TECHNOLOGY DEMONSTRATION PROJECT REPORT: TDP12

BIOREMEDIATION OF THE COKE WORKS
AND FORMER COLLIERY AT ASKERN,
DONCASTER

CONTAMINATED LAND: APPLICATIONS IN REAL ENVIRONMENTS

CL:AIRE

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CL:AIRE was established as a public/private partnership in March 1999, to facilitate the field demonstration of remediation research and technology, including innovative methods for site characterisation and monitoring, on contaminated sites throughout the UK. The results of project demonstrations are published as research or technology demonstration reports and disseminated throughout the contaminated land community.

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Contaminated Land: Applications in Real Environments (CL:AIRE)

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Bioremediation of the Coke Works and Former Colliery at Askern, Doncaster

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Contaminated Land: Applications in Real Environments (CL:AIRE)

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This is a CL:AIRE Technology Demonstration Project Report. Publication of this report fulfils CL:AIRE's objective of disseminating and reporting on remediation technology demonstrations. This report is a detailed case study of the application of bioremediation technology at the coke works and former colliery at Askern, Doncaster. It is not a definitive guide to the application of bioremediation. CL:AIRE strongly recommends that individuals/organisations interested in using this technology retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

Askern Colliery is located in the town of Askern, approximately 10 miles north of Doncaster, South Yorkshire.

Askern Colliery was a derelict colliery and coke works, consisting of two shafts with the associated process and ancillary installations. The site was identified, with many other colliery sites in Yorkshire during the 1980s, as requiring redevelopment to encourage local economies and prosperity. The responsibility of the redevelopment was placed with the relevant regional development agencies. Askern Colliery fell under the jurisdiction of Yorkshire Forward.

Many of the former colliery sites have severe soil and groundwater contamination issues and this was also the case at Askern. The coke works closed in 1986 and the colliery shortly afterwards. Geotechnical and contamination investigations commenced in 1993. The contract for the remediation of the site was tendered in 2001 and was won by Mowlem Remediation. The consultant engineer was Carl Bro Group and the bioremediation was carried out by Ecologia Environmental Solutions.

The general geology of the site was reported as being deposits of made ground which are over thin lenses of drift deposits of glacial sand and gravel which are underlain by solid deposits of marl and magnesian limestone.

Prior to the bioremediation of the contaminated soils, the contaminated area was mapped and investigated by Mowlem to allow the accurate segregation of the materials at the site. This had the effect of reducing the volume of material requiring treatment or disposal from an estimated 52,000 m^3 to 24,000 m^3.

Bioremediation was selected as an appropriate technique to remediate the contamination at the site, which was predominantly made up of hydrocarbons. Bioremediation is the use of bacteria to metabolise hydrocarbon contamination and is employed in a variety of technologies. The type of bioremediation used by Ecologia at Askern was biopiles.

Biopiles are static, engineered, soil piles which have aeration lines installed to facilitate the active transfer of gases through the soil, thereby providing oxygen for the bacterial population. At Askern the aeration was induced with a vacuum blower.

The biopiles were constructed on an impermeable base formed from colliery spoil which was present at the site. The nutrient content and moisture content of the contaminated soils were adjusted during the formation works and the biopiles were then covered to prevent saturation. Proprietary bacterial products were not added, as the biopiles were designed to remove limiting factors for the bacterial population present rather than replace it.

Composite samples of the contaminated soils were taken during the formation works to provide a contamination baseline and subsequent samples were taken every four weeks for the twenty week duration of the project. For sampling purposes the 22,000 m^3 of soil undergoing treatment were sub-divided into 1,000 m^3 lots.

The gases within the biopiles were monitored on a weekly basis. The gas monitoring showed that the oxygen content, and therefore the biodegradation within the soils, is highly dependent upon the active aeration system. The monitoring also showed that very few volatile hydrocarbons were lost during the project.

The chemical analysis revealed that 20 of the 22 lots achieved the risk assessment target values. Two of the lots remained above the 1,000 mg/kg target for total petroleum hydrocarbons (2,600 mg/kg and 1,800 mg/kg) and were placed in a part of the site over marl bedrock to comply with the risk assessment.

The study of the project has revealed that bioremediation can be shown to remediate hydrocarbon contaminated soils. Careful monitoring can allow the process to be controlled and validation data produced.

ACKNOWLEDGEMENTS

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ABBREVIATIONS

BTEX   Benzene, Toluene, Ethylbenzene and Xylenes (ortho, meta, para)

EA   Environment Agency

GC-FID   Gas Chromatography coupled with Flame Ionisation Detection

HDPE   High Density Polyethylene

MPL   Mobile Plant Licence

pA   picoamps
PAH   Polycyclic Aromatic Hydrocarbons
PCB   Polychlorinated Biphenyls
PID   Photoionisation Detector
ppm   parts per million

TCCS   Composted Sewage Sludge
TPH   Total Petroleum Hydrocarbons

UCM   Unresolved Complex Mixture
USEPA   United States Environmental Protection Agency

VOC   Volatile Organic Compounds

1. INTRODUCTION

1.1 BACKGROUND

Askern Colliery was a derelict colliery and coke works, consisting of two shafts with the associated process and ancillary installations. The site was identified during the 1980s, along with many other colliery sites in Yorkshire, as requiring redevelopment to encourage local economies and prosperity. The responsibility of the redevelopment was placed with the relevant regional development agencies. Askern Colliery fell under the jurisdiction of Yorkshire Forward.

Many of the former colliery sites have severe soil and groundwater contamination issues and this was also the case at Askern Colliery. The coke works closed in 1986 and the colliery shortly afterwards. Geotechnical and contamination investigations commenced in 1993. The contract for the remediation of the site was tendered in 2001 and was won by Mowlem Remediation. The consultant engineer was Carl Bro Group and the bioremediation was carried out by Ecologia Environmental Solutions.

Prior to the bioremediation of the contaminated soils, the contaminated area was mapped and investigated by Mowlem to allow the accurate segregation of the materials at the site. This had the effect of reducing the volume of material requiring treatment or disposal from an estimated 52,000 m^3 to 24,000 m^3.

The development plan for the site was for the provision of a local amenity, including landscaped areas and sports facilities. One section of the site has been identified as a possible future residential area.

This report focuses mainly on the bioremediation using biopile technology. The wider site works are discussed only to the extent that they place the bioremediation in context.

1.2 REPORT ORGANISATION

A background to the microbiology of bioremediation is given in Chapter 2. Chapter 3 presents a general overview of biopile technology. A brief description of the site is provided in Chapter 4, and Chapter 5 discusses supporting issues associated with the technology demonstration. The exercise in contamination mapping and subsequent excavation is detailed in Chapter 6 and the design and formation of the biopile are given in Chapter 7. Chapters 8 and 9 focus on monitoring and evaluating the performance of the biopile, while Chapter 10 discusses the economic issues of the remediation. Conclusions and lessons learned are provided in Chapters 11 and 12 respectively.

2.   MICROBIOLOGY OF BIOREMEDIATION

2.1   INTRODUCTION

The term bioremediation refers to the treatment or remediation of contaminated soils and groundwater using biological means. Engineered bioremediation systems enhance naturally occurring microbial processes to degrade organic pollutants more rapidly into harmless, natural substances.

Indigenous microorganisms in the soil or groundwater use the petroleum hydrocarbons and hydrocarbons of other organic chemical compounds as a carbon source, i.e. food. In metabolic processes the hydrocarbons of the contaminants are decomposed step by step into carbon dioxide and water.

Although, nature "designed" these processes over millions of years for the degradation of natural organic matter, it has been shown that microorganisms, in particular certain bacteria, are also effective against an immense number of new chemical products which have been introduced into the environment since the beginning of the industrial revolution.

During bioremediation the optimal chemical and physical requirements of the concerned microorganisms need to be achieved. Some of the essential parameters in bioremediation treatment systems are nutrients, oxygen, water, pH and temperature. A clear understanding of microbiology is needed when designing and undertaking projects which involve the bioremediation of contaminated soils.

Bioremediation treatment systems can be grouped into two basic categories: *in situ* and *ex situ* (or non-*in situ* or above-ground). The term *in situ* indicates that the contaminated medium (soil and/or groundwater) is not physically moved or transported from its original location. *Ex situ* systems involve bringing the contaminated medium to the surface for treatment. The project at the Askern Colliery which is described in detail in this report is an *ex situ* bioremediation system.

This chapter will give a brief background to the microbiology of bioremediation and will discuss the classification of microorganisms, their physical and chemical requirements and will provide examples of some common hydrocarbon degradation pathways. Additional discussion can be found in Boyd (1988).

2.2   WHAT ARE MICROORGANISMS?

The term 'microorganisms' includes bacteria, archaea, protozoa, algae and fungi. All living organisms can be divided into prokaryotes and eukaryotes (see Figure 2.1). Prokaryotes consist of bacteria and archaea whilst eukaryotes consist of unicellular organisms (protozoa, fungi and algae) and multicellular organisms (animals and plants). In engineered bioremediation systems, bacteria and fungi are the important microorganisms.
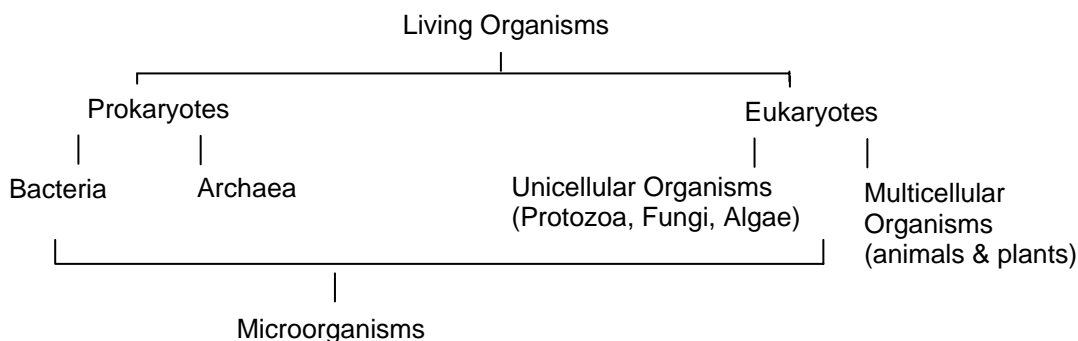
Figure 2.1: Classification of living organisms

2.3   BIODEGRADATION REQUIREMENTS

The physical and chemical requirements to sustain bacterial life are illustrated in Figure 2.2.
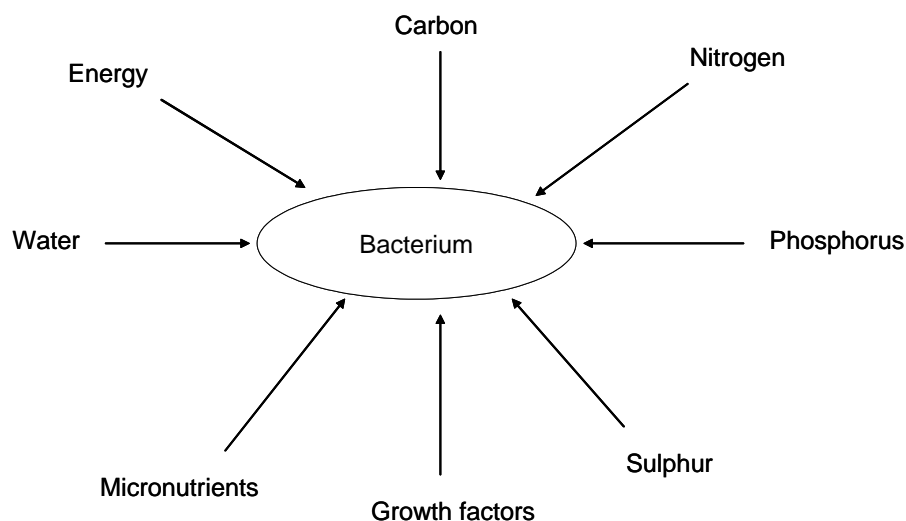
Figure 2.2: Physical and chemical requirements for bacteria

The following sections explore in more detail the nutritional and energy requirements of microorganisms.

