

GAS MIGRATION AND CONTROL AT SANITARY LANDFILLS IN HONG KONG

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SYNOPSIS

Economic and population pressures in Hong Kong have created a large demand for land resources resulting in both rapid and intense infrastructural expansion. As a consequence a number of previously remote completed landfills have been largely surrounded by urban encroachment. Many of the Territory's landfills are located in two contrasting physiographic environments, namely upland valleys and coastal areas. The former type occupy inland valleys with steep terrain forming the surrounding side-slopes. The coastal sites, by contrast, normally commence on land and prograde over the shoreline into retained marine-lagoons and are often located close to engineered reclamations established to create new land for the development of high density housing or industrial areas. Some of the engineering features which enable safe construction in these environments may provide landfill gas migration pathways, other infrastructure may similarly act as accumulation zones for mobile gas. Where development is adjacent to former landfill sites, foundations and other below-ground structures set in deeply weathered soil and rock, or in engineered fill, may form zones of potential hazard. Risks of asphyxiation, fire and explosion can occur in a variety of locations both within and beyond the landfill site boundary. Health risks caused by the accumulation of toxic trace gases could also pose problems under adverse conditions. The potential for landfill gas to migrate into the surrounding substrate and to accumulate in man-made structures is examined by reference to two simple schematic models representing both the upland-valley and coastal landfill sites typically developed in the Territory. Hazard mitigation is examined by reference to both site specific and institutional control perspectives.

INTRODUCTION

The current waste management strategy in Hong Kong includes the development of large, deep replacement landfill sites in remote areas (Fig. 1). Previously relatively small, low capacity landfill sites were located close to the urban fringe for reasons of transport economy. These sites are now closed, but remain biochemically active and as a result produce large volumes of landfill gas largely comprising methane and carbon dioxide. The economic pressure to develop land adjacent to the edge of these landfills has resulted in multistorey residential and industrial blocks being placed

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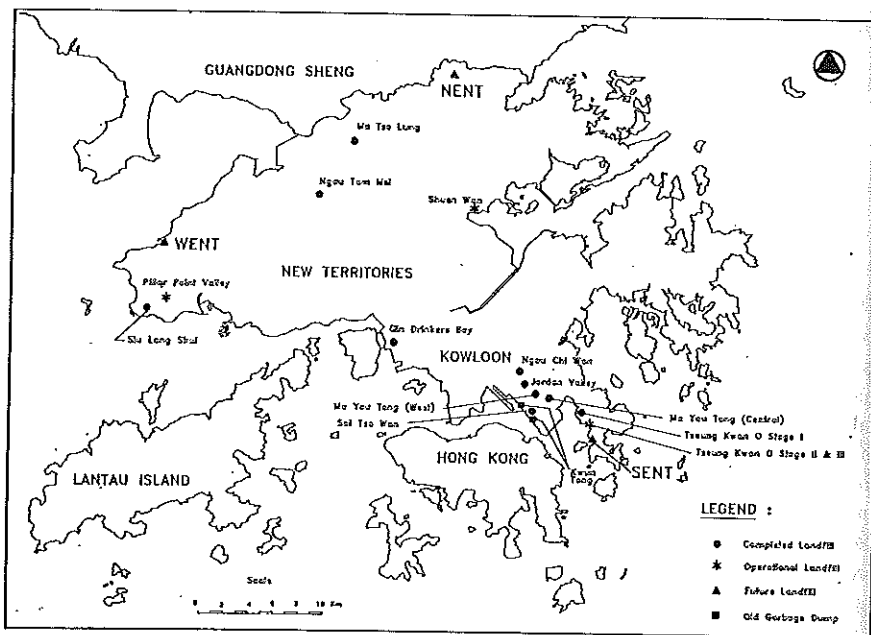


Fig. 1 Location of Landfill Sites in Hong Kong

close to the sites. These structures may be susceptible to the hazards created by migrating landfill gas under certain unfavourable conditions. Additionally, as a response for much needed recreational facilities many of the closed (derelict) landfills are now being earmarked as parks or sports areas in the crowded urban areas.

These sites are potential sources of hazard particularly where migrating gas may accumulate in confined spaces or is emitted at the surface. As a consequence programmes to monitor and identify landfill gas (LFG) migration and measures to mitigate against related hazards must be taken. Table 1 shows the geology and current land-use of all landfills and known refuse dumps in the Territory. Many of the closed landfills are located in Kowloon and represent large areas of land which are effectively sterilized for future development in districts where uncontaminated ground can fetch extremely high prices. The hazards posed by gas migration from landfills in the Territory are examined by reference to schematic models of typical sites. Some of the measures taken to prevent such occurrences are described by reference to an individual site where gas control measures have recently been installed.

Table 1 Geology, Classification and Land-use of Landfill Sites and their Surroundings.

Location	Type of Site and Area Under Refuse (hectares)	Geology of Substrate	Approximate Distance from Habitation or Public Land-use (m)	Type of Surrounding Development	Current or Planned Landfill Land-use
Yau Tong*	Marine Fill (various old reclamation areas) ()	Marine Mud	0	Industrial/Residential	Industrial infrastructure
Ma Tau Lung	Valley Build-up Platform (2.00)	Alluvium and Lok Ma Chau Formation Gap Metasediments	50	Leisure and Recreation Complex	Tannery materials drying area
Ngau Tam Mei	Valley Fill (2.02)	Alluvium, Colluvium, Tuffs and Metatuffs	250	None	Water Supplies Department Storage Compound
Siu Lung Shui	Valley Fill (11.66)	Alluvium, Colluvium and Granite	500	None	Livestock waste consolidation Plant
On Drinkers Bay	Build-up Platform/Marine (29.00)	Reclamation Fill on Marine Sand	30	Factories and Industrial Buildings	Theme park and recreation area
Ngau Chi Wan	Valley Fill (13.54)	Granite	25	Multistorey Residential Flats and School	Abandoned car compound and temporary car park
Sai Tao Wan	Valley/Build-up Platform (14.03)	Granite	50	Multistorey Flats, Cross Harbour Tunnel, Mass Transit Railway	Water Supplies Department storage area
Ma Yu Tong West	Valley Fill (6.57)	Colluvium and Granite	30	Multistorey Flats, Saltwater Pumping Station, Electricity Sub-station	Site office and works area
Ma Yu Tong Central	Quarry Fill (5.80)	Granite, Tuff and Basalt	40	Multistorey Flats	Used tyre storage area
Jordan Valley	Valley Fill (6.50)	Granite and Colluvium	200	Multistorey Flats	Closed
Plover Point Valley	Valley Fill (> 25.00)	Granite and Colluvium	500	None	Operational Site
Sheen Wan	Marine Fill (> 50.00)	Alluvium, Marine Sand and Marine Mud	40	Squatter Village, Industrial Estate and Sewage Treatment Works	Operational Site
Tsung Kwan O Stage I	Marine Fill (48.97)	Alluvium, Marine Sand and Marine Mud	500	Industrial estate and new town	Operational Site (Temporarily closed)
Tsung Kwan O Stage II	Valley Fill/Marine Fill (> 25.00)	metasediments Tuff and Colluvium/Alluvium, Marine Sand and Marine Mud	1000	Ditto	Operational Site
Total Area = > 240 hectares					

