Territory Development Department

KAI TAK AIRPORT NORTH APRON DECOMMISSIONING

ALTERNATIVE REMEDIATION STRATEGY FOR HOT SPOT B

March 1999

Maunsell Consultants Asia Ltd
Maunsell Environmental Management Consultants Ltd

Alternative Remediation Strategy for Hot Spot B

1. Introduction

In the KTA Decontamination Pilot Test Report, it was discussed that Soil Vapour Extraction (SVE) is a suitable technique for cleaning up the vadose zone soil in Hot Spot B within the remediation period (18 months) allowed in the Contract KL31/98. This estimated clean up time for Hot Spot B was based on the site contaminant data and typical clean up rates as the pilot test results at one location could not be generalised to represent the whole Hot Spot B. However, it was estimated that 1.5-3 years are required for the clean up of the more contaminated soil ("Heavy Hot Spot B") in the saturated zone using air sparging (AS) and this may exceed the allowed clean up period. Therefore, an alternative remedial approach is needed to address the "Heavy Hot Spot B" in the saturated zone.

Furthermore, the KTA Decontamination Pilot Test Report identifies some localised problems, namely short channelling, a Radius of Influence (ROI) in AS being smaller than the original design value, and groundwater upwelling resulting in lower SVE flow achievable.

This paper proposes an alternative remediation strategy that takes into account of the remediation objectives as approved in the EIA report, special site constraints of KTA, pilot test results and implementability of the project. The plan describes general procedures, sequence of clean up, decision tree, monitoring requirements and safety/ environmental protection measures.

2. Remediation Objectives

1) The recommended decontamination technologies can clean up the site to the remediation targets as presented in the EIA report within 18 months;
2) The environmental impacts during the excavation, construction and operation of the remedial systems are minimised; and
3) The construction workers are adequately protected from site hazards.

3. Site/ Contractual Constraints

1) The location and shallow depth of the Airport Tunnel in the central part of Hot Spot B poses constraint on remedial works especially those related to *ex situ* treatment i.e. excavation or large-scale groundwater extraction. Highways Department has required that a safety distance must be kept to protect the structural integrity of the tunnel. Large-scale excavation may lead to structural failure, settlement or water seepage into the vadose zone of the tunnel causing flooding.
2) The need for site hand-over as soon as possible for development will require the clean up method to be implementable and efficient.
3) The proximity of residents near the site and potential temporary use of certain areas of the KTA dictate that the decontamination works be carried out in a safe and environmentally acceptable manner.
4) The Contract KL31/98 has already commenced. Delay in the works or large change in the nature of the works would have a lot of contractual and programme implications.

4. Concept of Trigger Level

Using a trigger level, the saturated zone soil in Hot Spot B is divided into more contaminated area (>2750 ppm TPH, "Heavy Hot Spot B") and less contaminated areas (<2750 ppm TPH, "Light Hot Spot B")[1]. The derivation of trigger level is presented in Appendix A. The area of the "Heavy Hot Spot B" is about 35% of the total area of Hot Spot B.

5. Justification for Using SVE/AS for "Light Hot Spot B"

The calculation presented in Appendix A has demonstrated that SVE/AS can clean up the less contaminated soil. Full-scale biopile would not be feasible as it may cause a lot of potential hazard with the tunnel, workers safety, etc. It has been estimated that it will cost $100M more than the combination of limited biopile and SVE/AS conducted at Hot Spot B.

6. Justification for Using Biopile for "Heavy Hot Spot B"

The biopile process has higher efficiency due to the improved air permeability (thus oxygen delivery to and volatilisation of contaminants) owing to better mixing and draining of wet soil.

7. Justification for SVE/AS Pretreatment for "Heavy Hot Spot B"

1) Allow vapour and methane to be removed in a controlled manner to protect the construction workers and the nearby residents.
2) Allow free product recovery by means of a larger vacuum (dual phase vacuum-enhanced recovery). This will significantly help remove the source in an early stage so as to speed up the clean up.
3) Maximise treatment time of the heavily contaminated soil within Hot Spot B. This is because if extensive heavy hot spots are first excavated for biopiling, there may have to be temporarily stockpiled on site, as the capacity of the first phase of the biopile would have to be allocated to the Hot Spots A and C soils.
4) Allow several months of treatment of the saturated soil prior to biopiling.
5) Allow a degree of treatment of benzene in groundwater. Since benzene is easily volatilised and biodegraded, it is very likely the groundwater remediation goal (benzene) be achieved in 6 months time, prior to biopiling.
6) Allow treatment of the land near the airport tunnel. While a 5m safety distance is kept for SVE/AS, a minimum safety distance of 15m must be used for any excavation.
7) As it is more in line with the original design, the approach has advantage in programme and contractual implementation.

[1] *For the additional investigation (52 sampling points) proposed under Section 16, the volatile carbon fractions would be clearly differentiated. Based on these additional data, the trigger level of 2750 ppm would be reviewed.*

8. Overall Remediation Approach for Hot Spot B

The overall remediation approach is summerised in the Table 1. It should be noted that the current proposed approach is different from that presented in the EIA report in the following elements:

1) Biopile is a committed method for treatment of the Hot Spot B exceeding a trigger level, rather than as a fall back option;
2) The AS wells in the "Light Hot Spot B" has been spaced about 30% closer to increase the effectiveness; and
3) Other operational measures are added such as pulsed operation, increase in sparging rate, and re-injection in vadose zone.

Table 1 Remediation Approach and Their Justifications

	Remediation Technique	Justification
Areas exceeding trigger level ("Heavy Hot Spot B")	SVE/AS as pretreatment Excavation and Biopile *(for 8 months)*	• Worker protection from vapour • Some free product recovery • Groundwater treatment • Treatment of strip near airport tunnel • Higher efficiency than SVE/AS
Areas under trigger level ("Light Hot Spot B")	SVE/AS *Fall Back Option of Biopiling (for 4~6 months)*	• Much more cost effective than biopile • Worker protection (from vapour and trip-fall hazards) • Protection of airport tunnel • Groundwater treatment • Less need for land area • Less hazard due to haulage truck movement carrying contaminated soil

9. Remediation Sequence and Decision Tree

The steps and the decision tree for the alternative remedial strategy is shown in Figure 1. The general remediation sequence is that "Heavy Hot Spot B" would be pretreated with SVE/AS first then followed by biopile. Then the SVE/AS headers at these areas would be stopped, and the lateral pipes would be removed. Excavation would proceed and material removed to the biopile B for treatment. The plan for the commissioning procedure is presented in the Appendix B.