2.3.1   NUTRIENTS

The macronutrients carbon, nitrogen, phosphorus and sulphur are essential requirements because they form the basis of all living organisms whilst phosphorus is also essential to make nucleic acids. Micronutrients include elements like zinc, copper and molybdenum. Other essential growth factors (substrates) are pre-formed organic compounds, required as nutrients by the microorganisms. In general, materials can only be transported across cell membranes in soluble form, so water is a requirement for all biochemical processes.

Carbon is required by most organisms as a nutritional substrate (or food source) for energy and growth. Those organisms that use organic carbon (e.g. hydrocarbons) are called heterotrophs and most microorganisms, including bacteria, belong to this group. Heterotrophs are the key organisms for bioremediation of organic compounds.

2.3.2   ENERGY

Heterotrophs can be subdivided into photoheterotrophic bacteria which exploit light as a source of energy, and chemoheterotrophs, which exploit chemical forms of energy. Most microorganisms used in bioremediation are chemoheterotrophs.

The biodegradation of organic compounds (by chemoheterotrophs) is the result of microorganisms obtaining the energy that they require to survive and reproduce from the breakdown of chemical bonds in the carbon substrate. Enzymes are used to catalyse the bond-breaking process. The progressive breaking apart of the substrate eventually results in the conversion of harmful contaminant into either harmless or less-harmful substances.

The two main ways that heterotrophic microorganisms obtain the energy they require are via:

- Respiration (aerobic and anaerobic)
- Fermentation (anaerobic only)

During respiration an energy transfer process occurs which is mediated by a linked series of oxidation-reduction reactions that transfer electrons from a donor compound to another

compound called the electron acceptor. When oxygen acts as the terminal electron acceptor the process is called aerobic respiration and carbon dioxide and water are produced as by-products (see Figure 2.3). However, other compounds such as sulphate, carbon dioxide and nitrate can also act as electron acceptors and when this occurs the process is called anaerobic respiration. In fermentation an organic compound acts as the electron acceptor.
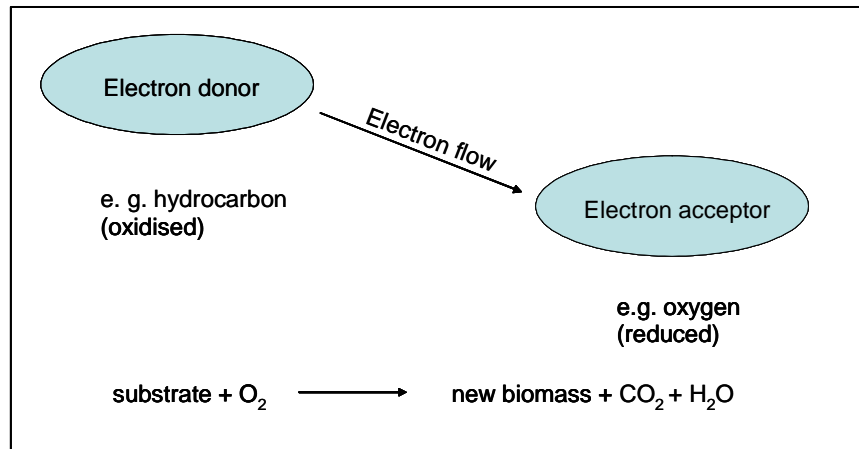
Figure 2.3: Aerobic respiration

Generally, bioremediation uses aerobic microorganisms (which use aerobic respiration) although anaerobic bacteria (which use anaerobic respiration) are increasingly being used in some field situations and bioreactors. Microorganisms which obtain their energy through fermentation are not generally used in bioremediation.

2.4 BIODEGRADATION OF HYDROCARBONS

2.4.1 INTRODUCTION TO HYDROCARBONS

Hydrocarbons are grouped into two classes, aliphatic and aromatic hydrocarbons. Whereas an aliphatic hydrocarbon is a straight or branched chain hydrocarbon (e.g. octane, C_8H_{18}) without a benzene ring, an aromatic hydrocarbon consists of one or more benzene rings. Aromatic compounds include the monocyclic aromatic compounds benzene, toluene, ethylbenzene and xylenes (BTEX compounds), phenols and polycyclic aromatic hydrocarbons (PAHs). These compounds can be found in petroleum products, which are widely used as fuels and industrial solvents.

The hydrocarbon type will affect the relative ease with which it will biodegrade. Straight chain aliphatic compounds are more easily biodegraded than aromatic compounds, whereas branched chain aliphatics are the least biodegradable. Hydrocarbon compounds containing both aliphatic and aromatic components are degraded sequentially, with the aliphatic portion of the molecule degrading first.

2.4.2 METABOLIC PATHWAYS

For the biodegradation of complex hydrocarbons, several different enzymes are usually required to complete full degradation of the compounds which constitute the contaminant(s). The series of reactions by which the compounds are metabolised are called biodegradation pathways. These complex pathways are often interlinked with other metabolic pathways which allow the organism to convert these compounds into a wide range of other compounds.

Any one compound can follow many alternative degradation pathways depending on the specific organisms involved and whether the degradation is aerobic or anaerobic. Many of

the common contaminants, such as naphthalene, phenol, benzene, phenanthrene and nitrobenzene, have interrelated degradation pathways.

An example of the degradation of the monocyclic BTEX compounds and phenol is shown in Figure 2.4, which illustrates that the degradation product for these compounds could be catechol, bearing in mind that this is just one of many possible biodegradation pathways.
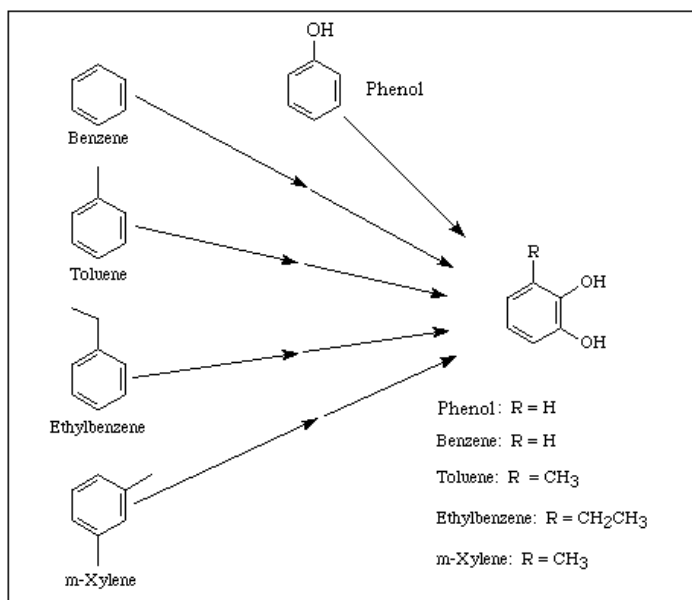
Figure 2.4: Degradation of monocyclic aromatic compounds to catechol

Polycyclic aromatic hydrocarbons (PAHs) form another group of aromatic hydrocarbons that are characterised by multiple fused rings. PAHs with 2- to 6-rings are commonly encountered in soil and groundwater contamination.

The ease with which PAHs biodegrade depends on the number of aromatic rings they have. Whereas 2- to 4-ring PAHs can potentially be degraded by microorganisms, higher condensed 5- and 6- ring systems are more resistant to microbial degradation. The main reason for the limitations in the biodegradability of large PAHs and other recalcitrant compounds is the absence of required enzymes or restricted enzyme activity.

Microorganisms degrade one ring of the polycyclic aromatic hydrocarbon at a time. Figure 2.5 shows the degradation of naphthalene, which with two fused benzene rings is the simplest PAH. Intermediate products of larger PAHs are further degraded via the catabolic pathway of the next smaller PAH. For example, the product 1,2-dihydroxynaphthalene in the phenanthrene (three fused benzene rings) pathway becomes further degraded to pyruvate and acetaldehyde via the naphthalene pathway.
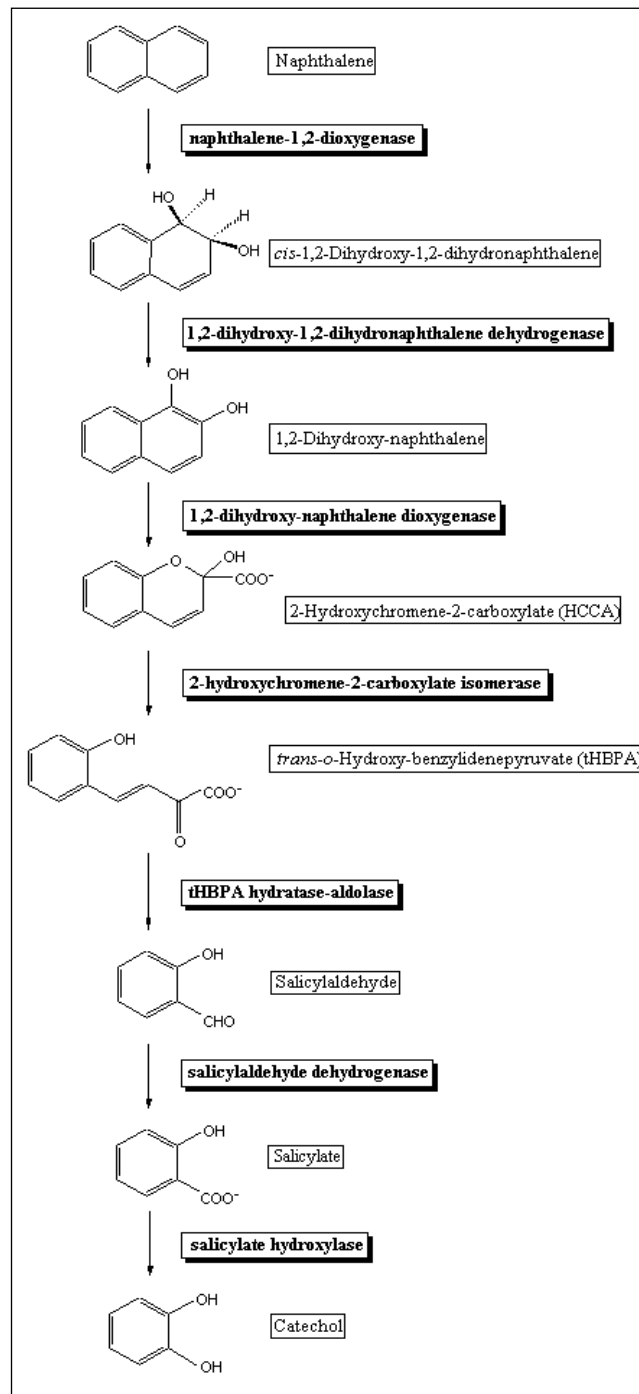
Figure 2.5: Degradation pathway of naphthalene

3. OVERVIEW OF BIOPILE TECHNOLOGY

3.1 INTRODUCTION

A large number of hydrocarbon and solvent contaminated sites require remediation in the UK. In the late 1980s the cleanup of these sites started on a large scale and since then more effective and less costly remedial alternatives have been developed and demonstrated. Biopile technology has been proven to significantly reduce the concentration of organic contaminants successfully.