* Open garbage dump (not controlled landfill)

MIGRATION OF LANDFILL GAS

Recent experiments in Hong Kong on large scale landfill test cells have demonstrated that the aerobic phase of landfill gas production is shortlived (Dent et al 1988). Entrained oxygen depletion often occurs within a few days after refuse deposition and full anaerobic conditions are quickly established as all free oxygen is rapidly depleted. Gas generation does not however appear to cease quickly and many sites, now over twenty years old, continue to produce gas in volumes large enough to create a potential hazard. In addition to convection and diffusion, various factors can combine to cause gas to migrate within the refuse and beyond its boundaries, these are as follows :-

- o **Physical effects of refuse breakdown** - This creates gas migration as the refuse fabric collapses during degradation reducing void space and causing the gas to move.
- o **Biochemical breakdown of the refuse** - Releases gas steadily, thereby creating a pressure gradient resulting in gas movement. The methane component of landfill gas is slightly buoyant, constituent gases may become stratified pockets where gas migration is prevented.
- o **Overburden pressure and refuse collapse** - Successive layers of refuse create increasing overburden pressure causing the filter-pressing of moisture and lateral mobility of gas.
- o **Heat engine effect** - High waste cell temperatures of up to 55°C drive gas and water vapour out of the landfill through discontinuities and jointing in the surrounding soils and rocks.
- o **Fluctuations in barometric/atmospheric pressure** - Low pressure tends to draw landfill gas out of the site.
- o **Fluctuations in water table** - A rise in water table resulting from heavy summer rain may cause a surge pumping effect compressing the gas into the upper part of the landfill. Conversely, dry season reduction in water table may create suction, thus drawing air into the waste from the exterior. This process may also be influenced by tidal effects at coastal sites.
- o **Landfill cover** - Daily, intermediate and final cover largely comprising soils formed from completely decomposed volcanic and granitic rock provide low permeability barriers. These prevent upward gas movement but may create favourable conditions for lateral migration.
- o **Gas pressure and rate of gas production** - A number of factors determine gas pressure and production rate including; temperature, pH, refuse composition, density, porosity and moisture content. Ambient temperatures are often high in Hong Kong and within insitu refuse can reach 55°C. Similarly moisture content of typical Hong Kong refuse also tends to be high.

- o **Changes in landfill operation** - The gradual introduction of proprietary compaction plant and improved emplacement techniques to Hong Kong's landfills may have resulted in 'rafts' of densely compacted material forming over older but less densely compacted waste.
- o **Adjacent ground conditions** - Soil and rock conditions adjacent to landfills may provide natural migration pathways for landfill gas in the form of rock jointing, faults and other discontinuities.

Hazards and problems associated with LFG occur when gas migrates and accumulates in voids and cavities and becomes density stratified into its component gas. The potential impacts of gas collecting in confined spaces such as service ducts, utility conduits, basements, foundations and tunnels are shown in Table 2.

Table 2 Hazards Associated with Landfill Gas

- **Asphyxiation** particularly in culverts, trenches, manholes and other low-lying or enclosed structures,
- **Fire hazard or risk of explosion** when methane mixture in air is between 5% to 15%, particularly if present in confined spaces and where an ignition source is present,
- **Risk of fires in the landfill** if gases are ignited (through cracks and fissures in the surfaces of the waste cell),
- **Adverse effects on vegetation** in or adjacent to the landfill site. Upward gas emission prevents oxygen diffusion into the soil causing anoxic conditions resulting in vegetation die-off, or stunting,
- **Noxious or toxic trace gases** resulting from a variety of chemical wastes codisposed in particular sites with related health and safety aspects for workers or the public in affected areas (Scott & Emberton, 1988),
- **Nuisance from odour**, mainly from sulphurous gases normally present at low levels, and
- **Corrosion and fouling** of metal pipework, degeneration of other construction materials such as concrete and PVC.

SCHEMATIC GAS MIGRATION MODELS FOR HONG KONG LANDFILLS

Campbell & Young (1985) have demonstrated various potential landfill gas migration pathways in the UK situation and their model has been adapted for landfills in Hong Kong's upland valley environment (Nash, 1988).

Gas movement and accumulation can occur where natural migration pathways

such as joints and fissures are intercepted by man-made structures. Foundations can be particularly vulnerable, whilst service ducting for utilities, tunnels, voids and air spaces in basements may also provide potentially hazardous environments.

Natural landforms, modified by landfilling, and their interconnection with man-made structures such as foundations and tunnels can be potent factors in introducing potential gas migration pathways and also possible zones of accumulation.

The majority of landfills in Hong Kong comprise either valley-fill or marine-fill sites (Nash & Arthurton, 1987). Valley-fill Sites (Fig. 2) normally occupy upland or mid-slope locations, often with intense surrounding urban development (Plate 1), whilst by contrast marine-fill sites are formed initially on low ground and prograde over the shore into the marine environment towards a boundary sea-wall (Plate 2). Engineered reclamation (fill) areas adjacent to coastal landfill sites may present a number of gas migration vectors and potential accumulation zones (Fig. 3). These may differ somewhat to those of the valley-fill sites due to the variations in foundation and construction techniques employed. These features can present potent vectors for landfill gas migration and provide voids or cavities liable to gas accumulation. Gas migration and build-up may occur not only in reclaimed areas next to coastal sanitary landfills but also in older uncontrolled garbage dumps developed on the foreshore and which have since been reclaimed and built upon. Several such sites are known to exist in Hong Kong (some dating back to 1945), the locations of others may not have been accurately recorded.

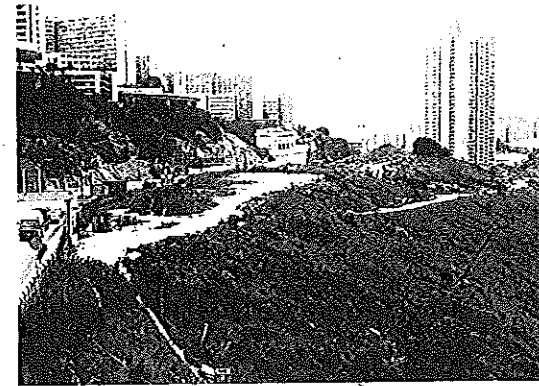


Plate 1 — A Valley-fill Site with Surrounding High-Rise Development and Associated Infrastructure-The landfill occupies the middle ground to the right of the carriageway

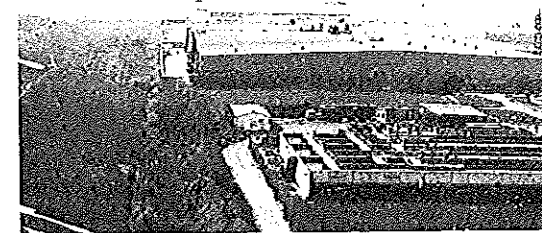


Plate 2 — A Coastal Landfill Site- The adjacent area is a conventional reclamation supporting an industrial estate, sewage works and other users