10. System Layout

The system layout is illustrated in Figures 2 and 2a. The figures show the additional biopile, which has a capacity of 80,000 cu-m for the treatment of "Heavy Hot Spot B" soil (which is estimated to be 75,000 cu-m). *The solid black line represents the area with only SVE wells installed in order to capture vapour sparged from the AS system. Prior to the operation of AS, SVE will be operated at a high flow rate such that groundwater and floating product can be extracted. After that, AS will be operated at a low flow rate (e.g. 1-2 cfm and gradually increased). Therefore, migration of the floating product from "Heavy Hot Spot" to "Light Hot Spot" would not occur.*

It should be noted that a safety distance of 15m would be kept from the tunnel during excavation. During excavation, precaution would be used to prevent any structural disturbance to the tunnel. The excavation would be carried out in dry season.

It should also be noted that the layout will be fine-tuned after the final round of site investigation.

11. Well Spacing

1) For "Light Hot Spot B"

In accordance with the interpretation of data of the Pilot Test Report, the ROI for SVE is 12m and the ROI for AS is 4m. The respective well spacing is 20.8m and 6.9m. The schematic diagram showing the well spacing is presented in Figure 3. *The schematic layout of SVE, AS and air intake wells is shown in Figure 3a.*

2) For "Heavy Hot Spot B" (SVE/AS Pretreatment)

The ROI for SVE is 12m and the ROI for AS is 6m (same as the original design values). The respective well spacing is 20.8 m and 10m. Using this design, the contaminant migration from heavy hot spot to light hot spot can be minimised. It can also result in cost saving.

12. Measures to Improve ROI and Distribution

1) Pulsed Operation

One option to improve the air movement within any stagnant spots is to employ a pulsed mode of operation (Suthersan, 1996). Pulsed mode allows more effective stripping of contaminant when the remediation becomes diffusion-rate determined. It can also reduce airflow requirement so that additional blower/ Cat-Ox unit capacity can be utilised for other areas. Pulsed mode can be operated on a "day on and night off" basis. By controlling the flow through different header laterals, pulsed mode can be practised at selected areas. The time to introduce pulsing can be determined during the operation stage.

2) Increase in Sparging Rate

In the areas of the site where the SVE flow rate is limited by upwelling we propose to use a higher air sparging flow rate to enhance aeration of the saturated and vadose zone (Brown, 1992a; Johnson, 1995; Lundegard & Anderson, 1993). The risk of contaminant migration is low provided that this is practised in the inner wells. Any escaped air would be captured by the outside rows of SVE wells.

3) Re-injection in Vadose Zone

Air would be re-injected in the vadose zone for problematic areas to minimise groundwater mounding and improve SVE flow.

13. Clean Up of Land Adjacent to Airport Tunnel

As discussed in Section 7, safety distances between the areas of remediation works and the airport tunnel must be kept (5m for SVE, 15m for excavation and AS). However, the zone of influence of SVE would extend into this area. This will lead to clean up of this area, albeit at a longer duration.

It is recommended that the operation of one row of SVE wells (no AS wells) installed near the airport tunnel be allowed to continue after the pretreatment period of 6 months, and beyond the period of 18 months if necessary. Groundwater extraction can depress the water table and allow SVE to treat the saturated zone soil. Groundwater will be recharged at appropriate location to ensure no adverse impact on the structure of the tunnel.

14. Air Quality Impact Due to the Cat-Ox Unit

There are two changes in the present design from the design presented in the EIA report. These necessitate a review of the air quality impact from the Cat-Ox unit. The changes are as follows:

1) Part of the Hotspot B would be biopiled after SVE/AS pretreatment; and

2) The Cat-Ox unit is relocated to a more eastern position.

For change No. 1: In the present design, there will be one centralised Cat-Ox unit, which will collect vapour from both the SVE/AS system and the biopiles, the same as the original design. In the EIA Report, the emission factor was derived from the total air flow of the system (SVE/AS and biopile), which will remain unchanged in the present design. Therefore, although there would be increase in the size of biopile after the first 6 months of operation, the effect would be cancelled out by a smaller SVE/AS operation at Hot Spot B. In summary, this change would not affect the 120m buffer distance from the Cat-Ox emission point.

For change No. 2: Section 7.2. of the EIA Report shows that at the worst affected elevation of 15m, exceedances of HPCL for benzene are not predicted at more than 120m from the Cat-Ox discharge point. Since the airport tunnel portal and any sensitive receptors are located beyond 120m away, there will not be any adverse air quality impact, as illustrated in Figure 4.

15. Safety Protection Measures

Protection of Site Workers

The following measures would be implemented.

- SVE to pretreat the vapour and methane prior to excavation
- Minimse the presence of trenches and pits to eliminate trip-fall hazard
- Personal protective equipment
- Chemical exposure and explosive monitoring for workers

Protection of Airport Tunnel

The following measures would be implemented.

- Excavation during dry season to prevent water seepage
- 'Incremental' excavation at both sides of the tunnel and instantaneous backfill to protect the structural integrity of the tunnel

