in, for example, rates of gas emission across the area of the site or over time compared with those measured at particular places and during the evaluation period.

The maximum safe rate of gas emission was therefore calculated as follows:

1.0 m x 0.01 day^{-1} (equivalent to m^3 CH_4 m^{-2} day^{-1})
= 0.01 $m^3 CH_4$ m^{-2} day^{-1}
= 10 litres m^{-2} day^{-1}

(3) Report 152: Risk Assessment for Methane and Other Gases from the Ground, CIRIA, 1995.

There are two points to note about this approach to determining safe rates of gas emission:

(a) The assumption is that the gas entering the room is derived from the same area of site as the area of the room at risk. This is a reasonable assumption for the assumed low rates of ventilation of the rooms as they are unlikely to act as 'collectors' for wider areas of ground.

(b) The time scale used for assuming accumulation of the gas, one day, is in line with CIRIA's assumption that an 'unventilated' room will have one air change per day. Typical 'natural' ventilation rates may vary from 0.5 to 3 air changes per hour.

The suggested maximum rate of methane emission per unit area provides a reasonable general guide for determining whether the rates of methane emission pose an unacceptable risk to unrestricted development on a potentially gassing site. However, this specified emission rate should be used only as a guide and the likely risk for a particular development should be reassessed in the light of a review of the proposed development plans for the site.

The London Scientific Services has recommended that development should not take place on sites where significant gas concentrations (>1% gas v/v) have been recorded with methane emission rates in excess of 0.05 m s^{-1} from a 50 mm diameter monitoring borehole. This is equivalent to a methane flux of approximately 84.7 litres m^{-2} day^{-1} (4) assuming that the borehole vents gas from an area of ground of 100 m^2. It should be noted that the limit recommended by the London Scientific Services should be considered as the 'absolute' cut-off level for development to be built in areas where methane gas may be generated.

12.4 *ESTIMATION OF LIKELY RATES OF GAS EMISSION*

As discussed above, the derivation of acceptable rates of gas emissions for determining when a landfill site may be regarded as being safe, as specified in *WMP26A*, were based on measurement of gas emissions from boreholes drilled into the waste. This method is appropriate and practical for a completed landfill because the heterogeneous and unpredictable nature of landfilled waste does not lend itself to accurate modelling whereas by taking measurements from several boreholes across the surface of a site over a period of time allows the spatial and temporal variations of gas emissions to be taken into account.

This is particularly important because, at the very low rates of gas emission being considered, it is not so much the rate of gas generation which is important but the rate of gas emission from the ground. As the gas (landfill gas or 'biogas') is generated, a 'reservoir' of gas will accumulate within the pore spaces of the waste (or reclamation fill) and, as the pressure builds up

(4) *Calculation as follows:*
- 0.05ms^{-1} from borehole = 4,320 m day^{-1}
- From cross-sectional area of borehole (1.96 x 10^{-3} m^2) = 8.47m^3 day^{-1}
- Assuming that the gas released from the borehole is being collected from an area of ground of, say, 100m^2 (radius of influence = 5.6m),then maximum safe rate of emission is:
  8.47/100 m^3 CH_4 m^{-2} day^{-1}
  = 0.0847 m^3 CH_4 m^{-2} day^{-1} or 84.7 liter CH_4 m^{-2} day^{-1}

within the reservoir, gas will vent to atmosphere (or migrate laterally). The rate at which this occurs will depend in part on the difference in pressure between the gas in the reservoir and the atmosphere. Thus, a major factor influencing the rate of gas emission is likely to be change in atmospheric pressure: as atmospheric pressure falls there will be an increase in emission rate and when atmospheric pressure rises emission rates will decrease. The exact way in which emission rates respond to changes in atmospheric pressure is quite complex and depends on a number of factors including the nature of the gas reservoir and the nature of the pathways along which gas is vented to atmosphere. Empirical evidence from the monitoring of landfill gas indicates that there can be variable lag times between changes in atmospheric pressure and impacts on rates of gas emission. As a general rule, however, the highest rates of gas emission are to be expected during or immediately following a rapid and/or prolonged fall in atmospheric pressure which occurs following a period of steady atmospheric pressure. For any particular site it is very difficult to predict to the exact relationship between changing atmospheric pressure and gas emission rates.

In the absence of monitoring data, such as in the case of the proposed future STD, reliance has to be placed on estimates of gas generation. It must therefore be appreciated that the predicted rates of gas generation represent the average rates of gas emission and that instantaneous rates of gas emission may vary considerably from the average. The need to theoretically predict gas generation rates rather than being able to measure them also presents another level of inaccuracy although it would be expected that the organic material producing the biogas in the case of marine sediments beneath a reclamation will be more homogeneous than the waste materials which give rise to landfill gas and any spatial variations will therefore be less marked.