SAFETY PRECAUTIONS AND RISK AVOIDANCE

Two main methods are normally employed to measure constituent gas as follows :-

- **Insitu monitoring** - Samples of gas are analysed on-site using portable equipment for determination of methane, carbon dioxide and oxygen content, and

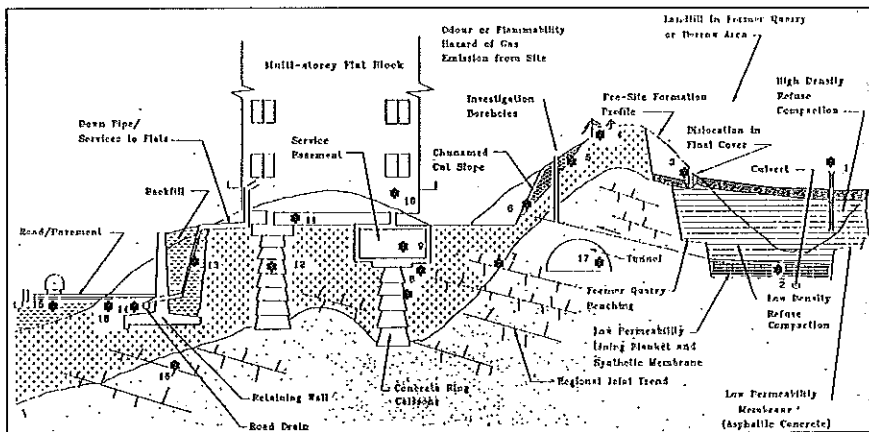


Fig. 2 Valley Landfill-Gas Migration Hazards

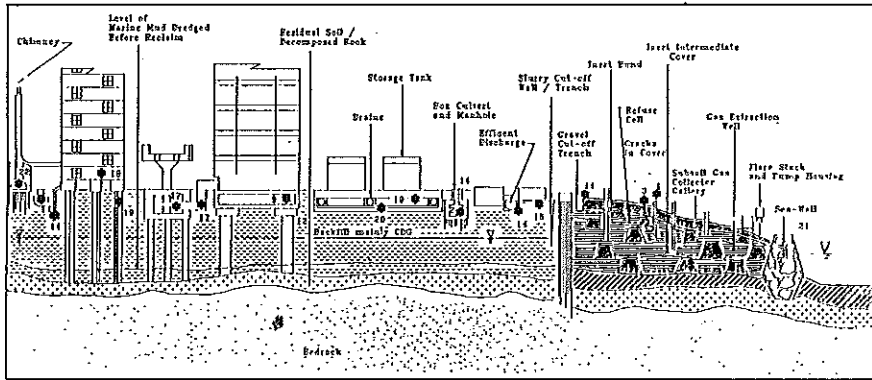
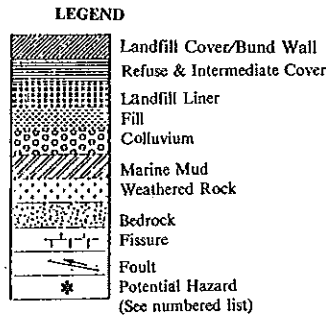


Fig. 3 Coastal Sanitary Landfill-Gas Migration Hazards

- | | |
|------------------------------------------|--------------------------------------------------------------|
| 1 Gas vent or collector system | 18 under Pavement |
| 2 Culverts | 19 Pad Foundation, Gravel Foundation, Sheet piles Foundation |
| 3 Outgassing through fissures and cracks | 20 Impermeable Liners |
| 4 Vegetation die off and odour problems | 21 Sea Walls |
| 5 Lithological boundary or boreholes | 22 Other Structure |
| 6 Chunamed slope weepholes | |
| 7 Weathering grade boundary | |
| 8 Outer skin of caisson | |
| 9 Basements | |
| 10 Building superstructure | |
| 11 Enclosed podiums | |
| 12 Within caissons/bored pipes | |
| 13 Service pipes | |
| 14 Drains, grating, and manhole | |
| 15 Fill or cover | |
| 16 Fissures and faults | |
| 17 Tunnels and Subway | |



- **Gas collection** - Samples are collected and analysed for the main constituent gases and also for trace gases.

Gas concentration readings of methane, carbon dioxide and oxygen are taken from a variety of locations including boreholes, vent-pipes, culverts, weepholes in chunamed (cement plaster) slopes and fissures in bedrock. The mixture of major and trace gases from borehole pumping trials can also be measured as LFG is extracted from the landfill.

Soil gas sampling can be achieved by the use of hand-operated impact searcher-bars (Plate 3) which can sink temporary probe holes in unconsolidated materials up to a depth of 500 mm. Gas extracted from these temporary holes is then



Plate 3 — Drift Holes for Landfill Gas Sampling Being Prepared by a Searcher-Bar Probe

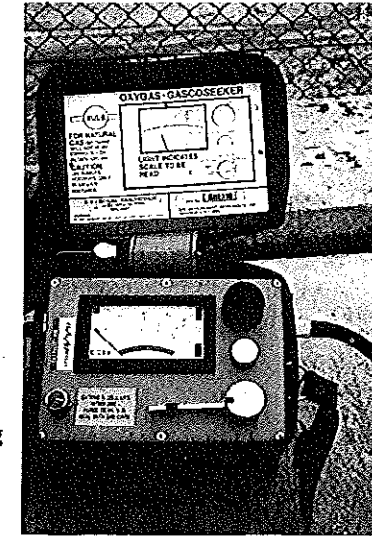


Plate 4 - Operation of a Handheld Portable Gas Detector

monitored for methane and oxygen content (Plate 4) using a portable gas detector. 'Casagrande' type drive-in perforated probes with a removable cap are also employed to provide more permanent monitoring stations, particularly in soft insitu material or fill.

Safety precautions and risk avoidance are necessary during site investigation, monitoring and site works in and adjacent to landfills. This includes compliance with regulations and care when entering confined spaces. Education of site personnel with respect to potential sources of ignition, and the use of suitable sampling equipment is also important. The Gas-Co Seeker can be calibrated for methane and gives gas readings in the various explosive limit ranges. It is also important to measure other constituent gas such as carbon dioxide, as this can modify the explosive limits of methane. Some suggested safety measures adopted in Hong Kong are shown in Tables 3 and 4.

Monitoring instruments which should remain at the site and be employed by a capable person may include both H₂S diffusion tube indicators, for example Draeger tubes, and methane analyzers including various alarm systems for personal or insitu use. Site work should proceed only after identification of any minor gas constituents which may be of special health and safety concern.

GAS MIGRATION CONTROL

Once methanogenesis commences gas will move within the waste cell via

Table 3 General Safety Measures.