16. Additional Investigation (Prior to Works)

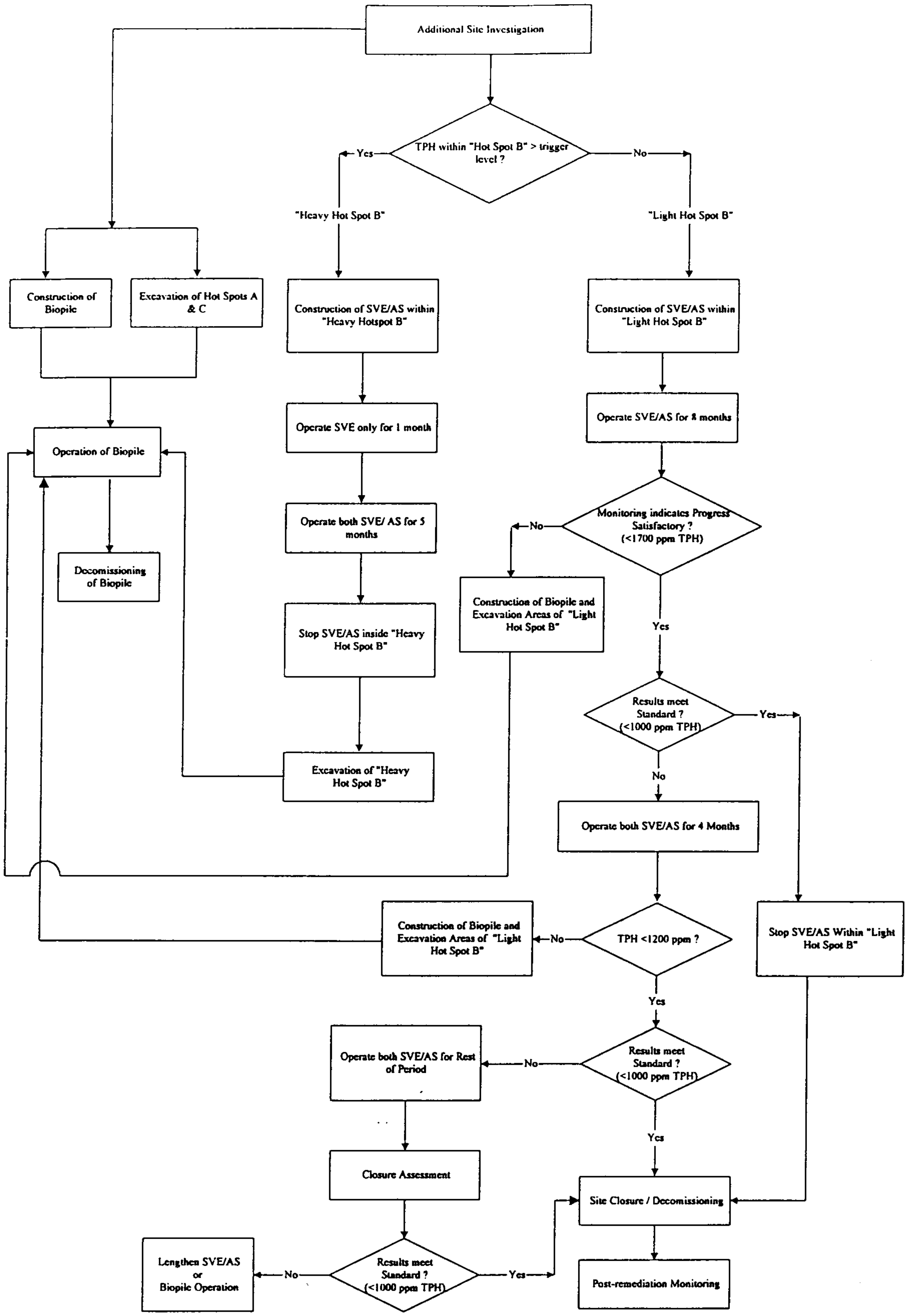
We propose to undertake a further investigation at Hot Spot B in order to delineate the trigger concentration contour with more accuracy. There will be about 52 sampling points based on a 50m x 50m grid. The investigation plan is presented in Figure 5.

17. Interim Site Investigation For "Light Hot Spot B"

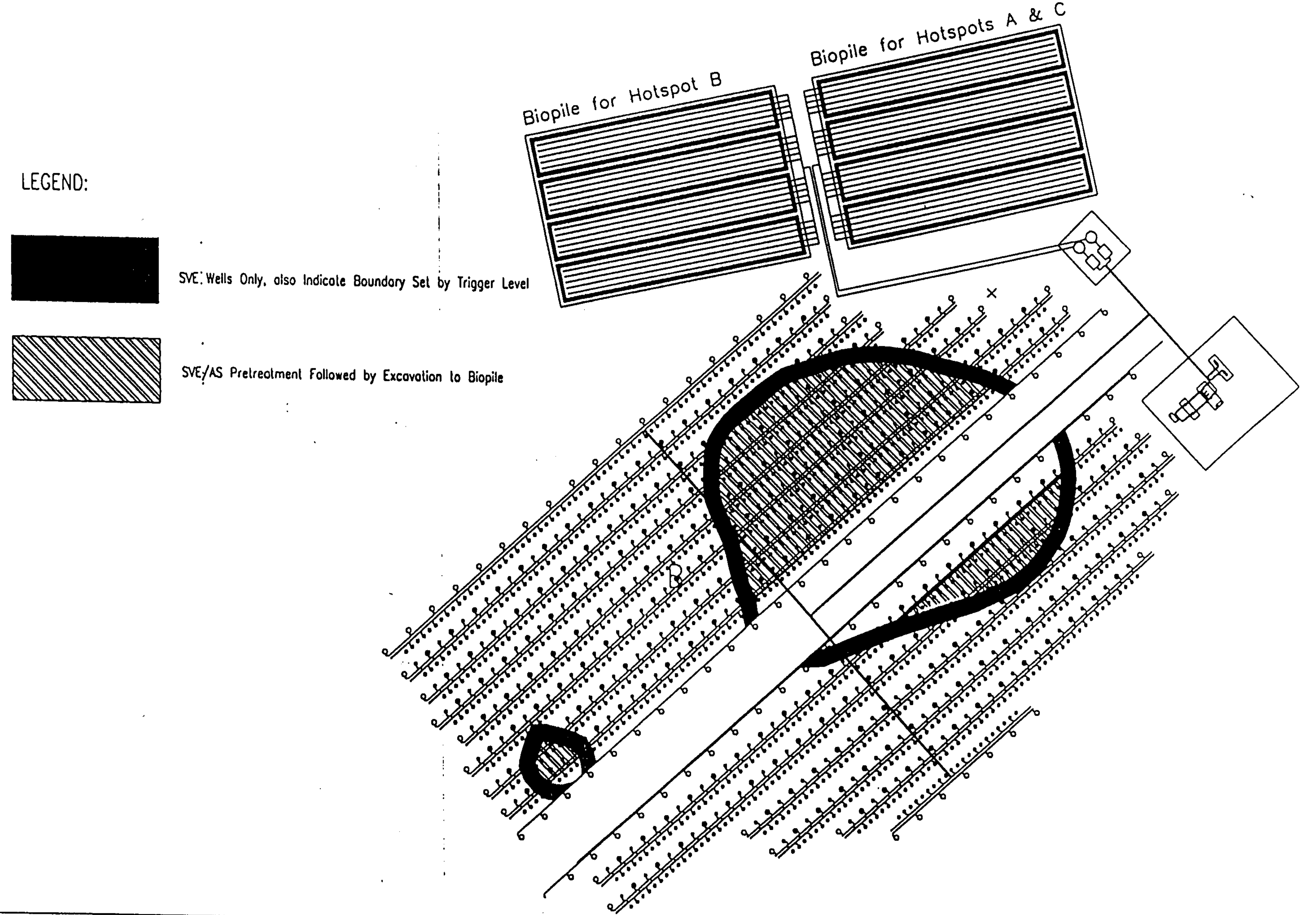
An interim site investigation will be undertaken for "Light Hot Spot B" after SVE/AS has been conducted for 8 months. This site investigation will comprise soil sampling and testing of the soil samples for TPH and BTEX. If the TPH levels of the soil samples still exceed 1700±10% ppm, then the soil at "Light Hot Spot B" will be further treated by means of biopiling. Reduction of 200-700 ppm TPH can be achieved within biopiling period of 4 months.