Various methods are used for the theoretical estimation (prediction) of the rate of biogas (or landfill) gas generation. A number of biological methane potential (BMP) tests have been developed [(5)] [(6)] [(7)] and these are generally regarded as providing the best estimate of potential yield of gas. They involve incubation of samples of the subject material and collection/measurement of the evolved gas. They do have a number of serious disadvantages in terms of their widespread use as practical tests, however, for the following reasons:

- they are relatively specialised and complex tests which can only be performed by specialised laboratories;
- they require specially prepared innoculum and nutrient solutions;
- they take between 3 and 10 months to carry out; and
- there is no recognised standard methodology.

(5) Shelton David and Tiedje J (1984) General Method for Determining Anaerobic Biodegradation Potential. Applied and Environmental Microbiology, 47(7), pp850-857.
(6) Biotal Ltd (1992) further Development of Landfill Assessment Methods: The Potential Gas Yield and Gas Production Rate Test. DoE Report CWM 090/93, September 1992.
(7) Croft B C and Campbell D J V Assessment of a Test for Biological Methane Potential, DoE Report CWM 103/94, May 1994.

As a substitute for BMP tests, a number of other biological, chemical and physical tests have been employed to estimate potential biogas generation. The most commonly used analyses are as follows:

- calorific value;
- volatile solids content;
- total organic carbon (TOC);
- chemical oxygen demand (COD); and
- biochemical oxygen demand (BOD).

Of these, it is considered that those tests which provide a measure of the biologically degradable organic material present in the sample, as opposed to that material which may be chemically degraded, are likely to be more representative. Thus, TOC and sediment oxygen demand (SOD), a specific type of BOD test were used to estimate the methane generating potential of the sediment at STD.

12.5 *SEDIMENT SAMPLING AND TESTING PROGRAMME*

The depth of sediment left within the reclamation area varies from 0 to 8.7 m. For the biogas assessment, sediment samples were taken from four vibrocore stations (see *Figure 12.5a*) across a pocket of marine sediment located at the centre of the proposed reclamation. The area of the marine sediment pocket is about 33 000 m^2 and the depth of the sediment varies from 2 to 8.7 m (an averaged depth of 4.6 m). In some areas of the sediment pocket a layer of marine sand is sandwiched by the marine sediment. At each of the vibrocore stations, subsamples were taken at seabed level and thereafter at the following depths: 0.9 m, 1.9 m, 2.9 m, 5.9 m and 8.9 m below seabed or until the bottom of the marine sediment. The sediment subsamples were analysed for TOC and SOD.

To determine the total quantity of oxygen that will be required to biologically stabilise the organic matters present in the sediment samples and hence to determine the total amount of biodegradable organic carbon in the sediment, it is considered that $SOD_{24\ hours}$ would be a suitable parameter for the calculation of total biodegradable organic carbons in the sediment. However, in order to ensure that all the biodegradable organic carbons in the sediment samples are degraded at about 24 hours, it is recommended that all sediment samples will also be tested for $SOD_{5\ days}$ and 30% of the sediment samples will be tested for $SOD_{20\ days}$. By comparing the SOD results for 24 hours, 5 days and 20 days, it will be able to determine if the $SOD_{24\ hours}$ test is appropriate for estimating the total biodegradable organic carbon. The relationship between $SOD_{24\ hours}$, $SOD_{5\ days}$ and $SOD_{20\ days}$ will also be established from the test results.

12.5.1 *Sediment Testing Results*

The analytical results of SOD and TOC analyses[(8)] for the sediment samples are presented in *Table 12.5a*. TOC levels in the undredged area range from <0.1% to 1.4% (w/w) dry matter (with an average level of 0.41%). The depth averaged TOC concentrations at seabed, 1 m, 2 m, 3 m and 6 m below seabed vary from 0.13 to 0.7%. Dry matter concentrations of the sediment samples range from 64.7% to 87% (with an average level of 79.6%).

$SOD_{24\ hours}$ levels of the samples vary from 97 to 1020 mg kg^{-1} per hour (w/w) dry matter (with an average level of 538 mg kg^{-1} per hour). $SOD_{5\ days}$ levels of the samples vary from 161 to 1850 mg kg^{-1} per hour (w/w) dry matter (with an average level of 865 mg kg^{-1} per hour). $SOD_{20\ days}$ levels of the samples vary from 500 to 2571 mg kg^{-1} per hour (w/w) dry matter (with an average level of 1385 mg kg^{-1} per hour). The SOD results indicate that the longer the sediment is incubated the higher the value of the SOD. This suggested that readily biodegradable organic matters will be degraded within the 24 hours but it will take a longer time to assimilate the less readily biodegradable organic matters. From $SOD_{20\ days}$ curves, it is possible that some biodegradable organic matters have not yet been assimilated and the SOD value could be higher if it allowed to incubate for a longer period. For the purpose of determining the total biodegradable portion of the TOC, the $SOD_{20\ days}$ value will therefore provide a better estimate. The proportion of the biodegradable organic matters in TOC is about 13% [(9)]. It is comparable with the figure (15%) reported in the *South East Kowloon Development EIA Study*[(10)].