Biopile technology involves forming petroleum-contaminated soils into piles or cells above ground and enhancing aerobic microbial activity through aeration of the soil. To optimise the degradation, moisture and nutrients, such as nitrogen and phosphorus, are added.

The aeration of the pile is facilitated by a perforated pipe network within the pile, which is connected to a blower and constructed above an impermeable base. The base aims to reduce the potential migration of leachate to the underlying soil and groundwater. A leachate collection system is advisable in some cases. Generally, the piles are covered with impermeable membranes to prevent the release of contaminants into the environment and to reduce the effect of weather conditions on the system.

3.2 ADVANTAGES AND LIMITATIONS

Compared to other commonly used above ground treatment technologies, such as thermal desorption and soil washing, the biopile technology has a number of advantages including:

- The contaminants in the soil are destroyed and not simply separated from the soil and transferred into another medium.
- The design and construction of biopile systems is relatively easy.
- Compared to other remediation systems the installation and treatment costs are low (£20 – £40 per m^3).
- Biopile treatment as a variation of bioremediation is a cost-competitive alternative to landfilling.
- Remediation requires a relatively short time. A period of three to six months offers sufficient time for most soil treatment, depending upon the contaminants in question.

Biopile technology is applicable to most biodegradable compounds. Examples of treatable common contaminants are listed below:

- Hydrocarbons and derived products
- PAHs
- Fats, oils and greases
- BTEX compounds
- Phenols
- Non-halogenated organic solvents
- Cyanides
- Ketones
- Alcohols

The biopile treatment may also be applicable for soils contaminated with less common contaminants that are not specified in this document e.g. specific types of organic solvent. Although the biopile technology can be engineered to be potentially effective for most combinations of site conditions and hydrocarbon products, it is not universal. It is normally not applicable for soils with the following contaminants:

- Toxic metals
- Polychlorinated biphenyls (PCBs)

- Dioxins / furans
- Asbestos
- Sulphate
- Clinical wastes

3.3   SITE PREPARATION

Before construction works can begin, the possible site has to be examined for its suitability. Ideally, the site will have appropriate topography, good accessibility and infrastructure, adequate space and utilities.

As far as the topography is concerned, a flat area with good drainage and reasonable distance from residential areas is recommended. An existing site is favourable and ideally the site should not be located in a floodplain. Infrastructural aspects include the accessibility of the site.

Electrical services will be needed to operate equipment such as blowers, pumps and instruments. Water will be required for hydrating the soil and general purposes. It may also be necessary to dispose of contaminated water and a sewer connection should be considered.

3.4   BASE PREPARATION

The biopile base serves three main functions. Firstly, it forms a stable foundation for the biopile and the associated soil handling operations. Secondly, it provides a barrier against potential migration of contaminants into the soil beneath the biopile. Thirdly, it should provide a slight slope to ensure the water runs off towards the leachate collection drain or sump.

The biopile base typically consists of several layers of different materials. At the bottom a newly laid or existing foundation is situated. As foundation material, soil or clay can be used and between 150 mm - 300 mm of loose material is spread and compacted to approximately 80 % - 85 % of maximum dry density. If an asphalt or concrete surface exists, it can serve as a foundation (e.g. car park) instead of compacted soil or clay. Ideally, the foundation for the storage area and the biopile is smooth with a gradient of approximately 1 to 2 degrees to ensure the run off of leachate. The foundation should exceed the pile width for about 1 m to allow room for the installation of the aeration pipes and if necessary the leachate containment bund and irrigation lines.

After the foundation is laid, an impervious liner is placed over the foundation to lower the potential migration of contaminants. The liner is typically a thick plastic material, such as high density polyethylene (HDPE) and has to be large enough to cover the desired area. For secure attachment it can be fastened to the leachate containment bund that surrounds the biopile.

3.5   LEACHATE COLLECTION

The design of a biopile system includes eliminating the escape of leachate. Any leachate formed in the remediation process migrates to the bottom of the pile where the impermeable base hinders further migration into underlying soil.

The leachate collection system usually consists of pipework at low points in the fill, a containment bund or structure around the pile, a leachate collection pump connected to the drain piping, and a leachate collection tank.

One possible way of constructing the leachate collection system is by sloping the biopile base toward one corner of the pile to channel any leachate to a leachate collection pipe. The leachate collection system can be incorporated into the aeration system. If the aeration system is operated in the extraction mode, experience has shown that the leachate in a

covered pile system flows to the aeration pipes rather than flowing to a low-point leachate collection sump.

When a leachate collection system is incorporated into the aeration system, a water knockout tank has to be installed ahead of the blower. Periodically, a pump transfers the water from this tank to the leachate collection tank. The size of the leachate collection tank varies and depends on the area of the biopile floor plan and the expected maximum rainfall.

Depending on the level of contamination, the leachate may be reused for hydration of the pile or has to be disposed of. Disposal options will vary from site to site. Potential options include direct disposal to foul sewer, treatment and disposal to foul sewer, discharge to controlled waters (with Environment Agency consent), and offsite disposal via an appropriately licensed waste contractor.

The treatment of leachate is possible with one or a combination of the following options: oil/water separator, solids settlement, biological treatment and activated carbon treatment.

3.6 AERATION

The success of remediation of contaminated soil through the use of biopiles depends mainly on the sufficient provision of oxygen for the degrading microbial processes. The aeration of soils depends on the total amount of air filled pore space. This space is reduced when the soil is waterlogged or compacted. Without an aeration system, the degradation process of organic material in the top layers will deplete the oxygen reserves in the soil and not enough oxygen will diffuse into deeper layers. Therefore, aeration is required in most applications.

Aeration systems can be divided into:
- Passive aeration
- Active aeration
  - Air injection
  - Air extraction

Passive aeration requires no blower and is therefore the simplest and cheapest aeration method. The aeration occurs due to natural currents. At various heights slotted pipes are integrated into the pile. These components stick out of the pile and allow the transfer of air through the soil. This method can be effective for permeable soils with low levels of contamination.

In spite of the lower costs of passive aeration, active aeration is the preferred method in most cases. It ensures a more thorough and more controllable airflow. There are two types of active aeration: air injection and air extraction. Pipework in the pile is connected to a blower that pushes air into the pile (injection) or pulls air through and out of the pile (extraction). The pipework is covered with washed gravel in order to avoid soil particles clogging the suction holes during operation. To prevent volatilisation of organic compounds the airflow rates are ideally just great enough to keep the soil above oxygen-limiting conditions.

Air injection is the less cost-intensive method. Using this method the blower does not need to be preceded by a water knockout system to protect it from exhaust gas condensate and possible biopile leachate. In cases where the treatment of exhaust gases and/or leachate collection is necessary, the system has to be operated in the extraction mode. Using this method the emissions of the biopile can be collected, monitored and treated if necessary. Various vapour treatment technologies are available but will not be discussed here.

3.7 IRRIGATION

Another critical factor for successful bioremediation is the moisture content in the soil. Neither excessive nor insufficient moisture is desirable in the remediation process. Hydrocarbons are only degraded in the presence of water. A bacterial cell contains approximately 70 % to 90 % water. To maintain the cell structure, to transport nutrients and

to carry out metabolic processes, water needs to be available in sufficient quantities. However, excessive moisture in the biopile would cause a decline in the air permeability of the soil, resulting in insufficient supply of oxygen for bacterial processes. Additionally, with increasing moisture content the undesirable leaching of contaminants and nutrients from the pile augments as well.

Different types of soils can hold different amounts of water in their pore spaces. The recommended moisture content ranges from 70 % to 95 % of field capacity. The moisture content can be included into the list of parameters when soil samples are taken and analysed.

If necessary, adjustment can be made during the initial preparation. In the case that the soil to be treated is too wet, dry bulking agents can be added. There are various ways of adding moisture if the soil is too dry. For instance, if the soil is being shredded or screened, a precise amount of water can be added per batch of soil processed. Alternatively, moisture can be added while the soil is still on the storage pad. Irrigation of the soil from the top with a hose or sprinkler may cause excessive runoff if the soil cannot rapidly absorb the water. Digging holes partially into the pile with a hand auger and filling the holes up with water may achieve more thorough hydration than irrigation from the top. In some cases no initial adjustment of the moisture content needs to be carried out prior to remediation.

During remediation the soil undergoes changes in moisture content. The pile loses moisture because the air flowing through the pile becomes saturated with water and removes moisture from the soil. The biodegradation process compensates a part of the water loss, since hydrocarbons are converted to carbon dioxide and water. For every kilogram of total petroleum hydrocarbon (TPH) degraded, approximately 1.5 kg of water is produced.

In moderate climates or during summer months, a biopile tends to lose 1 to 2 weight % of the original amount of water over a 3 to 4 month operating period. Usually, hydration during the construction phase is enough and no irrigation system is required during the remediation period.

3.8 NUTRIENT ADDITION

Microorganisms use carbon from organic compounds for biosynthetic processes. Contaminants and natural organic compounds in soil typically provide an adequate amount of carbon. Other macronutrients required by the bacteria population are nitrogen and phosphorus. Both elements may be naturally present in the ground in sufficient amounts. Their content should be determined in the course of the analysis of soil samples during the site investigation. Typically, the samples are analysed for nitrogen in the form of ammonia (NH_3) and nitrate (NO_3^-), and phosphorus in the form of orthophosphate (PO_4^{3-}).

The C:N:P ratio is recommended to be brought in the range of between 100:10:1 to 100:10:0.5. The amendment should be added during construction. It can be combined with the moisture adjustment by dissolving the nutrients in water and spraying them onto the pile. Alternatively, nutrients can be applied in granulated form and mixed with the soil. Excessive amounts of nutrients will be lost in the leachate and wasted unless the leachate is re-circulated for irrigation purposes.

3.9 MICROBIAL AMENDMENT

Petroleum-degrading microorganisms are commonly part of the indigenous microbial population. Many studies indicate that these naturally occurring microorganisms are capable of sufficiently degrading the contaminants. Microbial amendments increase the overall costs and have not been clearly demonstrated to improve the degradation of petroleum hydrocarbons. Most biopile users reject the addition of exogenous microorganisms, i.e. microbes added to the soil. However, if the amendment is included in the biopile design, it can be added to the nutrient solution and sprayed onto the soil prior to or during construction. These cultures of bacteria and fungi are naturally occurring but are claimed by some to be specifically cultured to optimise degradation.

3.10 pH ADJUSTMENT

The correct pH in the biopiles should range between 6 and 9. If required, the pH can be adjusted by means of addition of agricultural grade lime (if too acidic) or sulphur (if too alkaline) to the soil. The addition should take place at the same time as the nutrients are added.

3.11 GENERAL CONSTRUCTION

In most cases, the soil to be treated requires addition of water and nutrients prior to the biopile formation works. However, it is possible that the moisture content and nutrient concentration will be adequate and the grain size will be coarse enough to provide sufficient air permeability without any amendment.

Some soils need treatment because the grain diameter is relatively small. This is often the case in soils with high clay content. To improve the soil structure and porosity in such soils, soil shredding / screening may be performed. The soil can also be blended with bulking agents to improve the mass transfer of gases within the soil undergoing treatment.

Biopiles have been constructed in a variety of sizes and shapes. The dimensions of a biopile are normally not restricted in width and length, but the height usually does not exceed 2.5 m. Tall piles (> 3 m) complicate the construction process and cause compaction of the soil under its own weight, which in turn leads to a reduction in the amount of pore spaces and the efficiency of the process. It is possible to construct higher biopiles but they require the placement of extraction pipework in layers at various depths through the biopile to overcome the mass transfer problems, great care is also required to construct high biopiles to avoid compaction as far as possible.