After 12 months of SVE/AS treatment, another round of interim site investigation using a cut-off value of 1200±10% ppm would be used to determine whether biopiling is needed.

A separate submission would be prepared after the completion of the additional investigation and implementation of the clean up system for EPD agreement. This separate document should specify the number and location of sampling points for the interim site investigation for "Light Hot Spot B".



Maunsell	TITLE **Revised Sequence of Remediation within Hotspot B**	MAUNSELL ENVIRONMENTAL MANAGEMENT CONSULTANTS LTD			
		PROJECT NO	C411	FIGURE NO.	Figure 1
		DESIGNED/ CHECKED	EL	DATE	March 1999



Project	Decontamination and Site Preparation at Kai Tak Airport	Figure	2
Title	Revised Remediation Layout for Hotspot B	Scale	N. T. S
		Date	March 1999

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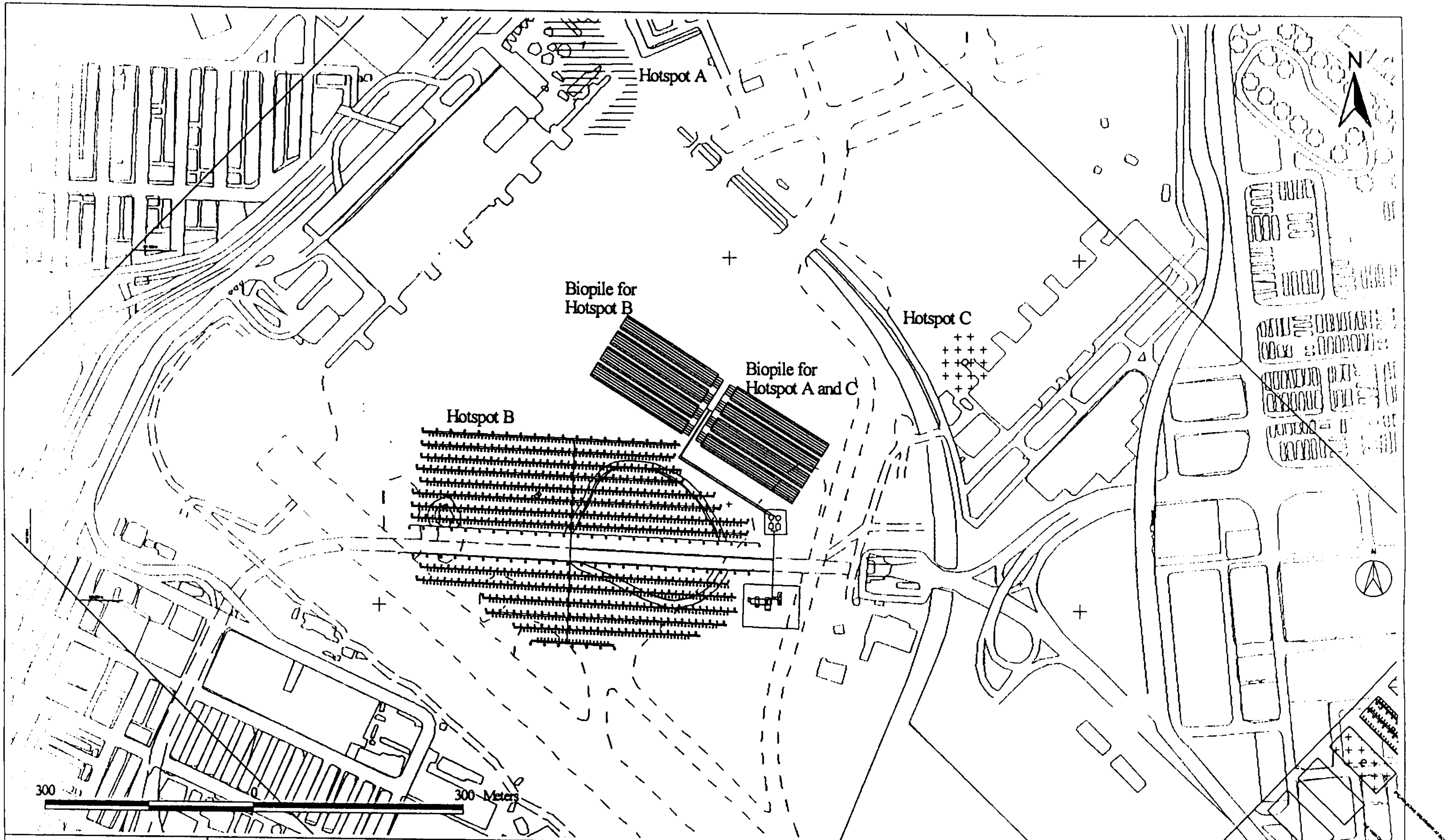