(8) Testing methods of SOD and TOC are agreed by EPD.
(9) It is calculated based on the methane generation potential.
(10) South East Kowloon Development Environmental Impact Assessment, *Final Assessment Report,* 1998.

Table 12.5a Sediment Analysis Results

Vibrocore Station	Depth Below Seabed (m)	Dry Matter (% w/w) (a)	TOC (% dew) (b)	$SOD_{24\ hours}$ (mg kg^{-1} dew hr^{-1})	$SOD_{5\ Days}$ (mg kg^{-1} dew hr^{-1})	$SOD_{20\ days}$ (mg kg^{-1} dew hr^{-1}) (c)
BID1	0.60 -0.90	77.3	0.2	434	569	1,259
BID1	0.90 - 1.20	76.6	0.4	601	796	-
BID1	1.90 - 2.20	72.6	0.2	495	936	-
BID1	2.90 - 3.20	64.7	1.4	1,020	1638	-
BID2	0.00 - 0.30	86.7	<0.1	303	161	500
BID2	0.90 - 1.20	87.0	<0.1	321	229	-
BID2	1.90 - 2.20	80.2	0.1	369	374	-
BID2	2.90 - 3.20	76.6	0.2	887	613	-
BID2	5.90 - 6.20	83.9	<0.1	83	274	-
BID3	0.00 - 0.30	78.0	0.3	431	1025	1,837
BID4	0.90 - 1.20	68.7	1.1	645	1397	2,571
BID4	1.90 - 2.20	82.1	0.1	97	609	-
BID4	2.90 - 3.20	69.7	0.5	602	1850	-
BID4	5.60 - 5.90	72.0	0.9	703	1444	-
BID4	7.00 - 7.30	70.5	0.8	728	1290	-
BID4	8.90 - 9.20	79.2	<0.1	896	631	-
Depth Average	0.00 - 0.30	80.7	0.20	389	585	1,198
	0.09 - 1.20	77.4	0.53	522	807	2,571
	1.90 - 2.20	78.3	0.13	320	639	
	2.90 - 3.20	70.3	0.70	836	1367	
	5.90 - 6.20	78.0	0.50	393	859	
	7.00 - 7.30	70.5	0.8	728	1290	
	8.09 - 9.20	79.2	<0.1	896	631	
Overall Average		***76.7***	***0.41***	***538***	***865***	***1,385***

Notes:

(a) w/w = by weight

(b) dew = dry weight

(c) Only 30% of the sediment samples were tested for $SOD_{20\ days}$.

12.6 ESTIMATION OF POTENTIAL GAS EMISSION FROM STD

Upon completion of reclamation, approximately 175 000 m^3 of sediment (see *Table 12.6a*) would be left *in situ* in the middle (about 33 000 m^2) of the reclamation (*see Figure 12.5a*). The average depth of sediment in this area is about 4.6 m. From the ground investigation surveys, the marine deposits of the remaining areas (about 13 ha) consists mainly of sandy materials with very little or no marine sediment. It is considered that the amount of biogas to be generated in these areas will therefore be minimal.

The generation rate of biogas will depend on a number of parameters including concentrations and biodegradability of the organic matters in the sediment, age of the reclamation, redox potential, temperature, moisture content, presence of toxic matters which may inhibit biological activities. These parameters may vary at different depths and locations within the reclamation area and their interactions are complex and difficult to predict. For the purpose of this preliminary assessment, the potential methane risk will be assessed based on the theoretical biogas production rate.

The formation of biogas under anaerobic conditions can be described as a first order degradation process. This process is characterised by high gas generation rates at the early stage of the process, followed by an exponential decrease over the course of time. Although it is difficult to predict the extent of anaerobic conditions, the generation of biogas can be estimated theoretically based on the available data on TOC and the SOD.

12.6.1 *Estimation of Methane Generation Potential Based on TOC*

It is assumed that 50% of the gas produced from anaerobic degradation of organic matter of the sediment is methane and the remainder is carbon dioxide. The degradation process can be represented by the following equation:

$2\ C_6H_{12}O_6$ -------------> $6\ CH_4 + 6\ CO_2$

On this basis, the mass of methane generated from unit mass of TOC can be calculated as follows:

12 C --------------> $6\ CH_4 + 6\ CO_2$
12 x 12 = 144 6 x 16 = 96

The theoretical mass of methane generated will equal to 0.67 times of the mass of TOC in the sediment.

Based on the range of half-lives of 0.5 to 5 years[(11)], the estimated total theoretical methane generation potential and daily methane flux from STD are presented in *Tables 12.6a* and *12.6b*, respectively.