Typically, the installation of monitoring instruments within the pile is part of the biopile construction. Essential for monitoring the biodegradation are tubes for gas sampling (oxygen, carbon dioxide, methane) and thermocouples to measure the temperature.

After the pile is formed it should be covered with a plastic sheeting material. The purpose of the cover is to retain moisture and heat, to prevent excessive water addition from rain as well as to prevent the wind from blowing dust from the pile. The cover also serves to protect the upper layer of the soil from cementation due to wetting and drying. In hot climates the covers provide limited protection against desiccation of the soil, however this should be counterbalanced with an irrigation system.

Proper construction of the biopile is essential for the successful treatment of contaminated soil for a number of reasons. One of them is to avoid excessive temperatures in the biopile. The degradation process releases heat, which increases the internal temperature of the pile. Some increase is desirable because it stimulates microbial activity. However, if the temperature rises above the optimum (20 °C to 40 °C), the degradation rate declines.

4. SITE DESCRIPTION

4.1 SITE LOCATION

The site is the former colliery and coking plant in Askern, approximately 10 miles north of Doncaster, South Yorkshire. A site location map is shown in Figure 4.1.
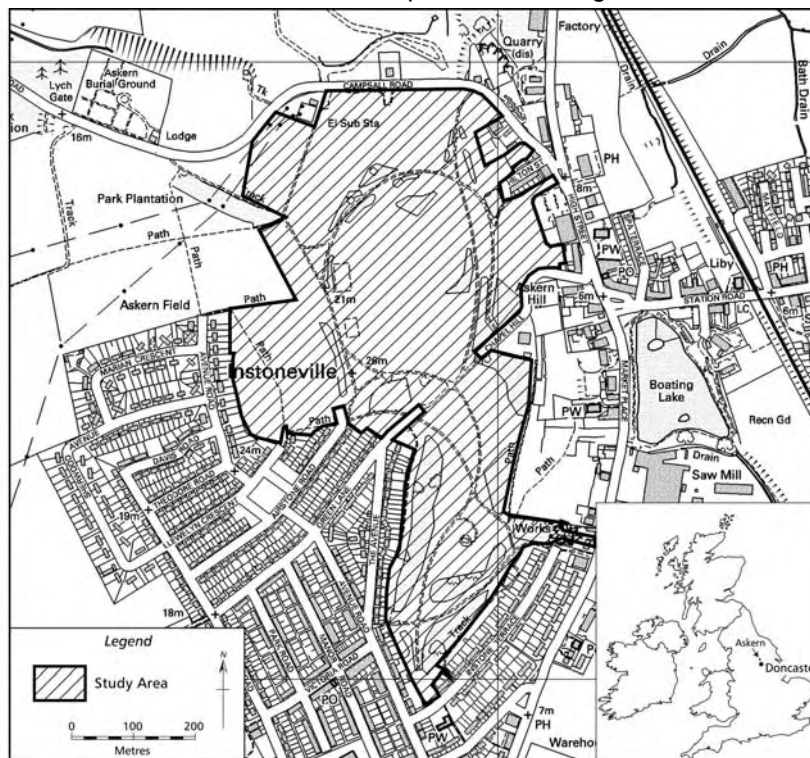
Figure 4.1: Site location map

4.2 HISTORICAL BACKGROUND

The site had been developed as Askern Main Colliery by 1911 and coal was extracted from two seams, the Barnsley and Flockton seams. The two shafts were located at the northern end of the site (see Figure 4.2). This site operated relatively unchanged until 1929 when the Doncaster Coalite Works was present at the site.

The Coalite works used the Parker process, patented in 1906, to produce carbonised coal or coke. The process involved heating the coal in vertical retorts for 4 hours at a temperature of 640 $^{\circ}$C. The retorts were arranged in groups known as batteries. The Coalite Works at Askern initially used four batteries with another fourteen being added later. The structures and process equipment for the Coalite works were located in the centre of the site. The Coalite process produces several by-products in addition to the carbonised coal which are themselves the primary source of contamination at the site. The by-products include:

- Oils and tars
- Ammoniacal liquor
- Gas

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Some of the processing of these by-products was performed at the site. As with the main Coalite process the plant and equipment associated with the processing of the by-products was undertaken in the centre of the site. The plant and equipment consisted of many tanks and structures, most of which were reported to have been built on natural ground with little or no protection of the ground surface.
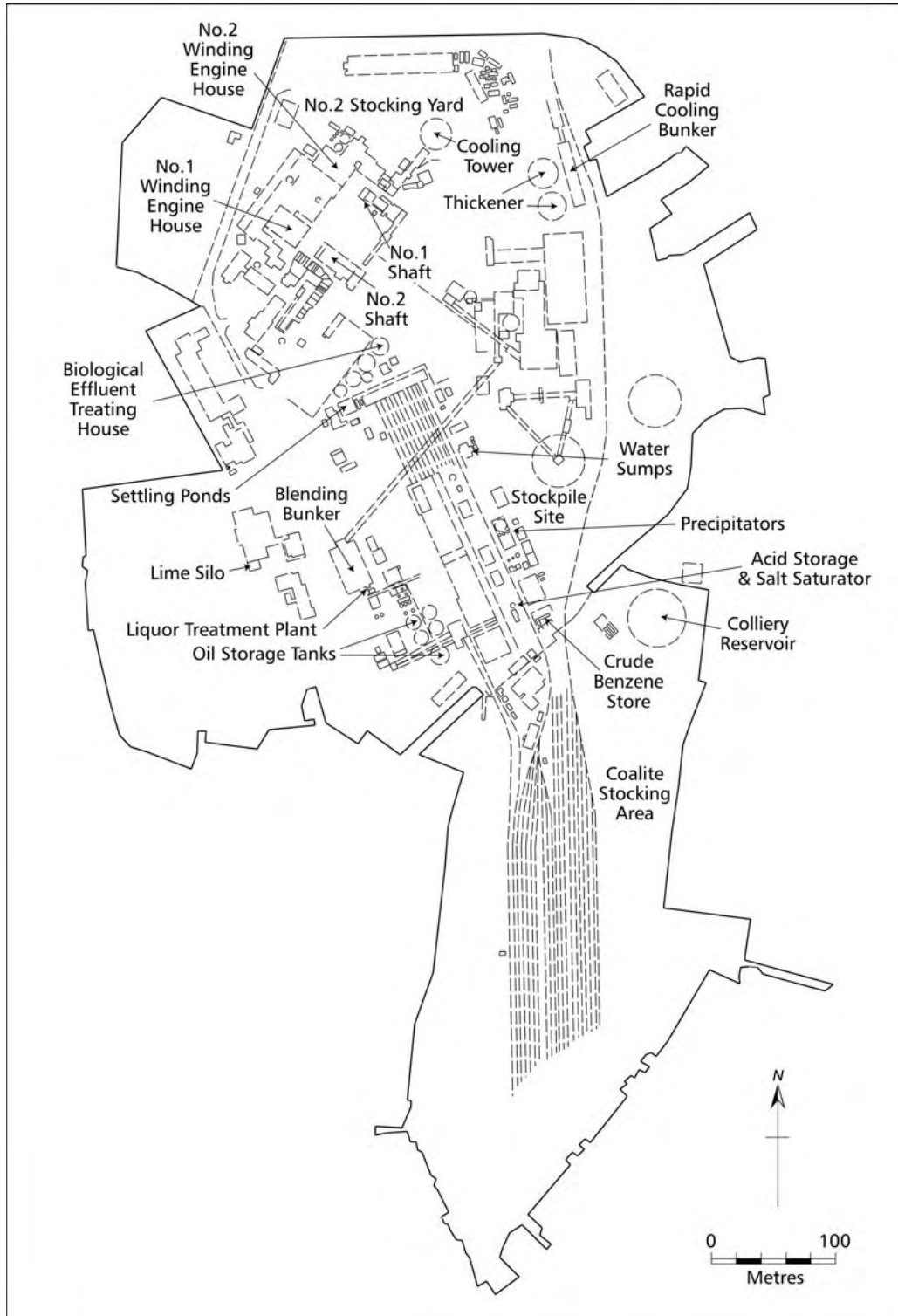
Figure 4.2: Plan of former structures

The coke produced from the plant was stored at the southern end of the site where it was transported away by railway. In addition to the coke storage area, the railway sidings used for the transportation of the coal and the coke were located at the southern end of the site.

The works continued to produce coke through to the mid 1980s when production ceased and the works were closed. Works to investigate the site commenced in 1993 and were completed in 1999. Table 4.1 gives a summary of the investigation works that were carried out at Askern Colliery.

Table 4.1: Site investigation works summary

Date of Study	Author	Title	Area Investigated	Field Work Undertaken
Aug 1993	Soil Mechanics Ltd (SML)	Askern Coalite Plant : Geotechnical and Contaminants Survey	Coalite Plant Coalite Stocking Yard Spoil Tip	• 60 trial pits • 12 boreholes • No installation of gas and groundwater monitoring wells
Jan 1995	International Mining Consultants Ltd (IMCL)	Land at Askern Colliery: Report on Site Conditions	Colliery Plant	• 50 trial pits • No installation of gas and groundwater monitoring wells
Dec 1995	FWS Consultants	Contamination Survey of Askern Coalite Plant and Colliery Sites	Colliery Plant Coalite Plant	• 171 trial pits • 11 boreholes • 5 gas and groundwater monitoring wells
Nov 1996	Carl Bro Aquaterra Environmental Consultants	Askern Colliery Redevelopment Geo-Environmental Investigations	Review of Existing Information	
Dec 1996	International Mining Consultants Ltd (IMCL)	Interim Report on the Proposed Reclamation of Askern Mine Site to soft End-Use (Moynihan)	Colliery Plant	• 22 trial pits • No installation of gas or groundwater monitoring wells
	HLM Architects	Redevelopment Brief: Askern Colliery and Coalite Plant	Colliery Plant Coalite Plant Colliery Spoil Tip Peripheral areas	
Jun 1998	Carl Bro Aquaterra Environmental Consultants	Final Draft Remediation Method Statement Askern Colliery and Coalite Plant	Remedial Works Proposals	
Nov 1998	Carl Bro Aquaterra Environmental Consultants	Environmental Statement	Coalite Area Colliery Site Colliery Spoil Tip	
Nov 1998	Carl Bro Aquaterra Environmental Consultants	Remediation Assessment and Geotechnical Survey Volume I & II	Coalite Area Colliery Site Colliery Spoil Tip	• Factual Report • Trial pit logs
Jul 1999	Carl Bro Group Limited	Geotechnical Assessment – Factual Report	Colliery Coalite Plant	
Jul 1999	Carl Bro Group Limited	Supplementary Geotechnical Assessment –Factual Report Area F only	Colliery Coalite Plant	
Jul 1999		Supplementary		
Jul 1999	Carl Bro Group Limited	Quantitative Risk Assessment	Colliery Coalite Plant	
Jul 1999		Quantitative Risk Assessment		
Aug 1999	Carl Bro Group Limited	Post Remediation Validation Report - Phase 1 Enabling Works	Colliery Site – Phase 1 Area	• Factual Report

4.3   INITIAL SITUATION AND EXTENT OF CONTAMINATION

The remediation work at Askern colliery (phase 2) followed phase 1 work at the site, during which the above ground structures shown in Figure 4.2 were demolished.