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FEASIBILITY STUDY FOR SOUTH EAST KOWLOON DEVELOPMENT

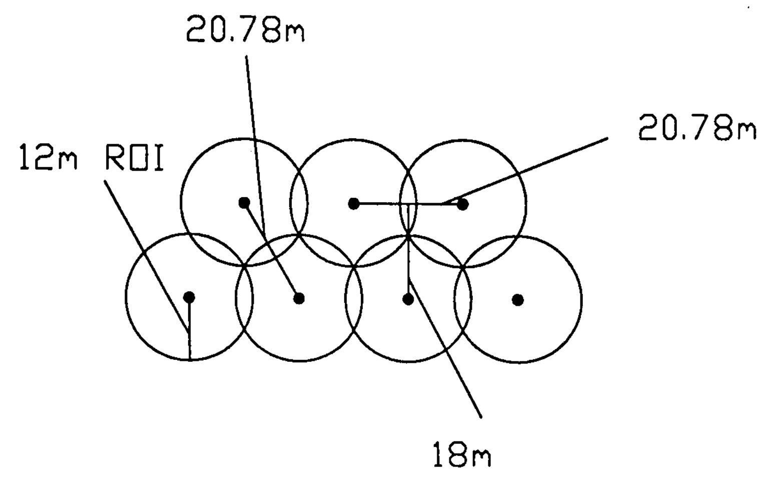
TITLE

Revised Remediation Layout for Hotspot B

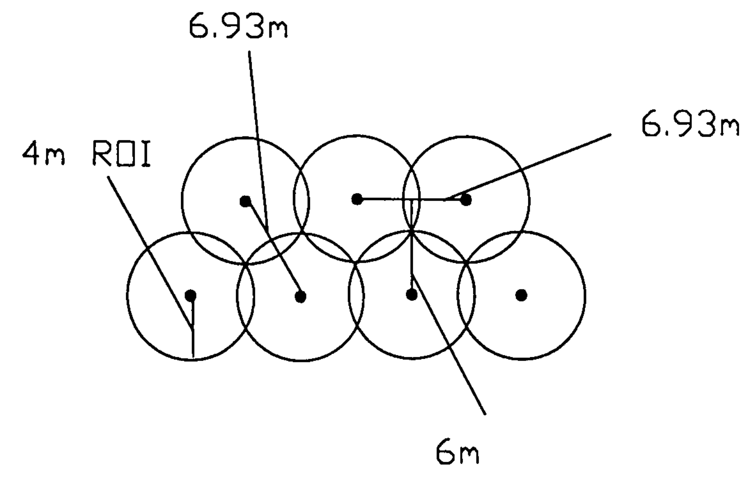
Territory Development Department, Hong Kong
Kowloon Development Office

SCALE	1 : 7500	DATE	Mar. 1999
DESIGNED CHECKED	Matthew Ko	DRAWN	Fanny Lau
CAD REF.	C410	DRAWING NO.	Figure 2a
		REV	0

SVE Well Layout for 12m ROI



AS Well Layout for 4m ROI



Project	Decontamination and Site Preparation at Kai Tak Airport	Figure	3
Title	SVE/ AS Wells Spacing for "Light Hot Spot B"	Scale	N. T. S.
		Date	March 1999

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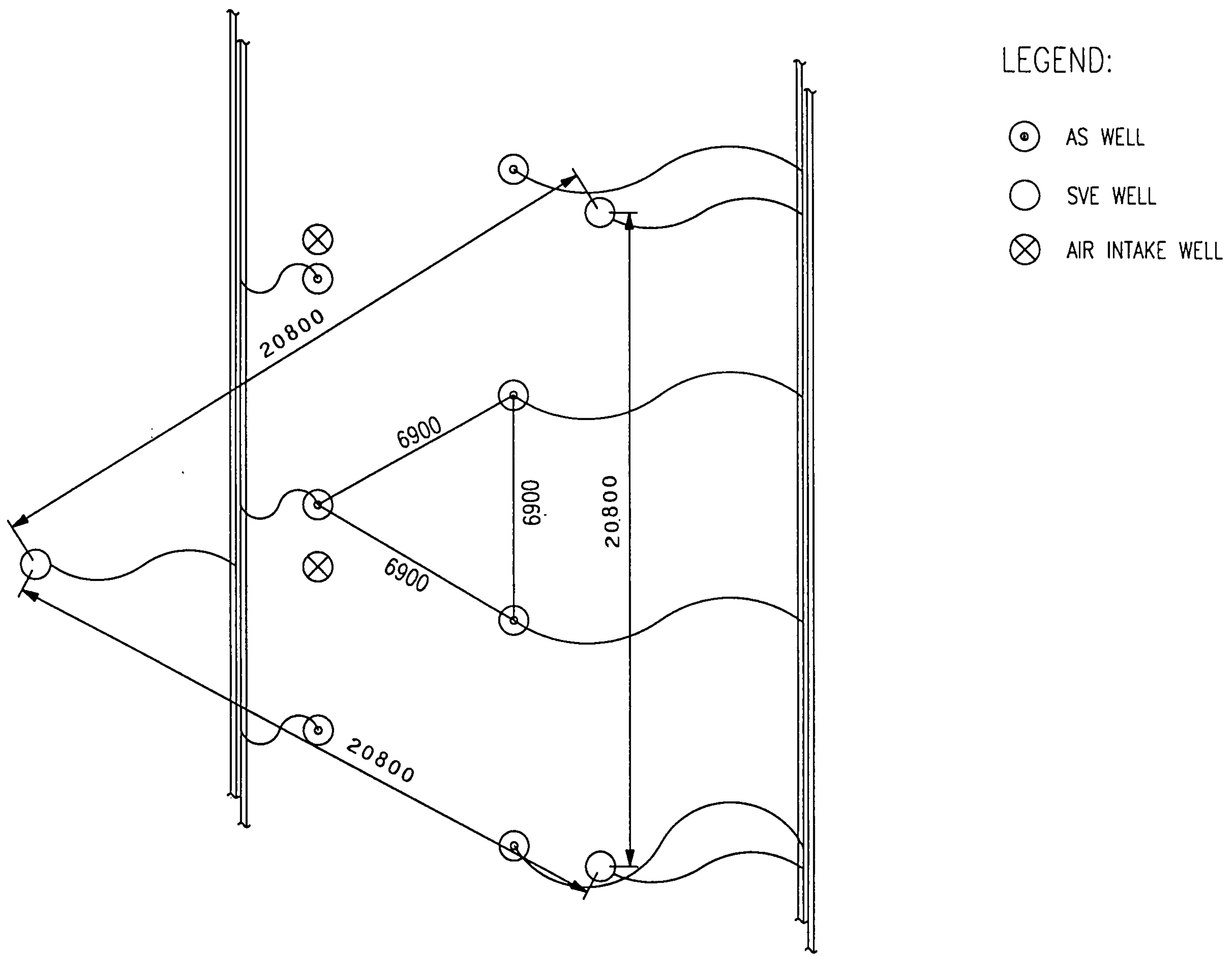

Project	
Title	Schematic Diagram of SVE/AS Wells Layout for "Light Hot Spot B"
Figure	3a
Scale	N. T. S.
Date	March 1999