- Personnel should be physically able and willing to comply with all safety requirements,
- A copy of the safety plan should be posted at the site,
- Programmed meetings should be held to review the safety procedures,
- Unsafe acts should cease immediately upon their discovery,
- Required safety equipment shall be onsite and shall be checked to verify completeness and function,
- All employees who may be required to wear a respirator shall be trained in their proper use,
- Trenches and excavations deeper than 1 metre shall be monitored for oxygen deficiency and concentration of combustibles/hydrocarbons (measured as methane). Minimum oxygen concentration is 19.5 percent. Maximum concentration level allowable for working in an atmosphere containing organic vapors is 1,000 ppm measured as methane in air,
- If 'Immediately Dangerous to Life and Health' (IDLH) levels of constituents are determined to be present or levels and types of constituents are determined to be present which are incompatible with the current level of protection being used, work will stop and the person in charge will contact the safety officer,
- Individuals working at the site must be trained and properly fitted with required safety equipment, by a qualified individual,
- No personnel may eat or smoke on the site,
- All personnel shall clean up before leaving the site,
- The site contractor's personnel and subcontractors personnel shall comply with all the above requirements.

pathways of the least resistance. The direction of flow is normally upward through the landfill cover and top soil (assuming medium/high permeability material). However, exfiltration may be restricted vertically due to the application of low permeability cover as a means of reducing rainwater infiltration. If vertical movement of gas is impeded then lateral gas flow will occur through cracks, fissured rocks, voids and other discontinuities at the flanks of the site. To eliminate risks due to gas emission and migration, two basic mitigation systems can be employed, namely passive and active gas control. Institutional controls are a third system of measures which can be introduced through which codes of practice and safety measures are promulgated as guidelines for operation and aftercare of sites.

Table 4 Site Safety.

The following safety equipment shall be continuously available at the job site in sufficient quantities :-

- Clean water, soap, paper towels,
- First aid kit, eye wash station, stretcher, and blanket,
- Fire extinguishers (2) for each piece of equipment excavating in or around the landfill,
- "No Smoking" signs,
- Acid gas/organic vapor respirators for each worker and observer with replacement cartridges which fit the respirator,
- Explosimeter/oxygen indicator,
- Hydrogen sulphide indicator (direct reading instrument or Draeger tubes),
- Barricades.

PASSIVE CONTROL

Landfill gas can be passively vented through perforated pipes to the atmosphere employing the high internal gas pressures within the refuse. This method has been used in Hong Kong for dispersion but was discontinued in 1986 following recommendations by consultants. A series of wells or trenches may be installed beneath the surface to collect and divert gas to specific vent locations. This can be achieved only if relatively impermeable cover is used and surrounding strata are not porous to gas migration. The system relies on generated gas pressure and impermeable barriers beyond the site boundary. The latter can be constructed by laying membranes which are brought up the sides during construction, by injection of cement grout (Raybould & Anderson, 1987), or emplacing bentonite or puddled clay into a series of small drill holes extended to the base of the waste cell and forming a type of 'curtain wall'. These methods of gas control are currently under consideration at a number of completed 'urban' landfill sites in Hong Kong and have already been installed at one site.

An alternative method of controlling lateral migration is the construction of a perimeter trench with high permeability material such as coarse aggregate and rubble, through which gas can be intercepted and safely vented to the atmosphere.

ACTIVE CONTROL

Gas can be extracted from wells or trenches located within the waste cell and then burnt-off, or processed and delivered for utilization as a fuel or for electricity generation.

The most common method of collection in deep landfill sites is to construct a series of wells with perforated pipes extending from the bottom of the waste to a few metres below surface. These pipes are then coupled to a gas collection header. Gas control valves are used to control the recovery rate by varying the vacuum at different locations.

For shallow sites, or where high groundwater levels preclude the use of well collection systems, horizontal trenches containing perforated pipes with porous surrounds are normally employed. These are similarly connected to collection headers for gas extraction.

One disadvantage of using active control is the possible intrusion of air through the surface. This will inhibit the anaerobic fermentation process, adversely affecting methane production. Closely spaced extraction wells and an effective gas containment system around the refuse will normally prevent air entering the system. Gas pumping trials have been conducted thus far at one site in Hong Kong to optimise extraction rates (Plate 5) and ensure that over pumping does not induce air entrainment.

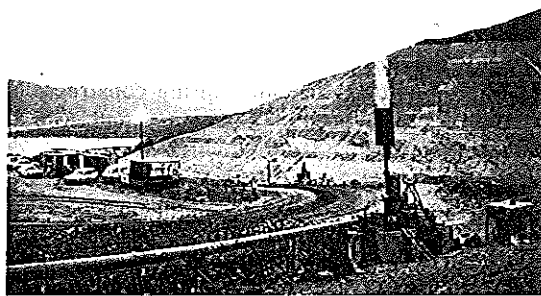


Plate 5 — Landfill Gas Pumping Trials at a Completed Landfill

Gas Migration and Control at Sai Tso Wan Landfill

General Description

Sai Tso Wan landfill is a derelict site situated near the Kowloon entrance of the Eastern Harbour Crossing tunnel in Kwun Tong District. The site was developed and operated by the Government between 1978 and 1981 and covers an area of 14 ha. About 1.6 million tonnes of domestic wastes were landfilled.

The site was formed in a former quarry. The completely decomposed granite (CDG) in the adjacent valley was removed to the bedrock to provide additional space for waste disposal.

In recent years, large scale commercial and residential development has occurred around the site. This includes the extension of the Mass Transit Railway and the construction of a station with a residential tower block development above. Multi-Storey housing and public buildings have also been constructed at the southern and western sides of the site (Fig. 4).

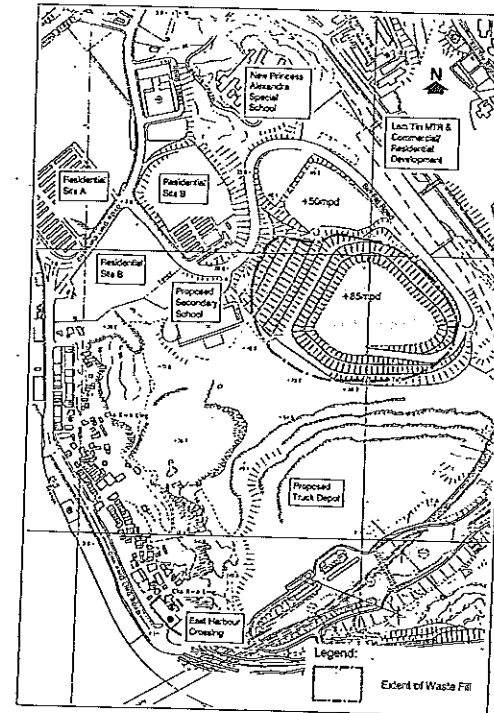


Fig. 4 Location Plan of Sai Tso Wan Landfill

Site Geology

The rock underlying the area is fine to medium grained granite. The valley is formed along a fault line passing NW-SE across the site. In addition on this fault, the rock is fractured by sheeting and tectonic joints. The former quarrying activities and the construction of Lam Tin Mass Transit Railway Station may also have opened up some latent joints. Discontinuities in the upper rock levels contains infills but clean open joints exit in some locations allowing landfill gas to migrate through the rock strata towards the nearby residential areas.