(11) "Biogas Risk Assessment" Report of Tsuen Wan Bay Further Reclamation for TDD, June 1998 and "Potential Methane Gas Risk" Report of South East Kowloon for TDD, 1998, CES (Asia) Ltd.

Table 12.6a Calculation of Total Methane Generation Potential from STD Based on TOC

Parameter	
Volume of Sediment to be left *in situ*	175 000 m^3
Assumed Density of sediment	1500 kg m^{-3}
Average dry matter of the undredged area	76.7% (w/w)
Mass of dry matter	1150.5 kg m^{-3}
Average TOC level of the undredged area	0.41%
Mass of TOC	4.72 kg m^{-3}
CH_4 generation potential [(a)]	3.16 kg m^{-3}
Total CH_4 generation potential	5.5 x 10^5 kg or 7.7 x 10^5 m^3

Note:

(a) The theoretical mass of methane generated equals to 0.67 times of the mass of TOC in the sediment.

The higher flux rate, corresponding to a half life of decay of 0.5 years, is not significant in terms of future development because after two years over 95% of the biodegradable organic matter would have been decomposed and the potential methane flux would have fallen proportionally to a rate less than that of the lower figure (corresponding to a half life of decay of 5 years) after the same time. Therefore, the half life of decay of 5 years represents the worse case after two years.

The above calculation is based on a number of broad assumptions which might affect the precision of the estimates. It assumes that all the organic matter is readily degradable (worse case scenario) and it takes no account of biological oxidation of methane that would probably occur in the upper layers (aerobic zone) of the fill. Oxidation efficiencies of 2% to 100% [(12)] were reported in the *Tsuen Wan Bay Further Reclamation Study*[(13)]. High oxidation efficiencies will occur when the fill material is well aerated and the gas is able to emit uniformly over the surface area. While low oxidation efficiencies will occur when the fill material is poorly permeable for gases and when the gas generation rate is rather high or when surface is low permeability, for example, hard surface such as roads, buildings. However, it is difficult to predict the likely oxidation efficiency for the reclamation area.

(12) Hock, J., (1992). Effect of leaking natural gas on soil and vegetation in urban areas, Wageningen.
(13) "Biogas Risk Assessment" Report of Tsuen Wan Bay Further Reclamation, for TDD, June 1998.

Insert Table 12.6b : Methane Generation Potential Based on TOC

Total Volume of Sediment with Reclamation = 175,500m^3
Solid Content of Sediment = 76.7%
Average concentration of TOC within sediment = 0.41% (w/w)
Assumed Density of Sediment = 1,500kg m^{-3}
TOC/methane ratio = 0.67

Total Methane Generation Potential in kg (Lo) = 553,074
Total Methane Generation Potential in m^3 (Lo) = 774,304

CASE 1 – Assume a Half Life of 0.5 year, K = 0.693/0.5 = 1.386
Area within Reclamation = 33,000m^2

Year After Sediment Becomes Anaerobic	*Remaining Methane Generation Potential (m^3)*	*Methane Produced (m^3/yr)*	*Methance Flux (l/m^2-yr)*	*Methane Flux (l/m^2-d)*
0.01	763,646	376,437	11,407	63.78
0.5	387,209	193,576	5,866	32.14
1	193,633	159,045	4,820	13.20
2	***34,587***	***25,938***	***786***	***2.15***
3	8,649	6,486	197	0.54
4	2,163	1,622	49	0.13
5	541	406	12	0.03
6	135	101	3	0.01
7	34	25	1	0.00
8	8	6	0	0.00
9	2	2	0	0.00
10	1	0	0	0.00
11	0	0	0	0.00
12	0	0	0	0.00
13	0	0	0	0.00
14	0	0	0	0.00
15	0	0	0	0.00

CASE 2 – Assume a Half Life of 5 year, K = 0.693/5 = 0.1386
Area within Reclamation = 33,000m^2

Year After Sediment Becomes Anaerobic	*Remaining Methane Generation Potential (m^3)*	*Methane Produced (m^3/yr)*	*Methance Flux (l/m^2-yr)*	*Methane Flux (l/m^2-d)*
0.5	722,462	48,371	1,466	8.03
1	674,090	87,243	2,644	7.24
2	***586,847***	***75,952***	***2,302***	***6.31***
3	510,895	66,122	2,004	5.49
4	444,773	57,564	1,744	4.78
5	387,209	50,114	1,519	4.16
6	337,095	43,628	1,322	3.62
7	293,467	37,982	1,151	3.15
8	255,485	33,066	1,002	2.75
9	222,419	28,786	872	2.39
10	193,633	25,061	759	2.08
11	168,572	21,817	661	1.81
12	146,755	18,994	576	1.58
13	127,761	16,535	501	1.37
14	111,226	14,395	436	1.20
15	96,831	12,532	380	1.04

12.6.2 Estimation of Methane Generation Potential Based on SOD

The amount of methane gas produced per kg of SOD can be estimated as follows:

Assume that the starting compound is glucose ($C_6H_{12}O_6$), the conversation of glucose to carbon dioxide and methane under anaerobic conditions can be represented by the following balanced equation:

$C_6H_{12}O_6$ ------------> 3 CO_2 + 3 CH_4
180 g 132 g 48 g

It should be noted that although the glucose has been converted to carbon dioxide and methane, the methane generation potential may be estimated by the oxygen requirement for complete conversion of the glucose to carbon dioxide and water under aerobic conditions.