At the commencement of the phase 2 works the site had been cleared and the material from the demolition works had been processed and stockpiled. The main body of the remediation work centred on the section of the site which was used for the Coalite works, as it contained the majority of the contaminated material. The buried structures and foundations remained within the centre of the site, containing tanks and sumps of various sizes, some of which contained coal tar and other contaminants. The fill surrounding the buried structures and the natural ground beneath had become contaminated by the coal tar and by the mishandling of contaminating substances during the operation of the Coalite works. The indicative area of the contamination covered approximately half of the central area of the site. The natural ground immediately beneath much of the Coalite works comprised marl and mudstones, which had confined the majority of the contamination to the top 1.5 m to 3 m. Other areas of the site contained limited amounts of contamination within the made ground and the natural ground, although these areas were confined to hotspots and were not extensive as in the case of the Coalite works area.

The contaminated source zone of the site did not extend into natural groundwater, although many of the buried foundations and structures contained perched groundwater which was heavily contaminated with hydrocarbons, phenols and metals.

4.4   GEOLOGY, HYDROGEOLOGY AND HYDROLOGY

The general geology of the site was reported by the consultant Carl Bro Group as being deposits of made ground overlying thin lenses of drift deposits of glacial sand and gravel which are underlain by solid deposits of rocks of the Roxby and Edlington formations (formerly the upper and middle Permian Marl) and the rocks of the Brotherton and Cadeby formations (formerly the upper and lower Magnesian Limestone).

The site is underlain by an anticlinal structure cut by a fault running northwest to southeast. Rocks of the Edlington formation lie to the north of the fault and rocks of the Brotherton formation encircle the site.

The limestone rocks are classed as a major aquifer with rapid fracture flow and any contamination of this aquifer represents a high risk to controlled waters. The groundwater in and around the site is not used for water abstraction and is not located within a source protection zone but forms baseflow for the River Went to the north of the site.

The surface water from the site flows to the River Went to the north via a series of drainage channels or the River Don (into which the River Went discharges) via similar minor surface water features. The surface water channels on the site were reported to be intermittent in nature, associated with periods of heavy rainfall.

4.5   RISK ASSESSMENT

The historical and environmental information gathered about the site was used by Carl Bro Group to assess the risk associated with the contamination at the site. The result of this exercise was the production of remediation treatment targets for the site. The targets are presented in Table 4.2. Details of the risk assessment are not available and are therefore not discussed.

Table 4.2: Remediation targets (values in mg/kg unless otherwise stated)

Determinand	Residential/ Infrastructure area		Landscape area	
	Limit			
pH	5<pH<8		5<pH<9	
Arsenic	40		120	
Mercury	1		15	
Cadmium	3		15	
Chromium (total)	600		1,000	
Lead	500		2,000	
Water soluble boron	3		3	
Copper	130		250	
Nickel	70		110	
Zinc	300		1,000	
BTEX	10 µg/kg		100 µg/kg	
Total Polycyclic Aromatic Hydrocarbons (PAH)	50		1,000	
	(a)	(b)	(c)	(d)
Diesel range organics ($C_{10} - C_{40}$)	2,000	1,000	5,000	1,000
Total phenol	5	1	5	1

Note:
(a) and (b) correspond to identified zones within the residential/infrastructure areas
(c) and (d) correspond to identified zones within the landscape areas

5. TECHNOLOGY DEMONSTRATION SUPPORT ISSUES

5.1 INTRODUCTION

This chapter discusses support issues associated with the bioremediation of the Askern colliery site, and covers the following:

- Regulatory issues, including waste management licensing
- Project team
- Health and safety

5.2 REGULATORY ISSUES

5.2.1 WASTE MANAGEMENT LICENSING

Land contamination remediation activities are regulated by the waste management licensing system, which is regulated by the Environment Agency (EA). Waste management licensing ordinarily regulates the activities of sites and facilities which are involved in some form of waste management, such as waste transfer stations, landfill sites and vehicle dismantlers, however, Part IIA of the Environmental Protection Act 1990 makes provision for the concept of a Mobile Plant Licence (MPL) which allows the treatment of waste to be undertaken on different sites so that the waste itself does not have to be transported. The treatment of contaminated soils falls within this category.

An MPL will describe, in detail, a particular remediation process and will set out the system by which that process will not cause harm to the environment and will provide records to demonstrate that it did not cause harm to the environment during its operation. The objectives of the remediation are also taken into consideration during the compilation of the licence documentation to ensure that the process undertakes the remediation it was designed to.

Each licence consists of a generic document which forms the basis of the licence. This documentation can be applied to any site. However, some parameters such as geology, will vary considerably at each site and there is therefore a site-specific component to the licence which must be agreed with the EA office local to the site in question. The compilation of the site-specific parameters and the control mechanisms to ensure protection of these parameters forms the site-specific licence document which is relinquished upon completion of the remediation at a particular site.

Each site must have a single person responsible for the duties described in the generic and site-specific licences and they must produce predetermined documentation on a regular basis for the EA so that the regulator can assess if the licence is operated in accordance with the legislation.

Ecologia Environmental Solutions Ltd holds the Mobile Plant Licence for the bioremediation undertaken at Askern Colliery. The site-specific licence was drawn up by Ecologia and approved by the local EA office within one month of the contract being awarded. Therefore, the arrangement of the MPL ran concurrently with other project organisation during the project set-up and did not cause any delay to the overall project programme.

5.2.2   OTHER ISSUES

Several other regulatory issues surround contaminated soil remediation although not all of them were encountered during the remediation works at the former Askern colliery.

The local government planning office has a regulatory role to play and will also ensure that the remediation process does not cause excessive volatilisation of contaminants to the atmosphere. The local authority were advised of the process to be undertaken at Askern and carried out analysis of the emissions from the mobile plant. They were satisfied that the emissions fell within acceptable limits.

The disposal of wastewater from the system can be carried out in three ways: disposal to controlled waters; disposal to sewer; and disposal to a licensed facility by road tanker. During the work at Askern the wastewater from the leachate collection system was disposed of by road tanker and therefore did not require additional licences or consents.

5.3   PROJECT TEAM

The project team for the Askern bioremediation is given in the management hierarchy shown in Figure 5.1. The client was Yorkshire Forward, the consultant engineer was Carl Bro Group, the main contractor was Mowlem Remediation and the bioremediation was carried out by Ecologia Environmental Solutions.
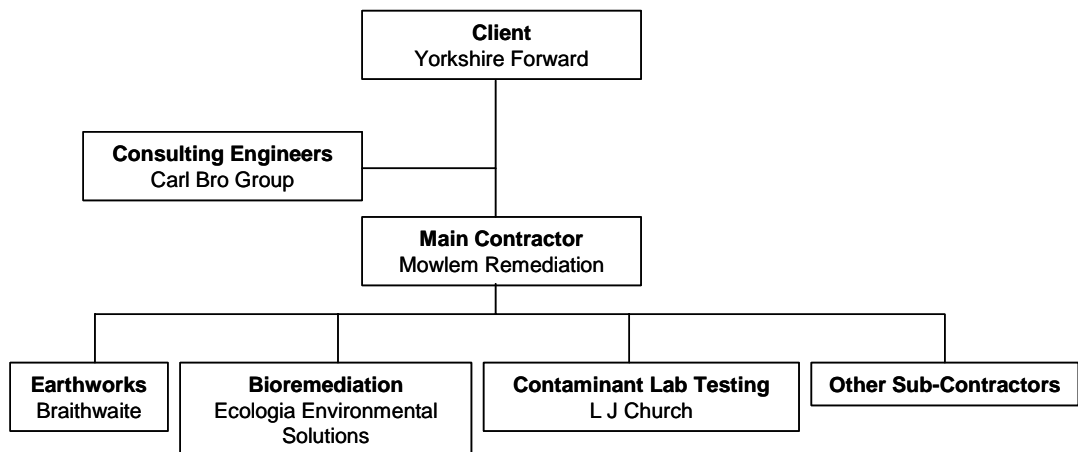
Figure 5.1: Management hierarchy

5.4   HEALTH AND SAFETY

Health and Safety requirements were governed by the Construction (Design and Management) Regulations 1994 and these were the responsibility of Mowlem Remediation.

In addition, Ecologia had to complete an interim report during the treatment of the soil as part of the MPL requirements and these were submitted to the EA on a monthly basis. This documentation covered health and safety issues, environmental protection, the maintenance of the process equipment to ensure it is operating correctly, the monitoring data that was derived from the weekly monitoring and the monthly chemical analysis. It also included general site monitoring information such as weather conditions, dust, noise, volatile organic compound emissions and groundwater.

All the site visits, testing, sampling and monitoring was carried out by the EA registered technically competent person for the site-specific licence at Askern Colliery who was Mr Tom Hayes of Ecologia.

6. CONTAMINATION MAPPING AND EXCAVATION

6.1 BACKGROUND

The contamination mapping and supervision of the excavation process was undertaken by Mowlem Remediation.

It is important to allocate and direct contaminated material at any given site to the treatment process which will best deal with the type of contamination which the soils contain. For example, it is not appropriate to send heavy metals for treatment by bioremediation. The bioremediation process is particularly useful for the remediation of hydrocarbons.

Similarly, it is inappropriate to treat soils which are grossly contaminated by coal tars by bioremediation. Material containing bulk coal tars must be actively separated from the material being sent for bioremediation.

To incorrectly identify material for bioremediation and non-bioremediation is harmful to the process and reduces the efficiency of the system. This could lead to the bioremediation process being unsuccessful. It is necessary to be realistic about what the chosen bioremediation technique can achieve and to ensure that an attempt to treat incompatible material is not made.

6.2 PRE-EXCAVATION ASSESSMENT

During the tender period a thorough understanding of the processes which had taken place on the site and the contaminants which would be encountered during the remediation was developed. Part of the research undertaken by Mowlem included contacting local members of the public previously employed on the coke works including the retired coke works manager.

A site visit with the former coke works manager was arranged and was used to identify areas of the derelict ground where particularly hazardous chemicals had been stored. The former coke works manager was able to point out areas of the site likely to contain certain chemicals which may have been allowed to escape from the former distillation processes. This research, and therefore better understanding of the contamination, enabled accurate identification of potentially problematic areas of the site.

6.3 CONTAMINATION MAPPING

The contaminants present in the made ground underlying the former coke works included, amongst others, polycyclic aromatic hydrocarbons (PAHs), phenols, toxic metals including arsenic, mercury, cadmium, chromium, lead, copper, nickel and zinc. Using the information gathered from the assessment work, areas were set out on the site where contamination was believed to be likely. These areas were subdivided into a 15 m x 15 m grid (Plate 6.1). At the centre of each grid square a sample of material or soil was taken and sent away for analysis. This sample was deemed to be representative of the grid square from which it was taken and for a depth of 0.5 m. The samples were taken by a site chemist from L J Church Laboratory Services. They were sent in amber glass jars to City Analytical Services (UKAS accredited) for analysis. The total cost for the sampling and analysis associated with the mapping exercise was £85,000.

Plate 6.1: Surveying of the sampling grid

Upon receipt of the data from the laboratory, each grid cell was classified as being in one of the following three categories:

- Material suitable for incorporation into the general earthworks because the agreed threshold limits were not exceeded.
- Material contaminated above the agreed threshold limits but suitable for bioremediation.
- Very heavily contaminated material, unsuitable for bioremediation and suitable only for off site disposed at an approved, appropriately licensed landfill.