The maximum thickness of the landfill was about 70 metres, forming a platform at +85 mpd with slopes on all sides. The respective thickness of the final cover on the platform and at the side slopes are 7.5 m and 3.5 m, with insitu densities varying between 71.7 and 96.1% of the Standard Proctor Density. It consists of a fairly well graded brown silty sand with a trace of clay and a little fine gravel.

Since completion of the site in 1981, settlement in the range of 1.4 to 5.5% of fill depth has been recorded. The current settlement rate is 100 mm/year. Leachate seepage has been reported from joints in the adjacent rock slope and from the toe of lower level fill slopes nearby.

Landfill Gas Migration

In a 1988 landfill gas migration survey, the rates of surface emission were determined and areas of offsite gas movement were located. These data were mapped (Fig. 5) to show gas concentration and gas flow by means of contour lines and vectors. These are grouped in accordance with the direction of the controlling topographical and geological features.

The major areas where high rates of emission, (ie. at concentrations greater than 5% methane by volume) occur are on the side slopes at about +60 mpd where the final capping was at its thinnest.

On the +85 mpd platform, high level gas emissions were not however detected. This is attributed mainly to the thicker final capping over the top platform.

Gas Analysis

Landfill gas from the Sai Tso Wan site was collected and analyzed in July 1990. It consisted of the normal proportions of major components such as methane and carbon dioxide with other gases such as nitrogen, hydrogen sulphide and trace gases (Table 5). As a comparison the trace gas analyses from an operational landfill at Jordan Valley are shown in Table 6 and compared to typical trace gases in UK landfills. The trace organic compounds detected at both landfills are similar but the older site reveals lower concentrations of volatile organic compounds in the gases than does the more recent site whilst other compounds such as some aromatic

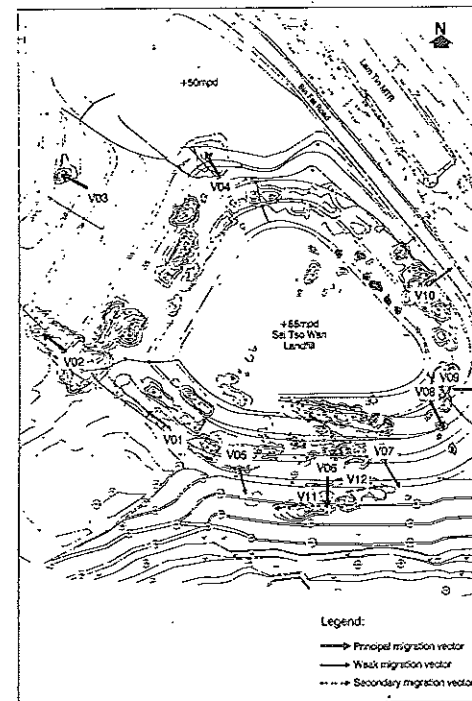


Fig. 5 Sai Tso Wan Landfill Gas Concentration

Table 5 Sai Tso Wan-Landfill Gas Characterisation.

Date of sampling	: 19 July 1990	
Sampling location	: (i) Borehole GW24 (ii) Borehole GW14	
Sampling period	: (i) Borehole GW24 - 10 : 00 to 10 : 39 hrs. (ii) Borehole GW14 - 10 : 41 to 11 : 22 hrs.	
Sampling depth	: (i) Borehole GW24 - 10 metres (ii) Borehole GW14 - 10 metres	
Compounds	Borehole GW24	Borehole GW14
Carbon dioxide	38	33
Methane	52	48
Nitrogen	5.5	15
Oxygen	0.5	1.0

Table 5 (Continued)

N.B. : The above items are in % v/v		
Aliphatic hydrocarbons		
Ethane	0.73	2.3
Propane	3.7	4.9
Butane	9.8	8.0
Heptane	0.3	0.43
Total non-aromatic (as heptane)	270	170
Aromatic hydrocarbons		
Benzene *	3.9	1.7
Ethyl benzene	15	5.5
Toluene	65	23
Total aromatic hydrocarbons (as ethyl benzene)	110	79
Cycloalkenes		
Terpenes (as 3-carene)	330	70
Oxygenated compounds		
Acetone	0.1	0.1
Methanol	0.1	0.1
Methyl ethyl ketone	24	0.1
Methyl isobutyl ketone	0.1	0.1
Other compounds		
Ammonia	2.0	1.5
Hydrogen sulphide	56	34
Total mercaptans (as methyl mercaptan)	0.21	0.55
Vinyl chloride monomer	2	2
N.B. : The above items are in ppm. v/v.		
Halogenated compounds		
Dichloroethane	1.0	2.9
Chloroform	0.06	0.01
Tetrachloroethylene	6.8	3.2
1, 1, 1-trichloroethane	0.47	0.21
Trichloroethylene	33	18
N.B. : The above items are in ppb v/v.		

Table 6 Comparison of Trace Gases at Hong Kong and UK Landfills.

Organic Compound	Hong Kong JVL*		Typical concentration of organic compounds in landfill gas at UK sites (in ppm)					
	Piezometer B1	Piezometer B2	(1) 6 UK sites WM Paper 26	(2) UK site Domestic (Baled) 7 mths	(2) UK site Domestic (pulverised) 3 wks	(2) 3 UK sites Crude or wet pulverised Municipal > 15 months	(2) UK site Co-disposal Municipal Ind. mainly 6 months	(2) UK site Co-disposal Industrial mainly 5 years
Vinyl Chloride	<3	<3	<0.04-12.6	-	-	0.01-1.2	-	-
Methylene Chloride	<0.01 ppb	0.004	-	-	-	-	-	-
Chloroform	<0.01 ppb	0.4 ppb	<0.02-0.17	-	-	<0.04-0.21	-	-
1,2-Dichloroethane	-	-	<0.03-1.98	-	-	-	-	-
1,1,1-Trichloroethane	0.01 ppb	0.0029	<0.02-32.6	-	3.3	<0.02-0.68	5.3	-
Carbon Tetrachloride	-	-	-	-	-	-	-	-
Trichloroethylene	0.02 ppb	0.1 ppb	<0.02-31.8	2.1	-	0.22-21.7	-	8.4
Tetrachloroethylene	0.02 ppb	0.2 ppb	<0.02-51.7	-	4.4	0.04-16.2	51.5	-
1,2-Dibromomethane	-	-	-	-	-	-	-	-
Benzene	1.4	0.6	0.13-35.8	1.3	-	0.19-0.38	-	6.9

* Jordan Valley Landfill

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	Toluene	7.3	22.0	2.13 - 122.5	19.2	> 25.3	4.8 - 52.5	-
Carbon Disulfide	-	-	0.03 - 0.65	-	-	0.16 - 7.1	-	-
Hydrogen Sulphide	16	8.8	-	-	-	< 2.08 - 14.7	30.6	-
Methanethiol))	< 0.05 - 44.4	-	44.4	0.05 - 220	-	-
Bithanethiol))	< 0.04 - 0.79	-	-	-	-	-
Ammonia	< 1.0	1.4	-	-	-	-	-	-
Methanol	7.8	11.0	< 0.08 - 160	-	161	-	-	-
Turpentine	5.1	64.0	-	-	-	17.95.7	-	-

* Jordan Valley Landfill

hydrocarbons are much higher in the older site possibly reflecting the previous lack of controls over the dumping of chemical wastes at the beginning of the last decade.