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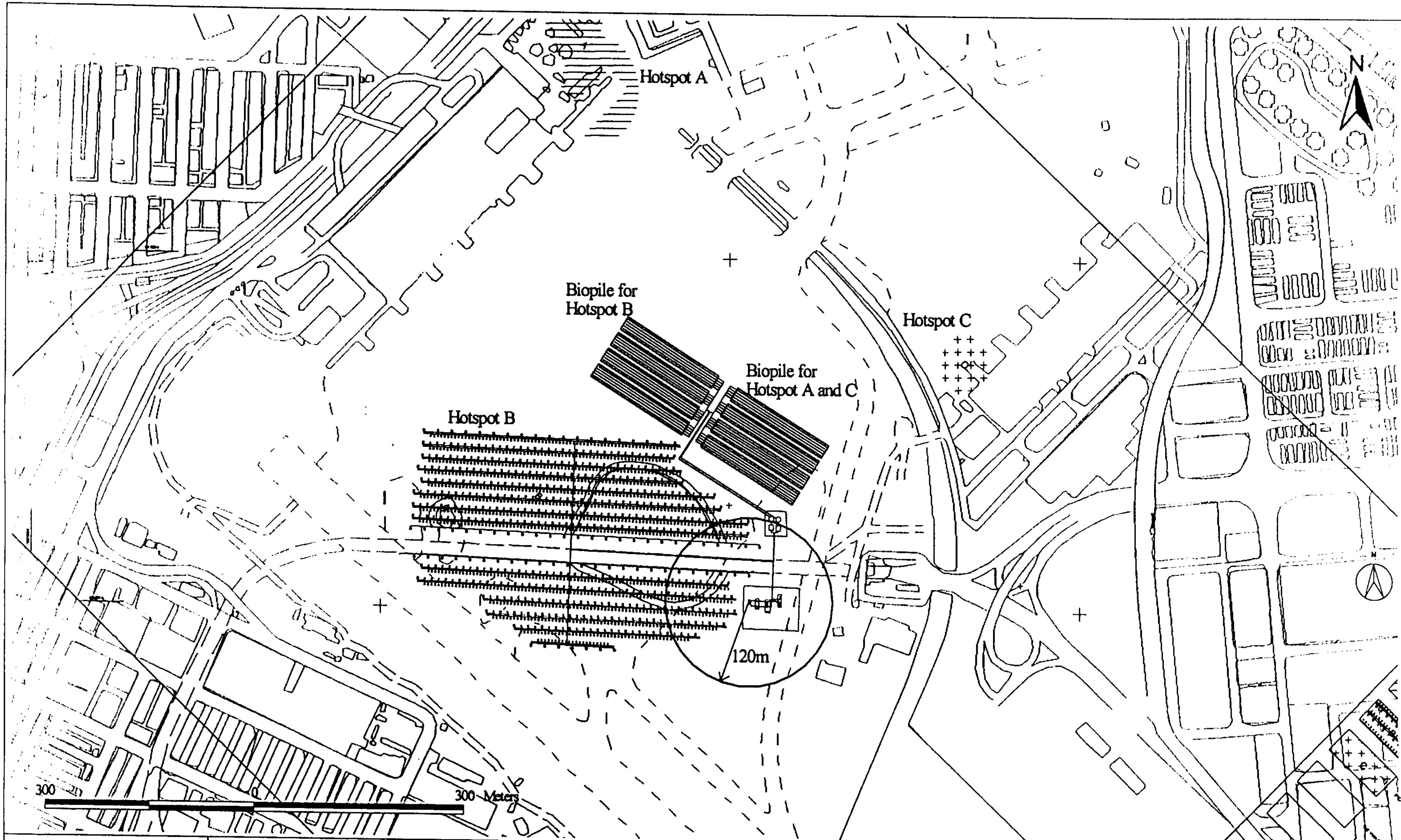

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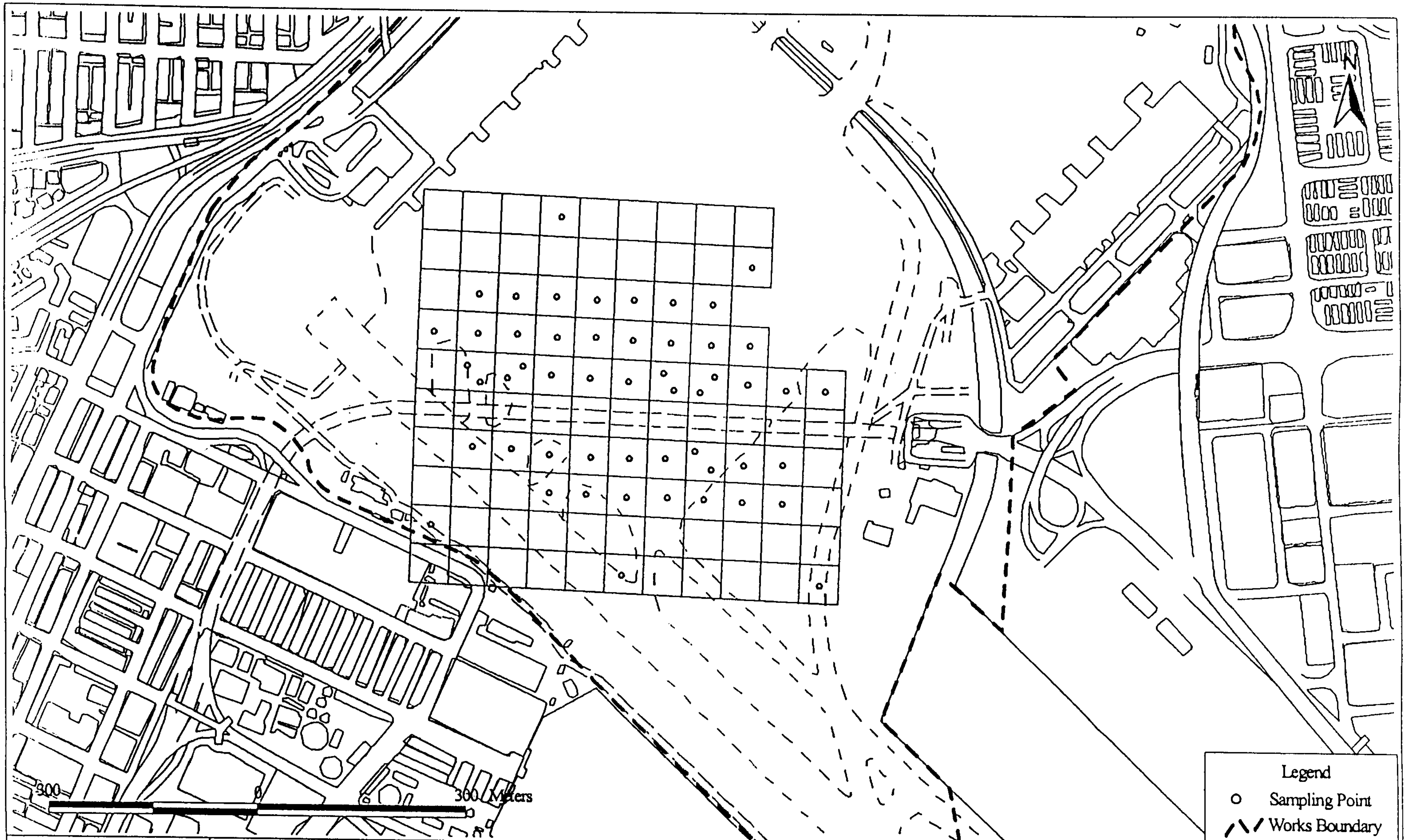
FEASIBILITY STUDY FOR SOUTH EAST KOWLOON DEVELOPMENT		Territory Development Department, Hong Kong Kowloon Development Office	
TITLE Predicted Max 1-hour Average Benzene Concentration at 15m Height (Worst Height) at 20% Extraction Rate and 0% Destruction Efficiency	SCALE	1 : 7500	DATE Mar. 1999
	DESIGNED CHECKED	Matthew Ko	DRAWN Fanny Lau
	CAD REF.	C410	DRAWING NO. Figure 4 REV 0