Following the excavation of the first 0.5 m, the sampling exercise was repeated so that the second 0.5 m could be classified. The process of working through the profile of the site did not occur in a uniform fashion and some areas were excavated more quickly than others, depending upon the requirements of the earthworks programme at the time. The mapping exercise was continued until material was found in the base of the excavation that met the agreed threshold limits. A photograph of the excavation process is shown in Plate 6.2.

Plate 6.2: Supervision of the excavation process

Prior to being sent for bioremediation the material in the second category was screened to remove large pieces of debris such as concrete and reinforcing bars. Screening the material led to a reduced volume of material requiring treatment.

In total, a volume of 2,000 m^3 was sent to landfill and a volume of around 22,000 m^3 was sent to the bioremediation treatment area. At this point the material sent for bioremediation treatment became the responsibility of Ecologia who were subcontracted to Mowlem Remediation and were responsible for the bioremediation of the contaminated material.

The contamination mapping exercise and careful material selection process employed at the site enabled a large reduction in the amount of material requiring physical treatment from that indicated in the original tender documents. The volume in the tender documents was 52,000 m^3 and the volume actually treated or disposed of off site totalled 24,000 m^3. These volumes clearly show the benefit of employing a methodical and measured approach to the excavation of contaminated sites.

7.   BIOPILE DESIGN AND FORMATION

7.1   BASE PREPARATION

As described in section 3.4 a base beneath a biopile should consist of an impermeable layer which is ordinarily an HDPE liner over a foundation of hardcore and clay. At Askern Colliery the base, or 'pad', for the biopile was constructed by Mowlem Remediation using materials won from the site, eliminating costs and the need to bring large volumes of materials onto the site. The base was constructed using colliery spoil which has a high clay content and can be compacted to give a sufficiently impermeable surface to protect the underlying ground from the contaminated material undergoing treatment. The base was constructed with a 1 % gradient to the north and a 1 % gradient to the east allowing the collection of run-off and leachate at a single point, thereby preventing escape of potentially contaminated water.

Plate 7.1: Biopile base following completion

Samples of the base were taken for permeability testing and the results were suitable to gain approval from the Environment Agency. Following approval of the impermeability of the base and the inclusion of the design alteration into the site-specific working plan of Ecologia's mobile plant licence, formation of the biopiles began on 2nd April 2002.

7.2   FORMATION WORKS

Material for treatment was received by Ecologia after screening, which took place in the contaminated zone of the site. The material was used to form the biopile directly onto the extraction pipes which were laid onto the base in pairs.

Plate 7.2: Biopile formation works

Gravel filters were used to cover each of the extraction pipes, prior to the placement of the contaminated material directly on top, to prevent soil passing into the extraction pipes during operation.

Amendments were added to the material during this stage of the works. The amendments that were used consisted of a custom blend of agricultural type fertilizer which was made to a specification set out by Ecologia prior to the works. The specification for the fertilizer was designed according to concentrations of relevant nutrients found in the soils within the contaminated zone of the site prior to the excavation works. The fertilizer was added by hand to the contaminated material. In addition to the custom blend fertilizer, composted sewage sludge (TCSS) was added to the material in a ratio of 7 % v/v. The addition of the TCSS allowed the introduction of organic material into the contaminated material which improved the moisture holding capacity and the structure, allowing better mass transfer of gases and retention of moisture for the bacteria.

During the formation works it became necessary to construct two biopiles due to the limitations of space and the underestimation of the total volume of contaminated material at the outset of the project. The first biopile was constructed to a height of 2.5 m with a width of 40 m. The second biopile was constructed with a width of 25 m due to limitations on available space at the site. An aerial view of both biopiles is shown in Plate 7.3. Thinner biopiles are less efficient with regard to materials as more extraction pipe to header pipe junctions are required but it serves as an example of how the shape can be versatile.

Following the completion of the formation works the covers were placed onto the biopiles and the header pipes were connected to the extraction pipes. Each of the two header pipes ran alongside each of the biopiles before entering a 'tee' joint upstream of the air/water separator.

Header Pipes

Air / Water Separators

Treatment Unit

Leachate Storage
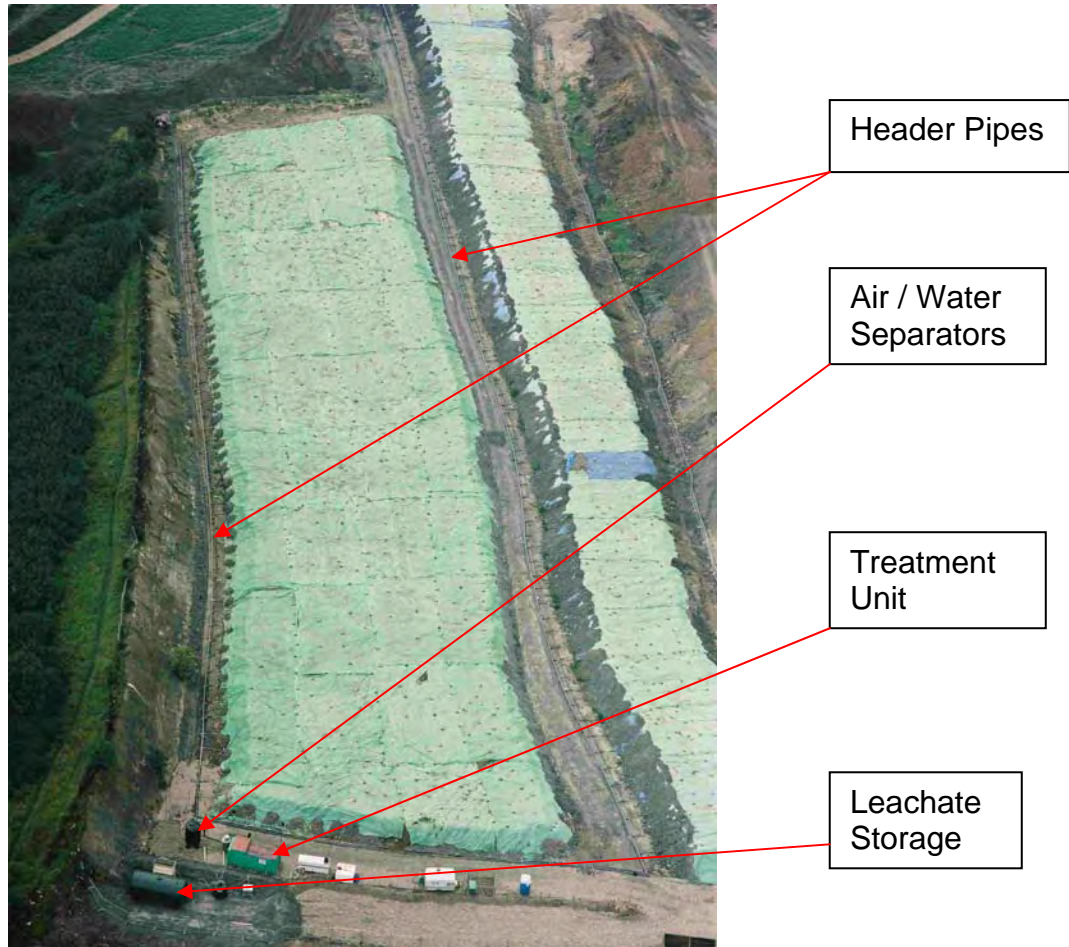
Plate 7.3: Completed biopiles

7.3   SYSTEM DESIGN

The biopile air/water separation system is shown in Figure 7.1. The main piece of equipment is a vacuum blower which draws air from the biopile through the header pipe and the extraction pipes. The air is drawn from the biopile rather than being blown in so that any volatile organic compounds (VOCs) which may be released from the contaminated soils can be monitored and controlled if required. The flow of air through the pipework system also has the effect of extracting the excess leachate from the system which is also drawn down the pipework system to the vacuum blower. The system at Askern employed a two stage air/water separation system to ensure that the air entering the vacuum blower was completely dry. The air/water separators were emptied automatically to a leachate storage tank. The ability to control the leachate in this manner ensured that potentially contaminated liquids were not released onto other parts of the site or into the ground beneath the biopile. The layout of the pipework for the biopile is shown in Figure 7.2.

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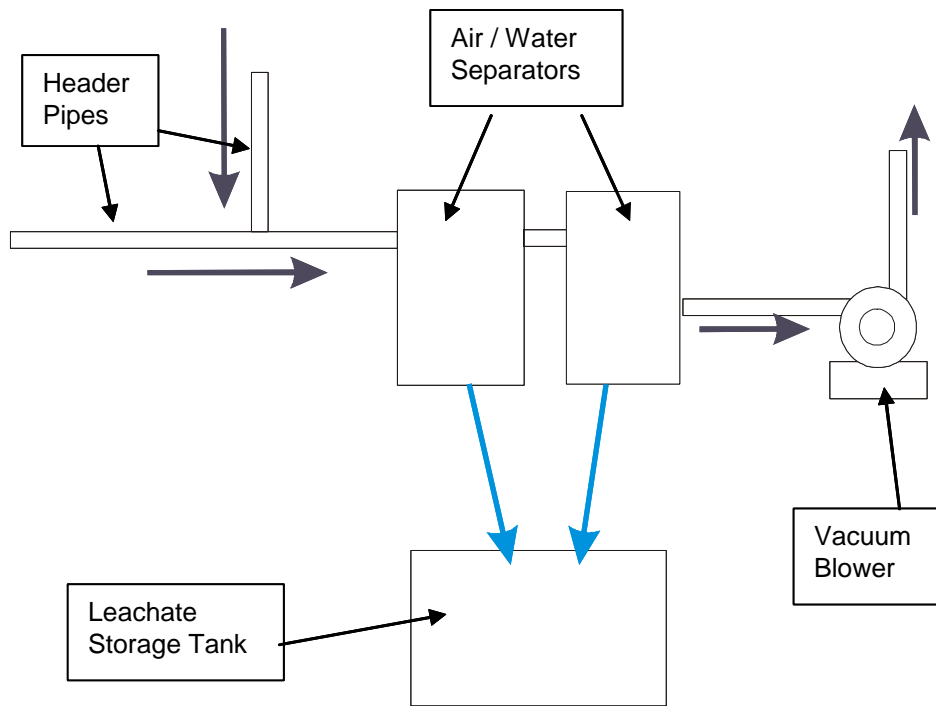
Figure 7.1: Biopile air/ water separation system
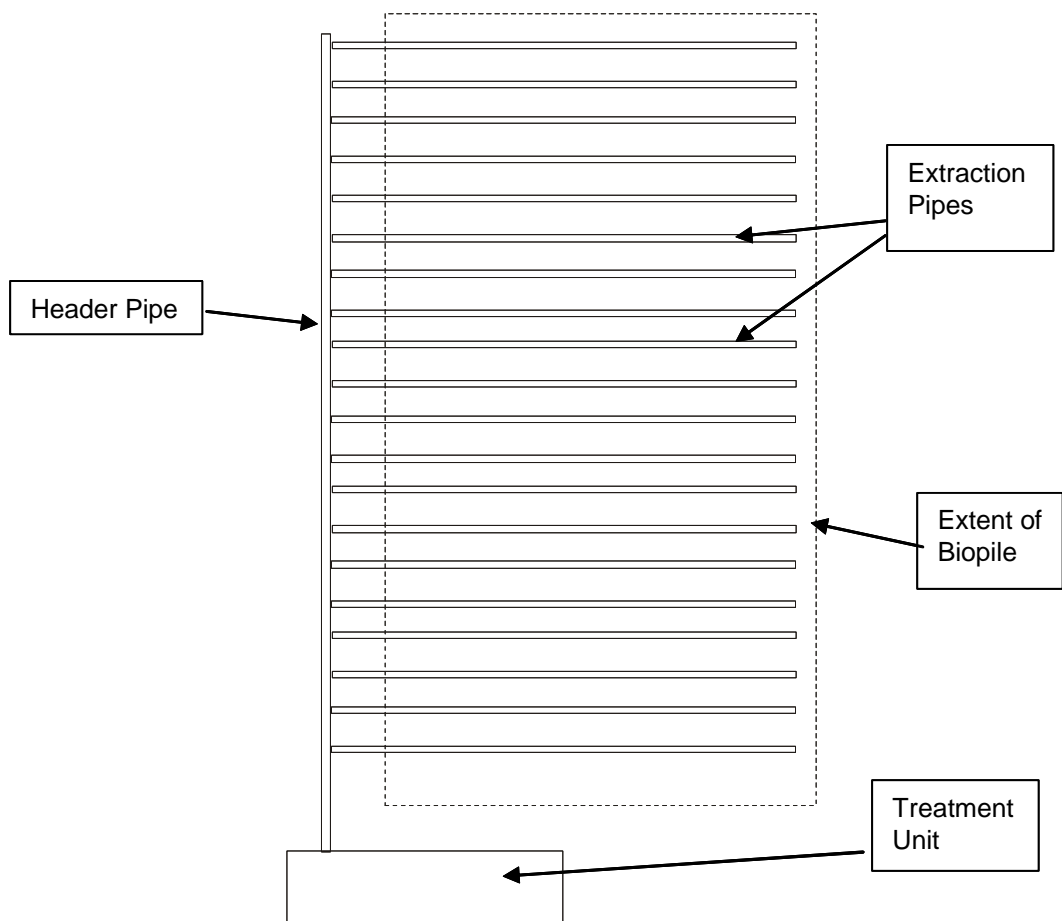
Figure 7.2: Pipework layout