Landfill Gas Control Scheme at Sai Tso Wan

In order to control landfill gas dissipation, including both gas migration and surface emissions from the site, a Landfill Gas Abstraction Plant (LFGAP) at the + 50 mpd platform (Plate 6) has been constructed for the collection and flaring of gas. Where gas migration vectors were identified a passive gas barrier in the form of a 3 metre deep, polyethylene lined and CDG-bentonite filled trench has been installed to intercept the gas. This barrier will also prevent air ingress from outside of the site as an additional safety function in maintaining a continuous methanogenic process in the landfill. Before commissioning of the extraction plant gas was allowed to vent freely to the atmosphere through perforated pipes installed during landfill construction.

To facilitate LFG collection from the site 29 gas abstraction wells with 110 mm perforated HDPE pipes have been constructed to 25 m depth into the +85 mpd platform (Fig. 6). The wells are spaced at 40-45 m intervals with the designed radius of influence of 22-25 m. The landfill gas is then transported via horizontal pipes to the LFGAP and combusted at a minimum temperature of 760 degrees Celsius for a minimum flare retention time of 0.5 seconds. The plant is capable of operation during wind gusts of 220 km/hr.

INSTITUTIONAL CONTROLS

Other forms of control, which may be termed 'institutional', can be introduced through the issue of codes of practice or guidelines. Gas mitigation can also be effected via environmental safety clauses included as part of land grants or leases (all land in Hong Kong is classified as Crown Land and can be leased to the private sector by the Government). In Hong Kong these controls are as follows :-

- o Advice or practice notes issued by the Authority to developers. The first known example in Hong Kong was issued in 1963 by the Building Authority to Registered Contractors and Structural Engineers regarding methane contaminated ground in Kwun Tong.
- o Guidelines and safety instructions for works on or near landfills and old garbage dumps (including both private and public sector works, and utility company installations). Advice and interim guidelines have already been issued by Environmental Protection Department regarding specific sites, further guidelines are currently being formulated by consultants.
- o Drafting and issue of Practice Notes. These are issued through Authority as

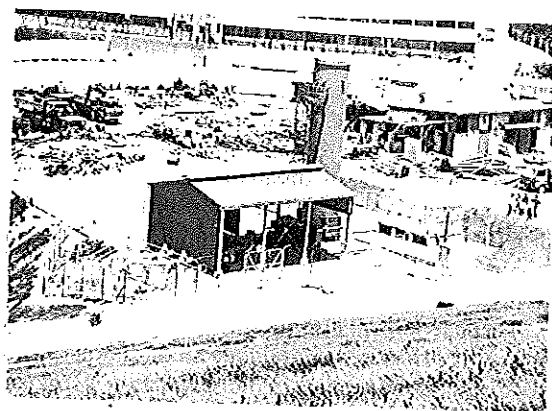


Plate 6 — The Landfill Gas Abstraction Plant (LFGAP) at Sai Tso Wan Landfill

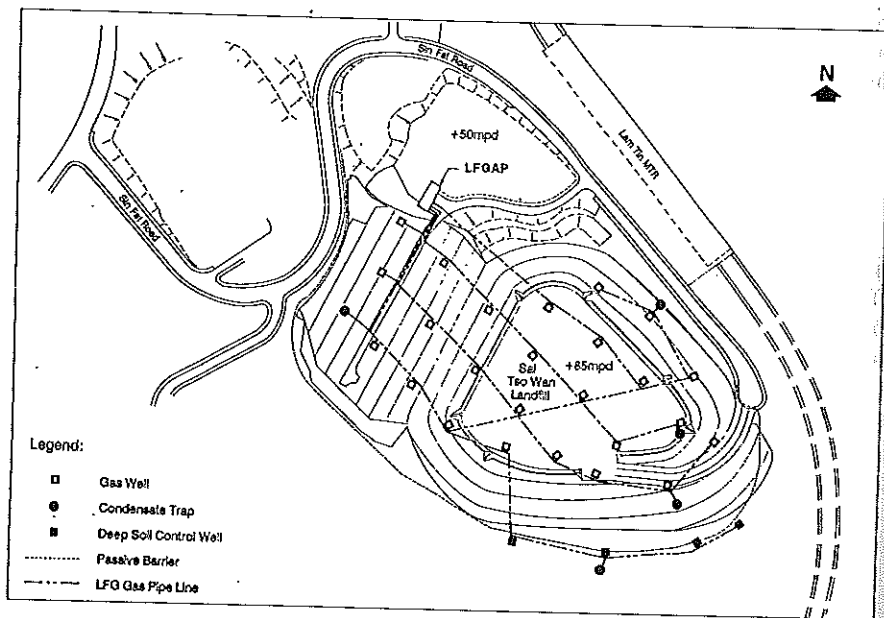


Fig. 6 Sai Tso Wan-LFG Control System

part of the Building Regulations and may include advice on landfill gas mitigation.

- o **Health and Safety at Work Guidelines.** The Labour Department of Hong Kong Government (1985 & 1986) have issued guidelines and safety regulations on working in confined spaces where hazardous gases may be present.
- o **The Hong Kong Planning Standards and Guidelines.** Inclusion of general clauses on developments on and adjacent to landfill sites. The Environmental Guidelines for Planning in Hong Kong (Hong Kong Government, 1991) also offers specific advice on development close to landfills. An extract from the above is shown in Table 7.

Table 7 Guidelines for Developments Close to Landfills.

- Landfills, whether completed or still in operation, may give rise to hazards in nearby land uses due to lateral migration of landfill gas (LFG). Landfill Gas has the potential to cause asphyxiation, fire or explosion as it migrates into and accumulates in confined air spaces during excavation and foundation work, basement construction and maintenance of drains or other underground services. Other susceptible locations include site huts, basements and similar poorly ventilated enclosures that exist during construction and in completed buildings.
- Building developments and community facilities should be sited away from landfills. The safe distances depend on such factors as the existence of gas control systems and barriers. Landfill gas has been reported to have migrated hundreds of metres away from the landfill sites. If buildings are to be developed close to landfills, features such as confined spaces at ground level, basements and other underground spaces should be avoided. The design of podiums requires special attention to ensure sufficient ventilation. Developments close to landfills should incorporate adequate monitoring measures and safety precaution measures. EPD should be notified at the earliest planning stage of such development so that the necessary controls are agreed upon before work proceeds.