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FEASIBILITY STUDY FOR SOUTH EAST KOWLOON DEVELOPMENT

TITLE

Sampling Point Locations

Territory Development Department, Hong Kong
Kowloon Development Office

SCALE	1 : 15000	DATE	Mar. 1999
DESIGNED CHECKED	Matthew Ko	DRAWN	Fanny Lau
CAD REF.	C415	DRAWING NO.	Figure 5 REV 0

APPENDIX A

Calculation of Trigger Level

Back-Calculation of Trigger Levels for Clean-up in Saturated Zone

Case I Assume 56% biodegradation
44% volatilization (based on contaminant data and the assumptn that the conc. of C_{11} is half of C_{11}-C_{12} also refer lab's certification attached.)
and Biodegradation rate = $\frac{1 mg}{Kg/day}$

For clean-up time for biodegradation in saturated zone
= 18 months = 540 days.

Biodegradation rate in saturated zone
= 158 Kg/day (refer to the calculation given in Appendix Q of Pilot Test Final Report)

M_{TPH} = 158 kg/day × 540 days = 85,320 kg

Mass of TPH in saturated zone × 56% - 1.58e5 kg = 85,320 kg

∴ Mass of TPH in saturated zone = 4.35 e5 kg

Mass of TPH in saturated zone = 4.35 e5 kg = 1.58 e8 kg × Average conc. × $\frac{1 kg}{10^6 mg}$

⇒ Average trigger level conc. = <u>2,750 mg/kg soil</u>

Case II Assume 56% biodegradation
44% volatilization
and biodegradation rate = $\frac{2 mg}{Kg/day}$

For clean-up time for biodegradation in saturated zone = 540 days

Biodegradation rate in saturated zone
= 316 Kg/day (refer to the calculation given in Appendix Q of Pilot Test Final Report)

M_{TPH} = 316 kg/day × 540 days = 170,640 kg

Mass of TPH in saturated zone × 56% - 1.58e5 kg = 170,640 kg

∴ Mass of TPH in saturated zone = 5.87 e5 kg

Mass of TPH in saturated zone = 5.87 e5 kg = 1.58 e8 kg × Average conc. × $\frac{1 kg}{10^6 mg}$

⇒ Average trigger level conc. = <u>3,700 mg/kg soil</u>

6.2.2 Clean Up Time Based on Typical Literature Values

Based on the results reported in Technical Report No. RA24[2], six most contaminated locations (MW241, MW242, MW250, MW253, MW259, and MW262) within Hot Spot B were selected for this calculation. The spatial distribution of TPH at each location is tabulated in Table 6.4.

Table 6.4 Vertical Distribution of TPH at Six Most Contaminated Locations within Hot Spot B

	MW 241	MW 242	MW 250	MW 253	MW 259	MW 261
TPH at 2-3m below grade (mg/kg)	338	5360	2675	20	52	4440
TPH at 3m or more below grade (mg/kg)	2522	29	133	4061	21728	No data
	Averaged TPH concentration = 3760 mg/kg					

As reported in the standard "CRC Handbook of Physical Properties of Organic Chemicals", the averaged vapour pressure of isomers of C10 and C11 are 2.1mm Hg and 0.52 mm Hg respectively, these meet the criteria of chemicals amenable to SVE (0.5 mm Hg). On the other hand, the laboratory quantification of the proportion of C6-C11 fraction (volatile fraction) within the whole C6-C36 fraction of the six most contaminated samples collected within Hot Spot B is tabulated in Table 6.5.

Table 6.5 Quantification of Proportion of C6-C11 Fraction

Sample ID	C6-C11 (mg/kg)	C6-C36 (mg/kg)	(C6-C11)/(C6-C36) x 100%
MW241-2	954	2522	38 %
MW242-1	2880	5360	54 %
MW250-1	1013	2675	38 %
MW253-2	2543	4068	63 %
MW259-2	7349	21728	34 %
MW261-1	1741	4440	39 %
			Mean = 44 %

Therefore, the percentage of volatile fraction of the THP contaminant is 44%. That means 44% of the TPH would be removed by means of volatilisation and the remaining 56% would be removed by means of biodegradation.

The following assumptions were made for this calculation:

1) Thickness of the contaminated zone is 2m (from 2 to 4m below grade)

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FACSIMILE TRANSMISSION

To	:	Matthew Ko
Company	:	Maunsell Environmental Management Consultants Limited
Fax	:	28910305
From	:	Andy Chan
Date	:	Mar 4, 1999
Subject	:	TPH Testing
No. of page	:	1 (Including this page)

Dear Matthew,

The sample results of C10 and C11-12 range of Total Petroleum Hydrocarbon are certified and as shown in the following:

	C10 (mg/kg)	C11-12(mg/kg)
MW241-2	310	770
MW242-1	1100	1400
MW250-1	230	1200
MW253-2	1200	930
MW259-2	1100	11000
MW261-1	550	1600

Regards,

Andy Chan

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TOTAL P.01

"Appendix Q" of Decontamination
Pilot Test Final Report

Calculation of Extraction Time

Monitoring Well	MW241	MW242	MW250	MW253	MW259	MW261
TPH Conc. at 2-3m	338	5360	2675	20	52	4440
TPH conc. below 3m	2522	29	133	4061	21728	No data
Average conc. of TPH = 3760 mg/kg						

Contaminated area = 59,500 m^2 ; Density of soil (ρ_{soil}) = 1765 Kg m^{-3}

Mass of vadose zone soil = 59,500 m^2 × ρ_{soil} × 0.5 (2m deep) (assume 25% of contaminated soil at vadose zone) (based on boring records reported in Technical Report RA24 issued by NCAL)