The collected leachate was disposed of by tankering away from the site because there was not a suitable connection to sewer available at the site and an application for a discharge consent to controlled waters would have required treatment of the leachate.

During the bioremediation at Askern Colliery bacterial amendments were not used to complement the existing bacterial population. Augmentation was considered, but rejected due to the established natural specialised bacterial population within the made ground at the site. In order to accelerate the process of bioremediation, the natural bacterial population required the removal of certain factors which were limiting their growth. Primarily the limiting factors were assessed to be oxygen and nutrient availability, both of which were addressed by the biopile design at Askern.

The off gas from the vacuum blower was monitored (see section 8.3) during the bioremediation process to ensure that it did not exceed limits set out by risk assessment and agreement with the local authority. If high levels of VOCs are discharged from the vacuum blower then it is possible to treat them using a variety of methods, dependent upon the specific compounds in question.

8.   PERFORMANCE MONITORING

8.1   INTRODUCTION

The monitoring of a range of different parameters is necessary to evaluate the performance of the bioremediation process. The course of the remediation can be observed and the completion of the treatment can be predicted and determined. Problems and deficiencies can be detected and removed.

The biopiles at Askern were divided into 22 lots, each containing 1000 m^3 of soil. A gas sampling and temperature device was placed into the centre of each lot at 1.5 m depth.

8.2   SOIL SAMPLING

With the exception of five lots, each of the 22 lots was sampled five times throughout the treatment period; the sampling frequency was four weeks. Initially, soil samples were taken during construction of the biopiles, after the movement of soils was complete, to determine the level of contamination before the start of the remediation process.

For the four sets of samples after the formation of the biopiles, a hand auger was used to take samples from the biopiles. At five different locations in each lot, samples were taken at two different random depths. Thus, a total of ten samples were mixed to form one composite sample for each lot. The samples were sent for analysis to a UKAS accredited laboratory. The soil testing included organic contaminants (TPH, PAHs, phenols and BTEX compounds), macronutrients (nitrogen and soluble phosphorus), pH and moisture content.

The use of composite sampling is important because it is a measure against erroneous results produced by the heterogeneity of soil. Contaminated material can be homogenised to a certain extent with screening, but it is not completely effective and heterogeneity will remain. If the heterogeneity of the soil is overcome by increasing the total number of samples then the sampling and monitoring regime becomes a large cost and each sampling interval may have to be increased in order to save costs. The use of composite samples enables the efficient use of financial resources to gain data about the effectiveness of the bioremediation.

8.3   GAS ANALYSIS

On a weekly basis, the monitoring of gases was carried out. A Geotechnical Instruments GA2000 gas analyser was connected to the monitoring point in each lot. The instrument read the percentage of O_2, CO_2 and CH_4 as well as the concentration of H_2S and CO in parts per million (ppm).

Measuring the concentrations of the gases allowed the level and type of microbial activity in the biopiles to be assessed (Plate 8.1). A relatively low percentage of O_2 and a high percentage of CO_2 indicate that the activity of hydrocarbon degrading aerobic microorganisms is present, but it also shows that the aeration system is not efficient. In order to investigate the health of the bacterial population within the biopile, it is necessary to undertake a respiration test. A respiration test involves switching the aeration system off line so the biopile does not receive fresh air. The percentage of O_2 and CO_2 must then be tested at regular intervals and the results analysed. A healthy microbial population should result in a reduction in O_2 and an increase in carbon dioxide over time. It is also possible to calculate metabolism rates from the respiration rate of the biopile.

High levels of CH_4, H_2S and CO show that anaerobic microorganisms are at work and therefore parts of the biopile are anoxic. Oxygen-limiting conditions in the biopile are undesirable during the biopile treatment.

Plate 8.1: Measuring gas concentrations

Apart from the gases mentioned above, the concentration of volatile organic compounds (VOC) was measured weekly with a photoionisation detector (PID) at the 22 monitoring points. In addition to the monitoring of the gases within each of the 22 lots, the gas exhaust from the vacuum blower was monitored on a weekly basis. These values have been taken into consideration in the calculation of the amount of contamination that was volatilised and therefore lost to atmosphere during the treatment.

8.4   TEMPERATURE MONITORING

The temperature of each of the 22 lots was monitored on a weekly basis with the gases. A thermocouple was positioned in the biopile at 1.5 m depth with the gas sampling probe to allow the temperature in the middle of the pile to be monitored. The temperature readings give an indication of when accelerated bioremediation has been induced, temperatures commonly rise within the first few days or weeks of the biopile being switched on line. If this does not occur then a limiting factor remains in the system.

8.5   LEACHATE MONITORING

Samples of leachate were collected during the remediation project and were analysed for TPH, ammonia and phenols. The leachate was analysed in order to aid the calculation of a mass balance within the system. Phenol has a solubility of 66 g/L, making it important to monitor the leachate to test if the phenol had been biodegraded or was simply washed out of the soils and into the leachate.

9. PERFORMANCE EVALUATION

9.1 INTRODUCTION

This chapter describes the results from samples and measurements taken over the course of the biopile treatment. The data are presented and discussed in the following sections:

- Soils analysis
- Gas measurements
- Temperature measurements
- Leachate measurements

9.2 SOILS ANALYSIS

As described in the previous chapter, the soils in the majority of the 22 lots were sampled and analysed five times during the remediation project, at time zero (after soil movement was complete) and then at a frequency of every four weeks. The parameters that were analysed were: TPH, PAHs, phenols, BTEX compounds, pH, moisture content, ammonia, phosphate and nitrate. Analytical results from the key chemical parameters are presented in Table 9.1 and will be discussed in more detail in the following sections.

Table 9.1: Mean analytical results from the key chemical parameters presented with standard error from 22 measurements.

	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
TPH (mg/kg)	20,740	5,179	6,813	5,405	851
Standard error	6,120	902	1,630	1,360	146
PAH (mg/kg)	234	70	86	72	87
Standard error	77	12	15	10	15
Total Phenols (mg/kg)	869	71	37	38	8*
Standard error	279	18	10	11	5*
BTEX (μg/kg)	9,432	279	231	107	31
Standard error	1,910	126	92	44	12
Ammonia (mg/kg)	120	51	18	17	11
Standard error	18	11	4	3	1
Nitrate (mg/kg)	34	134	109	141	47
Standard error	9	23	17	24	18
Orthophosphate (mg/kg)	57	46	65	118	39
Standard error	11	5	7	8	7

* Two of the 22 lots recorded anomalously high phenol concentrations (see section 9.2.3)

9.2.1 TOTAL PETROLEUM HYDROCARBONS

Table 9.1 and Figure 9.1 show the mean TPH concentrations, as determined by GC-FID, over the course of the biopile treatment period. The data show an initial large decline during the first four weeks of operation of the biopiles, with the mean TPH concentration falling from 20,740 mg/kg to 5,179 mg/kg. During the following eight weeks, the raw data showed that many of the lots exhibit continued decline in the TPH value, but the mean data presented here increase slightly at 8 weeks and then drop down again after 16 weeks. Following the level period during the middle of the treatment period, by the end the mean TPH data fell to 851 mg/kg, which was within the acceptance criteria of 1,000 mg/kg. The standard error for the TPH data was 146 mg/kg, however, it should be noted that this value is skewed by the

high concentration of TPH found in Lots G and H of over 2,000 mg/kg and 3,000 mg/kg respectively.

In fact, four of the 22 lots contained concentrations of TPH in excess of 1,000 mg/kg after 16 weeks; Lots C, G, H and T. Further sampling of these lots after continued treatment showed that the TPH concentration in Lots C and T had fallen to within the acceptance criteria, however, Lots G and H (a total of 2,000 m^3) did not reach the target and these were relocated to another area of the site following a specific risk assessment.
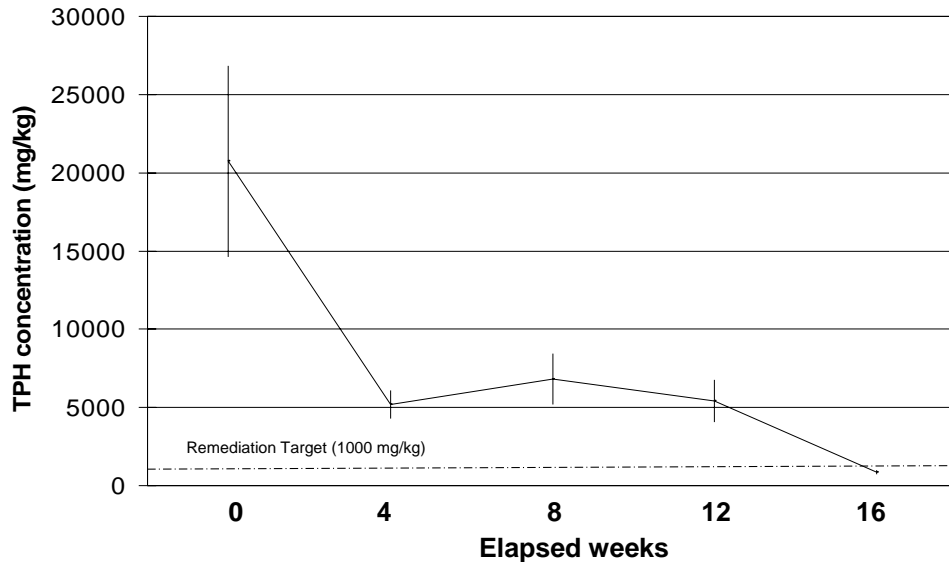
Figure 9.1: Mean TPH concentrations over time (vertical bars represent the standard error based on 22 samples)

Analysis of the raw TPH data showed a high degree of variation during the initial sampling data sets which indicates a high degree of variation between the different lots within the biopiles (see Appendix 1). The data also showed that as the remediation proceeded, the variation in the data declined as the TPH in each of the lots was reduced to the remaining recalcitrant hydrocarbons which remained within the soil at the end of the treatment.