- o Site licensing under the Waste Disposal Ordinance will come into force within the next few years enabling tighter controls to be written into landfill site licences. New contract conditions will also improve the operational standards of future landfills compared to those currently in force.
- o Environmental mitigation clauses relevant to landfill gas were first incorporated into land grant lease conditions in 1988. A typical example is shown in Table 8.

- o Future landfills will be licensed under the Waste Disposal Ordinance. As part of the license requirements each operator will require to submit a 'Working Plan' or Operations Manual. This manual will cover aspects of landfill gas control both on and off-site covering a period which extends beyond the operational phase of the landfill (Table 9).

CONCLUSION

Adverse environmental effects or hazards created as a result of landfill gas migration in Hong Kong are relatively few. A small number of minor incidents have nevertheless occurred signalling the presence of potential hazards and therefore the need to initiate control.

Siting of refuse landfills on the urban fringes has created zones of land which are now effectively sterilized in terms of major development but which represent areas that would otherwise have had great value in terms of real estate potential. Current planning to locate landfills in remote areas of the New Territories served by refuse transfer stations has overtaken this problem to a large extent, but most of the former urban area landfill sites remain bioreactive.

Table 8 Typical Land Grant Lease Conditions Related to Landfill Gas.

.....'The Grantee shall within twelve months from the date of this Agreement submit to the Director (Environmental Protection) for his approval in writing proposals to mitigate environmental problems identified by the Director of Environmental Protection who shall as soon as practicable after the execution of this Agreement but in any event not later than three months thereafter notify the Grantee in writing of full details of such problems, and upon receipt of the Director's approval to the said proposals the Grantee shall at his own expense implement the approved proposals in all respects to the satisfaction of and within the time limits stipulated by the Director. Without limiting the generality of this provision, environmental problems identified by the Director of Environmental Protection include, inter alia, the following :-

Possible lateral migration of gas and/or leachate from a landfill source on Government land adjacent to that part of the designated lot. The proposals to be submitted hereunder by the Grantee shall include design proposals for the inclusion and maintenance of a ventilation system to prevent accumulation of gas in confined spaces in any building or buildings to be erected on the lot which the Director of Environmental Protection may deem to be susceptible to such accumulation should gas migrate into the lot as aforesaid, and further proposals for the removal of any leachate which may migrate into the lot as aforesaid'....

Continued vigilance in terms of site maintenance and monitoring is necessary to mitigate gas hazards particularly in developed urban areas adjacent to closed landfills.

Purging of landfill gas using active and passive control systems is being actively pursued at several sites in Hong Kong including closed landfills where bioreactivity is apparently diminishing. Potential risks from landfill gas remain high particularly if gas pockets are intercepted by construction work during development adjacent to existing landfill sites. These risks may not reduce significantly with time. Landfill gas purging or ventilation of off-site structures can however remove the gas, or largely reduce concentrations to insignificant proportions.

Precautions against gas hazards during site investigation and site formation in the vicinity of landfills are necessary. Regular gas monitoring should be conducted for methane, carbon dioxide, oxygen levels and trace gases especially in enclosed working spaces. The installation of permanent gas mitigation and monitoring measures may be required at some sites. Threats may still exist from gas build-up in old marine reclamation areas which were used as uncontrolled garbage dumps more than two decades ago.

ACKNOWLEDGEMENT

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Table 9 Proposed Landfill Gas Precautions in the Operational Manual (Working Plan) of Strategic Landfills.

Prevention of Fires in Open Areas	Emergency Plan/Emergency Calls	Evacuation
<p>The surface of the restored area shall be monitored regularly to confirm the integrity of the cover soil or the capping system. If the concentration of methane gas measured is higher than 1% by volume (20% of LEL) in cracks or fissures in the soil, the landfill operator shall reseal the cracks or fissures. Much higher concentration may be detected at areas where control measures have not been taken and the landfill operator shall prevent flash fires in such circumstances by removing all ignition sources and post warning signs. The landfill operator shall consider putting up fences around the area until adequate control measures have been taken.</p> <p>Monitoring after high concentrations of methane gas have been detected</p> <p>The landfill operator shall monitor the building at weekly intervals until the concentrations of methane gas at the building are below 0.25% by volume. Where the concentrations of methane</p>	<p>The landfill operator shall submit an emergency plan to the WDA* (EPD) + for approval which will state the measures that should be taken when routine gas monitoring indicates a gas migration problem. The plans will state how to deal with these situations.</p> <p>Emergency procedures to be included in the emergency plan</p> <p>Emergency plan for controlling landfill gas at buildings or confined spaces within site boundary</p> <p>The plan shall include immediate response to assess the safety of site staff at buildings or temporary structures within the site boundary and temporary evacuation of the staff.</p> <p>Identify source of landfill gas</p> <p>The landfill operator shall establish the source of the gas and trace the points of ingress into the premises by means of portable instrument and visual examination. When the source has been identified and it has been confirmed that the gas has come from the landfill, the landfill operator shall take the appropriate control measures to rectify the condition.</p> <p>Monitoring off-site</p> <p>The landfill operator shall provide boreholes at the boundary of the site. At monthly intervals he will sample gas at the boreholes and analyse them at least for the concentration of methane and carbon dioxide, nitrogen and oxygen. The landfill operator will also measure the gas flow rate or pressure.</p> <p>Notify the WDA (EPD)</p> <p>When the concentration of methane gas measured in a building or confined space is at or above 0.25% by volume (5% of the Lower Explosive Limit (LEL) of methane gas), the landfill operator shall inform EPD and other relevant authorities immediately and confirm the notification by post within 5 working days. EPD will consider the situation with other relevant statutory authorities.</p>	<p>Where the methane gas is measured at concentration in excess of 1% by volume (20% of LEL) within a building or confined space, the landfill operator shall consider evacuation of all persons in the building immediately.</p> <p>The landfill operation shall extinguish all flames and naked lights and switch off the electricity at the supply if it is safe to do so. The landfill operator shall also open all windows or doors to enhance ventilation at locations where high concentrations of gas are found. Forced ventilation will be considered if passive ventilation has been shown to be not effective.</p> <p>The landfill operator shall take necessary measures to prevent any person from entering the building until control measures have been implemented and have been shown to be effective by further monitoring.</p> <p>If the concentrations of methane gas are found in excess of 1% by volume</p>
<p>gas are measured in a building between 0.25% and 1% by volume (5-20% of LEL), the landfill operator shall install continuous monitors at locations where gas is likely to accumulate. Such equipment must be fitted with an audible alarm, which gives warning to the building's occupants. The alarm will sound at 1% by volume. It continuous monitoring equipment is not available immediately, the landfill operator shall measure the concentrations of methane gas daily and this shall be undertaken by a competent person (s).</p> <p>The landfill operator shall maintain close supervision of the building if the concentrations of the non-flammable components of landfills gas are high.</p> <p>Odour Monitoring</p> <p>The landfill operator shall cover all the waste at the end of the day in order to prevent odour being emitted from the filled waste. He shall review the analysis results of the VOCs**, particularly those chemicals which contribute to odour.</p>	<p>ified and it has been confirmed that the gas has come from the landfill, the landfill operator shall take the appropriate control measures to rectify the condition.</p> <p>Monitoring off-site</p> <p>The landfill operator shall provide boreholes at the boundary of the site. At monthly intervals he will sample gas at the boreholes and analyse them at least for the concentration of methane and carbon dioxide, nitrogen and oxygen. The landfill operator will also measure the gas flow rate or pressure.</p> <p>Notify the WDA (EPD)</p> <p>When the concentration of methane gas measured in a building or confined space is at or above 0.25% by volume (5% of the Lower Explosive Limit (LEL) of methane gas), the landfill operator shall inform EPD and other relevant authorities immediately and confirm the notification by post within 5 working days. EPD will consider the situation with other relevant statutory authorities.</p>	<p>(20% of LEL) outside a building or confined space, the landfill operator must evacuate all persons immediately. No person will be allowed to enter the building until effective control measures have been implemented and there is no risk from any gas accumulation.</p> <p>Reporting on Monitoring</p> <p>All monitoring and analysis results are to be submitted in writing to EPD within 14 days of readings being taken or the analysis carried out. Should readings or data indicate failure to attain target values the landfill operator must inform the EPD site officer within 24 hours and his written report must be accompanied by detailed proposals for remedial actions.</p>