= 5.25e^7 kg

Mass of saturated zone soil = 59,500 m^2 × ρ_{soil} × 1.5

= 1.58e^8 Kg

Mass of TPH in vadose zone = 5.25e^7 kg × 3760 $\frac{mg}{kg}$ × $\frac{1\ Kg}{10^6 mg}$ = 1.97e^5 kg

Mass of TPH in saturated zone = 1.58e^8 kg × 3760 $\frac{mg}{Kg}$ × $\frac{1\ Kg}{10^6 mg}$ = 5.94e^5 Kg

Total = 7.91e^5 Kg

Time for Biodegradation In Saturated Zone

Assume 56% biodegradation → 4.43 e^5 kg

44% volatilisation → 3.48 e^5 kg

Mass of TPH in saturated zone × 56% − "allowable mass"

= 5.94 e^5 kg × 56% − 1.58 e^5 kg

= 3.33 e^5 kg − 1.58 e^5 kg

= 1.75 e^5 kg = 175,000 kg

Total mass of soil in saturated zone = 1.58 e^8 kg

(A) Assume $\frac{1 mg}{kg/day}$ biodegradation rate

Saturated zone biodegradation rate

= 1.58 e^8 kg × $\frac{1 mg}{kg/day}$ × $\frac{kg}{10^6 mg}$

= 158 kg/day

∴ Biodegradation time = $\frac{M_{TPH}}{\text{Bio. rate}}$

= $\frac{175{,}000 \text{ kg}}{158 \text{ kg/day}}$

= 1108 days

= 3 years

Case (B) Assume $\frac{2 mg}{kg/day}$ biodegradation rate

Saturated zone biodegradation rate

= 1.58 e^8 kg × $\frac{2 mg}{kg/day}$ × $\frac{kg}{10^6 mg}$

= 316 kg/day

∴ Biodegradation time = $\frac{M_{TPH}}{\text{Bio. rate}}$

= $\frac{175{,}000 \text{ kg}}{316 \text{ kg/day}}$

= 554 days

= 1.5 years

APPENDIX B

Procedure of Commissioning

General Plan for Construction and Commissioning Stages for the SVE/AS System at KTA

Objective

This plan highlights the precautionary elements and other provisions to be included in the construction and commissioning procedure to cope with unexpected conditions such as extra contamination, localised flow/ vacuum problems, channeling as identified during the pilot test. The commissioning procedure contained in the Operation and Maintenance Manual to be submitted by the Contractor will detail the step- by-step procedure of testing plant equipment (electrical & mechanical), process integration, control and instrumentation mechanisms. It will also analyse different scenarios during start up and operation.

Drilling and Construction Stage

1. *Laboratory Permeability Tests.* Collect Soil Samples at selected SVE wells and AS wells for bench scale permeability tests (column tests). Use test data to generate contours of permeability distribution across Hotspot B. Use this information to estimate the venting and sparging rates across different sections of the site. These initial estimates will be confirmed during the start-up performance monitoring.

2. *VOC analysis.* Test VOC levels at all SVE wells during installation to indicate the contaminant distribution within Hot spot B. At the boundary wells, if the levels exceed the 'cut-off value' *(100 ppm VOC)*, then the Engineer is consulted for instruction to expand the treatment zone.

3. *Contingency connection joints in sparge lines.* To prepare for localised poor permeability in vadose zone, T-off connection joints are installed at regular intervals at the sparge line (or at the tubing that connects the AS lateral to each AS well) which can be connected to the air intake wells for aeration of the vadose zone.

4. *Outside Monitoring wells.* Some vapour monitoring probes screened in the vadose zone (at least 10 in number) will be installed outside the treatment zone to ensure no migrating vapour due to sparging.

Commissioning Stage

1. *Equipment Check.* Individual equipment (blowers, Cat-Ox unit) will be tested after installation on site to demonstrate compliance with the performance specifications.

2. *Interlocks.* After completion of construction of the treatment system, interlocking mechanisms between SVE/AS/ Cat-Ox are checked. The interlock ensures that the AS will not operate when the SVE is off. The SVE will not operate when the Cat-Ox unit is off, unless under special situation when the VOC discharge is found to be acceptable.

3. *SVE Start up.* The SVE wells will be commissioned first. At the time of start-up, all SVE wells will be on-line, the valve on the main manifold is throttled, the bleed air valves at the blower intakes are fully open and the lower explosive limit (LEL) of the vapours will be monitored. The manifold and bleed air valves shall be adjusted as necessary to ensure that the LEL does not exceed 25% at the oxidiser inlet and that there is not an unacceptable temperature rise in the oxidizer to prevent overheating. It may take a few weeks for the LEL to decrease to less than 25%.

4. *SVE well adjustment.* The SVE wells will be throttled to ensure a desired distribution of vacuum and flow to each of the wells. Record the vacuum *vs* flow relation and record wells experiencing low flow or groundwater uplift. These will be later coped with by Item 7 and/or Item 10 described below.

5. *AS Start up.* After the flows are balanced on the SVE wells, the air sparging blower will be started. It may be necessary to close the valves of the lateral lines and to dedicate full flow and pressure to one well line at a time to develop the necessary flow at each well.

6. *Low SVE flow.* To address low permeability in unsaturated soil (SVE air flow limited in the low permeability soils by groundwater upwelling), a higher sparge rate would be used (say 10-20cfm per well).

7. *Vapour Capture by SVE.* The greater amounts of air injected at these high sparge rate areas would be captured by the high SVE flow rate in the perimeter wells. The total sparge rate would be set to be lower then the overall SVE rate so that no contaminated vapour can migrate off-site. Monitor probes outside the system shall be used to verify the contaminated air is not migrating away from the site.

8. *Air injection at intake wells.* If increased sparge rate alone cannot mitigate the groundwater mounding problem, then the air injection at air intake wells will be started at the problematic areas. The AS blower would have sufficient capacity for this purpose.

9. *Stagnant area checks.* Measure the dissolved oxygen (DO) at the selected air intake wells drilled into water table. Saturated soil with low DO may indicate stagnant zones, and an increase in sparge rate is needed to enhance the lateral spread of the air bubbles thus expand the AS wells' zone of influence.

10. *Pulse Mode.* If low DO persists in some areas, then pulse mode may be operated at these areas to mitigate any short channeling effects. Pulse mode will be operated on a day-on and night-off sequence or as necessary to optimise performance of the system.

11. *Cat-Ox Unit discharge.* Measure the VOC discharged from the Cat-Ox unit for compliance check.