The amount of methane formed per kg of SOD can be represented in the following balanced equation for the oxidation of glucose to carbon dioxide and water.

$C_6H_{12}O_6$ + 6 O_2 --------------> 6 CO_2 + 6 H_2O
180 g 192 g

The SOD of glucose is (192/180) kg, and 1 kg of glucose yields (48/180) kg of methane, so that the ratio of the amount of methane produced per kg of SOD is:

$(kgCH_4/kgSOD) = \{(48/180)/(192/180)\} = 0.25$

Therefore, for each kg of SOD, 0.25 kg of methane will be formed.

The volume equivalent of the 0.25 kg methane produced from the equivalent of 1 kg of SOD is:

$Vol_{CH4} = (0.25\ kg) * (10^3\ g\ kg^{-1}) * (1\ mol/16\ g) * (22.4\ l\ mol^{-1}) * (10^{-3}\ m^3\ l^{-1})$

$= 0.35\ m^3\ CH_4$ (at standard conditions of temperature and pressure)

Therefore, 0.35 m^3 of methane will be generated per kg of SOD converted.

SOD will also include the nitrogenous oxygen demand (that is, the oxidation of nitrogen and ammonia), but in the estimation of the methane generation potential it is assumed that the oxygen demand is entirely carbonaceous demand. This represents a conservative approach and the actual methane generation potential is expected to be lower.

The $SOD_{20\ days}$ levels of the sediment samples as presented in *Table 12.6a* ranges from 500 to 2,571 mg SOD kg^{-1} dry weight of sediment (with an average of 1,385 mg SOD kg^{-1}). The theoretical methane generation potential will be:

= 1385 mg SOD kg^{-1} dry weight of sediment x 10^{-6} kg mg^{-1} x 0.35 m^3CH_4 kg SOD^{-1}

= 4.85 x 10^{-4} m^3CH_4 kg^{-1} dry weight of sediment.

Table 12.6c Calculation of Total Methane Generation Potential from STD Based on SOD

Parameter	
Volume of Sediment to be left *in situ*	175 000 m^3
Assumed Density of sediment	1500 kg m^{-3}
Average dry matter of the undredged area	76.7% (w/w)
Mass of dry matter	1150.5 kg m^{-3}
Total dry matter of sediment	2.01 x 10^8 kg
SOD mg kg^{-1} dry weight of sediment	1385 mg kg^{-1}
Total SOD in sediment	2.79 x 10^5 kg
Total CH_4 generation potential	97 598 m^3CH_4

Note:

(a) 1 kg SOD = 0.35 m^3 CH_4

The total methane generation potential calculated based on SOD results is about 13% of that calculated from the TOC results as shown in *Table 12.6d.* The rate of methane generation predicted from the SOD results would be expected to be much lower than that calculated from the TOC data because TOC is a measure of the total organic carbon whereas some of it may not be biodegradable.

Table 12.6d : Methane Generation Potential Based on SOD Results

Total Volume of Sediment within Reclamation = 175,000m^3
Solid Content of Sediment = 76.7%
Average SOD value = 1,385mg/kg dry weight of sediment
Assumed Density of Sediment = 1,500 kg m^{-3}
1kg SOD = 0.35m^3CH4

Total Methane Generation Potential in m^3 (Lo) = 97,598

CASE 1 Assume a Half Life of 0.5 year , K = 0.693/0.5 = 1.386
Area within Reclamation = 33,000m^2

Year After Sediment Becomes Anaerobic	*Remaining Methane Generation Potential (m^3)*	*Methane Produced (m^3/yr)*	*Methance Flux (l/m^2-yr)*	*Methane Flux (l/m^2-d)*
0.01	96,255	47,449	1,438	8.04
0.5	48,806	24,400	739	4.05
1	24,407	0	0	0.00

CASE 1 Assume a Half Life of 0.5 year , K = 0.693/5 = 0.1386
Area within Reclamation = 33,000m^2