Table 9 (Continued)

Table 9 (Continued)

<p>Monitoring after high concentrations of methane gas have been detected</p> <p>The landfill operator shall monitor the building at weekly intervals until the concentrations of methane gas at the building are below 0.25% by volume. Where the concentrations of methane gas are measured in a building between 0.25% and 1% by volume (5-20% of LEL), the landfill operator shall install continuous monitors at locations where gas is likely to accumulate. Such equipment must be fitted with an audible alarm, which gives warning to the building's occupants. The alarm will sound at 1% by volume. If continuous monitoring equipment is not available immediately, the landfill operator shall measure the concentrations of methane gas daily and this shall be undertaken by a competent person (s).</p> <p>The landfill operator shall maintain close supervision of the building if the concentrations of the non-flammable components of landfills gas are high.</p> <p>Odour Monitoring</p> <p>The landfill operator shall cover all the</p>	<p>Gas monitoring at Property outside the site boundary</p> <p>The landfill operator shall inform EPD immediately when the gas monitoring results indicate a gas concentration at property outside the site boundary.</p> <p>Emergency Calls</p> <p>The landfill operator shall provide a copy of relevant emergency telephone numbers in the site diary and at the prominent areas in the site office. He shall update the persons of contact and their telephone numbers as appropriate.</p> <p>Monitoring on Site</p> <p>Surface Monitoring</p> <p>An accurate master map, tied in to a small-scale grid reference system, will allow a monitoring programme to be set up to determine gas seepage through the cover soil. The landfill operator shall carry out surface walk-over of the landfill following the grid reference system to identify any gas seepage. Portable gas detectors preferably having an audio signal as well as a visual</p>	<p>Working in Confined Spaces</p> <p>General Precautions</p> <p>Landfill gas may be trapped and accumulate in confined areas such as manholes, pump houses which require regular maintenance. The landfill operator shall ensure that workers will check for the presence and concentration of landfill gas before entering these areas. The workers shall never enter the area without knowing the area is clear of landfill gas. If methane gas is detected in the confined area and entry is necessary, the landfill operator must take all necessary protective measures (self-contained breathing apparatus may be necessary) before allowing any person to enter the area.</p> <p>He shall ensure that the person who enters and works in confined space shall wear an approved breathing apparatus. "Approved breathing apparatus" means any breathing apparatus approved by the Commissioner of the Labour Department as published in the Gazette. The landfill operator shall make reference to the Factories and Industrial Undertakings (Confined</p>
<p>waste at the end of the day in order to prevent odour omitted from the filled waste. He shall review the analysis results of the VOCs, particularly those chemicals which contribute to odour problems. He shall take appropriate action to rectify odour problems when the analyses indicate a high level of odourous gases or when complaints have been received from the public.</p>	<p>display shall be used. The landfill operator shall measure at least the concentrations of methane, carbon dioxide, nitrogen and oxygen at monthly intervals. When identifying gas, full use should be made of the senses (bubbles in puddles, heat shimmer, condensation plumes, vegetation die-off).</p> <p>Vegetation die-off at locations along the site boundary may be due to landfill gas. Therefore the landfill operator shall monitor for unusual die-off of vegetation at the site. Areas most affected may indicate local high methane concentration and the landfill operator will monitor these areas at weekly intervals.</p> <p>Monitoring at Shallow Depth</p> <p>Shallow probes are most valuable in provided relatively cheap fixed monitoring points which allow better data comparison.</p> <p>The landfill operator shall carry out gas surveys using shallow probes. Probes shall be placed in shallow piezometers, auger holes or searcher-bar drift holes. He shall measure the concentrations of methane, carbon dioxide, oxygen and nitrogen at monthly intervals.</p>	<p>Space) (Approval of Breathing Apparatus) (Consolidation) Notice when selecting the breathing apparatus.</p> <p>Where practicable, the landfill operator must ensure that the person who enters any confined space shall wear a belt with a rope securely attached thereto and the free end of the rope is held by person who is outside the confined space and who is capable of pulling him out of the confined space.</p> <p>Checking Safety Equipment</p> <p>(i) The persons working in confined spaces must check that they have at least the following safety equipment available in a serviceable condition :-</p> <ul style="list-style-type: none"> - Gas detection apparatus - Safety harness - 20 feet lifelines - First Aid Kit - Crowbar - Flame proof electric torch

Table 9 (Continued)

	<p>Borehole Monitoring</p> <p>The landfill operator shall provide boreholes and shall sample gas at monthly intervals. The percentage of methane, carbon dioxide, oxygen, nitrogen, hydrogen, hydrogen sulphide, carbon monoxide shall be measured. The landfill operator Instrumental monitoring of boreholes must be done carefully. The landfill operator must avoid overpumping of gas from the boreholes in order to avoid air being sucked into the boreholes. The landfill operator shall use suitable gas detectors (to be specified) and the measurement shall be done by a competent technician. The interpretation of results must be undertaken by competent persons familiar with the limitation and shortcomings of installation and monitoring techniques.</p> <p>The landfill operator shall take gas samples from the boreholes at quarterly intervals and analyse them for the selected volatile organic compounds. The frequency and parameters of monitoring shall be reviewed annually by both the landfill operator and Waste Disposal Authority (EPD).</p>	<p>(ii) Every person shall satisfy himself that the gas detectors and breathing apparatus are in good working order.</p>
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* Waste Disposal Authority
 + Environmental Protection Department
 - Volatile Organic Compounds

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