Year After Sediment Becomes Anaerobic	*Remaining Methane Generation Potential (m^3)*	*Methane Produced (m^3/yr)*	*Methance Flux (l/m^2-yr)*	*Methane Flux (l/m^2-d)*
0.5	91,064	6,097	185	1.01
1	84,967	10,997	333	0.91
2	***73,970***	***9,573***	***290***	***0.79***
3	64,397	8,334	253	0.69
4	56,062	7,256	220	0.60
5	48,806	6,317	191	0.52
6	42,490	5,499	167	0.46
7	36,990	4,787	146	0.40
8	32,203	4,168	126	0.35
9	28,035	3,628	110	0.30
10	24,407	3,159	96	0.26

12.7 ASSESSMENT OF METHANE HAZARD TO STD

12.7.1 *Results of Sediment Testing*

As discussed in *Section 12.6*, the estimated rate of methane generation (based on TOC results) for the STD will be approximately 75 952 m^3 per year (see *Table 12.6b*) after 2 years following reclamation. This will be evolved over the total area of 330 000 m^2 over the sediment pocket in the middle of the reclamation. Thus, the rate of gas emission can be calculated as follows:

= 75 952 m^3 CH_4 per year / 330 000 m^2
= 6.31 L m^{-2} per day

If it is based on the SOD results, the estimated rate of methane for the STD will be approximately 9573 m^3 per year (see *Table 12.6d*) after 2 years following reclamation. Thus, the rate of gas emission can be calculated as follows:

= 9573 m^3CH_4 per year / 330 000 m^2
= 0.79 L m^{-2} per day

The potential methane flux estimated for STD (6.31 L m^{-2} per day) is lower than the suggested risk assessment criterion of 10 L m^{-2} per day and is well below (about 6.4%) the limit (84.7 L m^{-2} per day) recommended by the London Scientific Services which is considered as the 'absolute' cut-off level for development to be built in areas where methane gas may be generated.

As discussed in *Section 12.3*, the safe emission rate is based on a number of assumptions about the size and rate of ventilation of 'at risk' rooms or voids as well as the general nature of the surface of the ground from which the gas is being generated. It is therefore necessary to consider the particular type of development being planned for the STD and what 'at risk' features are likely to be present in order to assess the likelihood of methane emissions presenting a significant risk.

12.7.2 *Features of the STD*

Examination of the proposed layout for the development on top of the sediment pocket indicates that it comprises a mixture of residential housing and schools. Some of the residential blocks will be developed above a podium.

Biogas emitted from the organic sediment beneath the reclamation will tend to pose limited risk to many of the multi-storey tower block type of residential developments or schools because, typically, these do not have any below ground rooms and often have car parking on lower levels with the residential apartments above a podium level. However, each block may have a few 'at risk' rooms, the vulnerability of which will depend on the exact detail of construction, size ventilation and use. Transformer rooms and refuse collection rooms, for example, are typically located at ground level but are usually provided with a relatively high rate of mechanical ventilation which will serve to disperse and dilute any gas which happens to enter such rooms. Other at risk rooms and voids will include lift pits and utility (services) voids within and around individual tower blocks.

12.8 CONCLUSIONS

Given that, at this stage, it is not possible to measure the rates of gas emission from the organic sediment left within the area of the proposed STD, an estimate of the future rate of gas generation has been made from the results of analysis of the sediment for TOC and SOD.

Several assumptions and estimations have to be made when making theoretical predictions about possible future rates of methane generation at the undredged areas. The estimated average rate of methane gas generation is well within the suggested maximum rate of methane emission per unit area of 10 L m^2 day^{-1} and the limit of 84.7 L m^2 day^{-1} recommended by the London Scientific Services. The former criterion provides a reasonable general guide for determining whether the rates of methane emission pose an unacceptable risk to unrestricted development on a potentially gassing site. The latter criterion represents the absolute "cut-off" level of methane flux which developments should be allowed to build on the potentially gassing site.

Overall, based on the results of the sediment analysis and comparison with published guidance on safe levels of gas emissions, it is considered that the predicted rates of gas generation from the undredged areas will not pose unacceptable risk or constraint to the future developments on top of the reclamation areas.

Given the inherent uncertainties involved in estimating future rates of gas emissions from theoretical calculations of rates of gas generation and given that mitigation measures for avoiding the potential risks may be very expensive, it would be of benefit to undertake monitoring of gas emission rates following the reclamation of the area of the proposed development to confirm the findings of this assessment.

12.9 RECOMMENDATIONS

12.9.1 *Monitoring*

It may take some time for fully anaerobic conditions to be established within the organic sediment and for a reservoir of gas to accumulate within the reclamation fill. Thus, monitoring should be undertaken for as long as possible prior to the commencement of construction of the development on the reclaimed land. Ideally, monitoring should be undertaken for a period of at least one year.

If there is only limited time between completion of the reclamation and commencement of construction, monitoring should commence immediately upon completion of the reclamation so that any trends may be observed and results extrapolated to the period of construction and occupation of the development.

Monitoring should be undertaken via purposely installed monitoring wells installed within boreholes drilled into the fill material. The boreholes should be drilled down to the level of the groundwater (mean sea water level) and standard landfill gas-type monitoring wells should be installed. These should be fitted with a removable cap and gas monitoring valve so that gas concentrations may be measured as well as flow rates from the open well.

It is recommended that two monitoring wells should be installed across the sediment pocket in the middle of the reclamation. They should be located in such a way that they are approximately evenly distributed across the area and at the open space of the future development so they could be retained for longer-term monitoring, if necessary. The wells should be monitored as follows:

- concentrations of the following gases should be measured using portable monitoring equipment with gas chromatographic (GC) analysis being undertaken on selected samples to confirm the results:
  - methane
  - carbon dioxide
  - oxygen
- gas flow rates from the open wells - very sensitive techniques (such as micro-anemometer) will need to be used to measure the anticipated very low flow rates. In addition, and if practical, emissions from the surface of the reclaimed land could be monitored using flux boxes.

It will be important to monitor gas flows from the wells under different meteorological conditions and to include some occasions when atmospheric pressure is falling quite quickly (eg immediately preceding a typhoon).

12.9.2 Protection Measures

General Guidelines

At this stage it is difficult to provide precise guidelines on what measures would be required for the specific rates of gas emission which may be measured by the proposed monitoring *(Section 12.9.1)* because this would depend on the exact pattern of the results and the design/ purpose of the specific buildings to be erected. However, the following criteria may be used as general guidelines:

Scenario 1

If rates of methane emission are consistently much less than the trigger value (10 L m^{-2} day^{-1}), including monitoring occasions when atmospheric pressure is falling quite quickly, and they do not show any rising trend over time, then the buildings will not require gas protection measures.

The trigger value of 10 L (methane) m^{-2} day^{-1} is an "area" emission rate (ie rate at which gas is emitted per unit area of the reclamation). In order to convert this into an emission rate from a borehole, it is necessary to make an assumption about the "area of influence" of a freely venting borehole which depends on a number of factors - mainly how easy it is for gas to escape from the surface of the site. Thus, for a site covered in a hard surface (eg paved) it would be expected that any borehole would have a much greater area of influence than if the site had soft landscaping.

Different people have assumed different areas of influence - in *WMP 26A*, it assumed 100 m^2 whereas in the South East Kowloon Development Study[14], the consultant assumed approximately 20 m^2 (radius of 2.5 m). To be conservative, it is proposed to adopt an area of influence of 20 m^2, which would give:

- Trigger value of 10 L m^{-2} day^{-1} x 20 m^2 = 200 L day^{-1} emitted from the borehole

In practice, such low rates of gas emission will be measured using 'flux box' methods as the velocity of the gas (m s^{-1}) will be too low to measure, unless a very sensitive flow meter is used. Thus, expressing the flow rate as a volume per day or volume per hour will be acceptable. Hence, the criterion for safe flow rate from the free venting boreholes becomes:

- Flow rate of methane (in terms of L day^{-1}) $<$ 200 L day^{-1}

or

- (Gas flow rate in terms of L day^{-1}) x (concentration of methane in gas (in % gas)) $<$ 200 L day^{-1}

Scenario 2

If the rates of methane emission from any borehole frequently exceed the trigger value or show a rising trend such that future emission rates are likely to exceed the trigger value, then any buildings to be constructed on that part of the site will require some form of gas protection measures. That is when:

- (Gas flow rate in terms of L day^{-1}) x (concentration of methane in gas (in % gas)) $>$ 200 L day^{-1}

The exact details of the gas protection measures would need to be designed to take into account the design and use of the particular buildings involved but would, most probably, include the installation of a low gas permeability membrane in the floor slab of the building. The exact area of the reclamation over which buildings would need to have gas protection measures would depend on the pattern of the results from different monitoring boreholes and further investigation may be required to determine the area of land which is affected by any biogas emissions. The analysis and assessment of the results and design of any gas protection measures, should be undertaken by suitably qualified and experienced professionals who are familiar with the properties of biogas and the way in which buildings may be protected against the impacts of gases derived from the ground.

Scenario 3

If there are occasional exceedances of the methane emission rate trigger value or if there is significant fluctuation of the results obtained with some readings coming close to the trigger value, then the exact pattern and any trends in the results will need to be assessed to determine their significance and whether any building protection measures are required. It might be necessary to

(14) South East Kowloon Development Environmental Impact Assessment, *Final Assessment Report*, 1998.

undertake additional monitoring by extending the monitoring period, for example, if an apparently spurious high reading is noted towards the end of the monitoring period or if it seems likely that future rates of emission may exceed the trigger value.

Whatever the results obtained from the proposed monitoring of gas emission rates, the analysis and assessment of the results and design of any gas protection measures, should be undertaken by suitably qualified and experienced professionals who are familiar with the properties of biogas and the way in which buildings may be protected against the impacts of gases derived from the ground.

Scenario 4

If the rates of methane emission from any borehole frequently exceed the limit value (84.7 L m^{-2} day^{-1}), or show a rising trend such that future emission rates are likely to exceed the limit value, then no buildings should be constructed on that part of the site. That is when:

- Limit value of 84.7 L m^{-2} day^{-1} x 20 m^2 = 1,694 L day^{-1} emitted from the borehole

or

- (Gas flow rate in terms of L day^{-1}) x (concentration of methane in gas (in % gas)) > 1,694 L day^{-1}

Typical / Generic Protective Measures

Depending on the results of the monitoring recommended above, it may be necessary (although at this stage it is considered that it is unlikely to be required) to incorporate a number of general protection measures into the design of the redevelopment and to include specific measures in the design of individual buildings. Specific details cannot be provided until the results of this monitoring (described in *Section 12.9.1)* and exact details of individual building designs are available. A combination of different measures may be used for protecting the development against possible risks due to biogas and discussions would need to be held with the developers and architects to determine which are the most appropriate.

Typical, generic, protection measures which may be employed (depending on the results of the monitoring and exact building designs) include the following:

Ventilation of Gas from the Reclaimed Land

Vertical boreholes/wells could be installed across the area of the reclamation to allow gas to vent to atmosphere thereby preventing the build-up of gas pressures within the fill material. Care would be needed in the design of the venting stacks to ensure that any gas was safely vented without causing nuisance or danger to users of the land. This technique is probably appropriate only if the monitoring indicates a relatively high rate of gas emission.

More specific areas of the development could be targeted such as the footprints of specific buildings or other sensitive areas. In this case the ventilation measures would be designed specifically to prevent the build up of gas pressure beneath a building, for example, and could comprise a network of horizontal gas collection pipes installed underneath the building connected to a number of risers to allow any accumulated gas to be dispersed to atmosphere at a suitable level above ground.

Barriers to Prevent Ingress of Gas into Buildings

There are a number of ways of ensuring that any gas derived from the ground does not enter a building. Typically these involve the incorporation of some kind of low gas permeability membrane in the design of the floor and any below ground walls of any ‘at risk’ rooms. In addition, measures must be taken to avoid or seal any openings in the floor (for example, at service entry points). Such techniques are commonly used where there is a risk of landfill gas entering a building and have been employed on a number of developments in Hong Kong.

There are various proprietary products which may be used and the specific details of their application will depend very much on the individual building design.

In all cases, extreme care is needed in the installation of the membrane and the other protection measures to ensure that they meet the design requirements and to avoid damage during installation and subsequent construction works. Adequate QA/QC procedures are therefore essential to ensure that such measures are effective.

Ventilation within Buildings

As an additional or alternative measure for the protection of specific rooms, ventilation (passive or mechanical depending on the circumstances) may be provided to ensure that if any gas enters the room it is dispersed and cannot accumulate in dangerous volumes. For particularly sensitive rooms, such as below ground confined spaces which contain sources of ignition, forced ventilation may be used in addition to the use of a low permeability membrane whereas for low sensitivity areas ventilation may be used on its own.

Protection of Below Ground Services

As they are installed below ground, conduits in which services (for example, electricity and other cables) are installed are particularly prone to the ingress and accumulation of gas derived from the ground. It is therefore important to prevent such conduits acting as easy routes by which gas may enter buildings by avoiding, as far as possible, any penetration of floor slabs by such services or, as a minimum, ensuring that any unavoidable penetrations are carefully sealed using an appropriate low permeability sealant.

In addition, accumulation of gas within any associated manholes or access chambers can present a risk to the staff of the utility companies. All such companies and organisations which may have cause to work on such below ground infrastructure should be warned of the potential dangers and advised to take appropriate precautions. Clear warning notices together with contact details for further information and advice should be provided on any access points to below ground chambers.

12.9.3 Precautions During Construction

Similarly, precautions may be required to ensure that there is no risk due to the accumulation of gas within any temporary structures, such as site offices, during any construction works on the reclamation area. It may be necessary, for example, to raise such structures slightly off the ground so that any gas emitted from the ground beneath the structure may disperse to atmosphere rather than entering the structure.

The exact requirements for precautionary measures during the construction phase would need to be specified following assessment of the results obtained from the monitoring recommended in *Section 12.9.1* and the details would depend on the depth of excavation or nature of the voids/structures involved.

Further information and advice, including the precautions required for the drilling of the monitoring boreholes, may be found in the Hong Kong Government's advisory document *Landfill Gas Hazard Assessment Guidance Note15* prepared by the Environmental Protection Department.

(15) Landfill Gas Hazard Assessment Guidance Note, EPD, 1997.