The analysis of TPH-containing samples by GC-FID produces a chromatogram trace or 'fingerprint'. Examination of these traces can provide an understanding of the way the composition of petroleum hydrocarbons within the soil changed during the treatment. Figures 9.2 and 9.3 display the TPH chromatograms from the analysis of the samples taken from Lot C at the start and the end of the bioremediation (time zero and 20 weeks).

Both of the chromatograms display a large unresolved complex mixture (UCM) 'hump', which is a common feature of hydrocarbon contamination resulting from coal tars. The primary difference between the chromatograms is the reduction in area of the peaks in the frontal section of the chromatogram and the reduction in size of the frontal region of the UCM hump in the 20 week example. This area of the chromatogram is made up of the light molecular weight hydrocarbons, which are more amenable to bioremediation, whereas the high molecular weight compounds, which make up the tail region of the UCM hump and the peaks which extend out of it, have been reduced to a lesser extent.
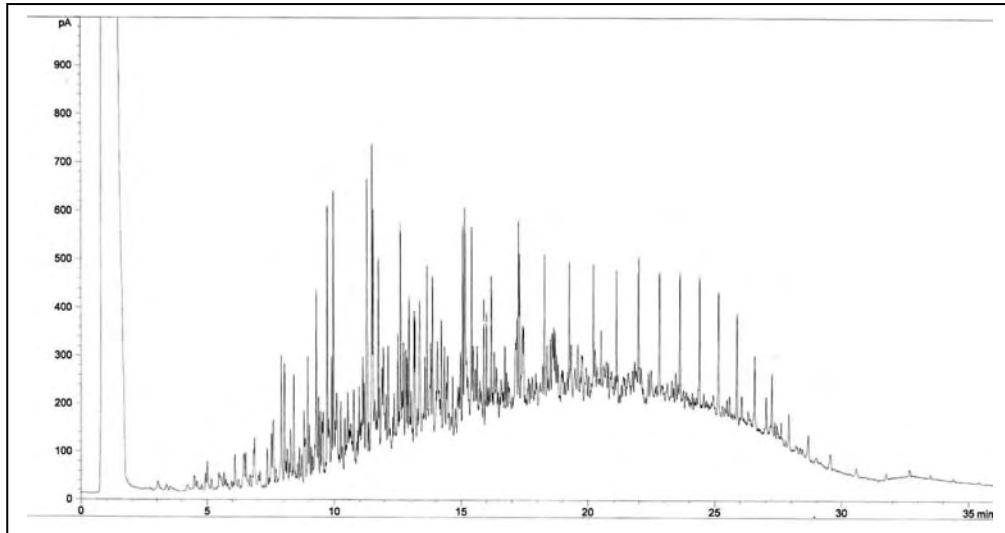
Figure 9.2: TPH analysis of Lot C (time zero) chromatogram
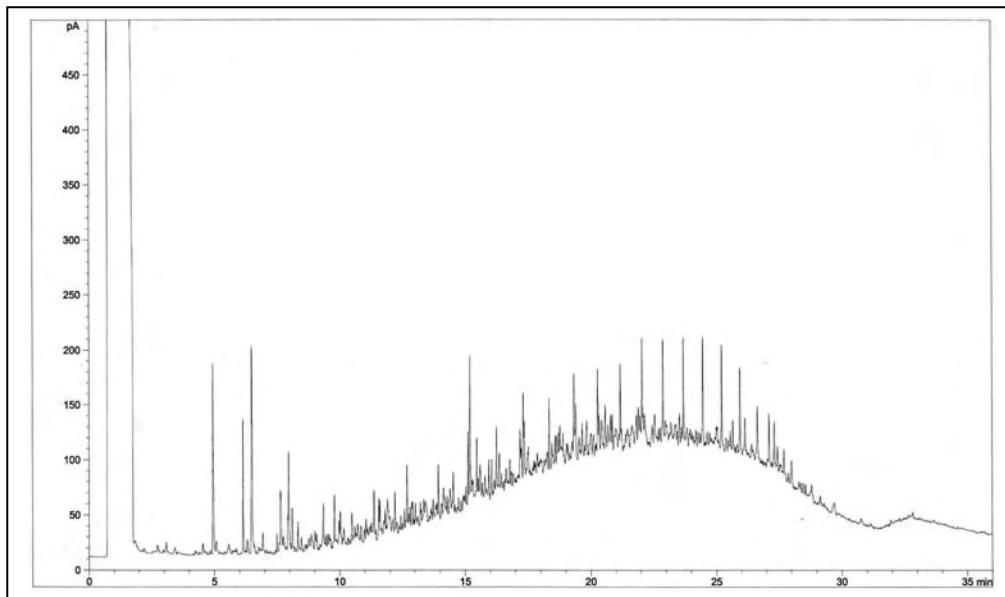
Figure 9.3: TPH analysis of Lot C (after 20 weeks) chromatogram

The chromatograms also show that a general reduction in the total quantity of hydrocarbons has been achieved. The UCM hump displayed in Figure 9.2 reaches a height of approximately 220 picoamps (pA) whereas the UCM hump displayed in Figure 9.3 only reaches a height of approximately 120 pA.

9.2.2   POLYCYCLIC AROMATIC HYDROCARBONS

GC-FID was used to determine the concentration of the USEPA suite of 16 PAH compounds in the soil samples. The individual compounds within the suite were not reported due to the fact that the remediation target did not require the speciation.

Table 9.1 and Figure 9.4 show the mean PAH concentrations over the course of the biopile treatment period. Only one of the 22 lots that were treated contained an initial concentration of PAH which exceeded the target limit set out in the specification by the consultant (1,000 mg/kg). Nevertheless, the data show a similar pattern of decline in concentration as the TPH data, with an initial decline in the concentration followed by a moderate decline over

the remaining period of the treatment. The mean total PAH concentration fell from 234 mg/kg at the start to 87 mg/kg at the completion of the treatment.
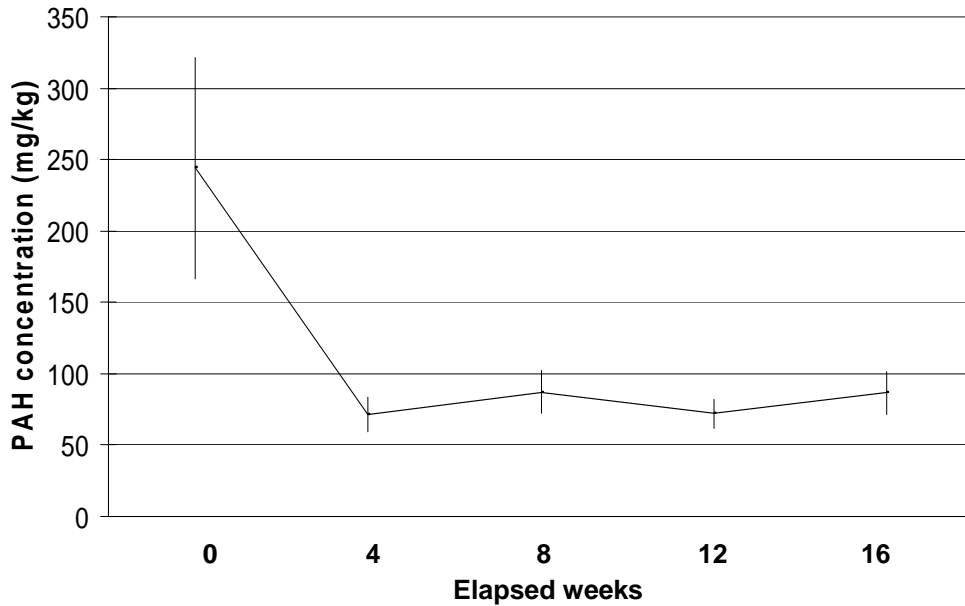
Figure 9.4: Mean total PAH concentrations (vertical bars represent the standard error based on 22 samples)

The raw data (see Appendix 1) show that the PAH concentrations do not exhibit the same reduction in the spread of values as shown by the TPH data. This suggests that although the mean shows a decline, the majority of the data may be subject to sampling and analysis error rather than a genuine reduction in concentration. However, the significant reduction in the concentration over the first four weeks does show that the removal of these compounds has taken place within the biopiles.

9.2.3   PHENOLS

Total phenols were measured as the cumulative sum of phenol, cresols, xylenols and trimethylphenols, and were analysed for using high performance liquid chromatography.

As with the previous data sets, the total phenol concentration data, shown in Figure 9.5, exhibit an initial rapid decline in the concentration followed by a steady decline. The mean phenol data for the two biopiles is reduced from 869 mg/kg in the soil at the start of treatment to 71 mg/kg after four weeks and further reduced to 38 mg/kg after 12 weeks. As noted in Table 9.1, two of the lots showed much higher phenols concentration compared with the others after 16 weeks, and as discussed for the TPH data in section 9.2.1, these problematic lots were G and H. Further sampling of these lots after continued treatment showed that the phenols concentration in these lots had fallen to within the acceptance criteria of 1 mg/kg after 20 weeks. However, as Lots G and H did not reach the required target TPH concentration they were relocated anyway to another area of the site following a specific risk assessment.

Phenols were one of the most readily biodegradable compounds to be treated by the biopiles at Askern and this is due to the electrophilic functional groups within the molecules. The size and rate of reduction in the concentration of these compounds can be attributed to the relative ease with which bacteria are able to metabolise them.
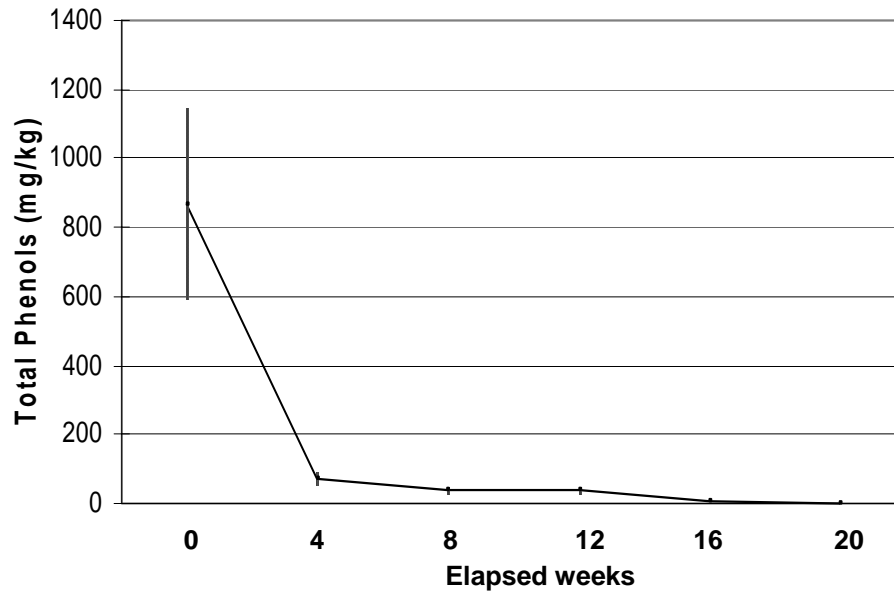
Figure 9.5: Mean total phenols concentrations (vertical bars represent the standard error based on 22 samples)

The compounds which comprise the total phenols concentration are phenol, cresols, xylenols and trimethylphenols and Figure 9.6 shows that the mean data for each of these compounds follow the same pattern of degradation as that for total phenols.
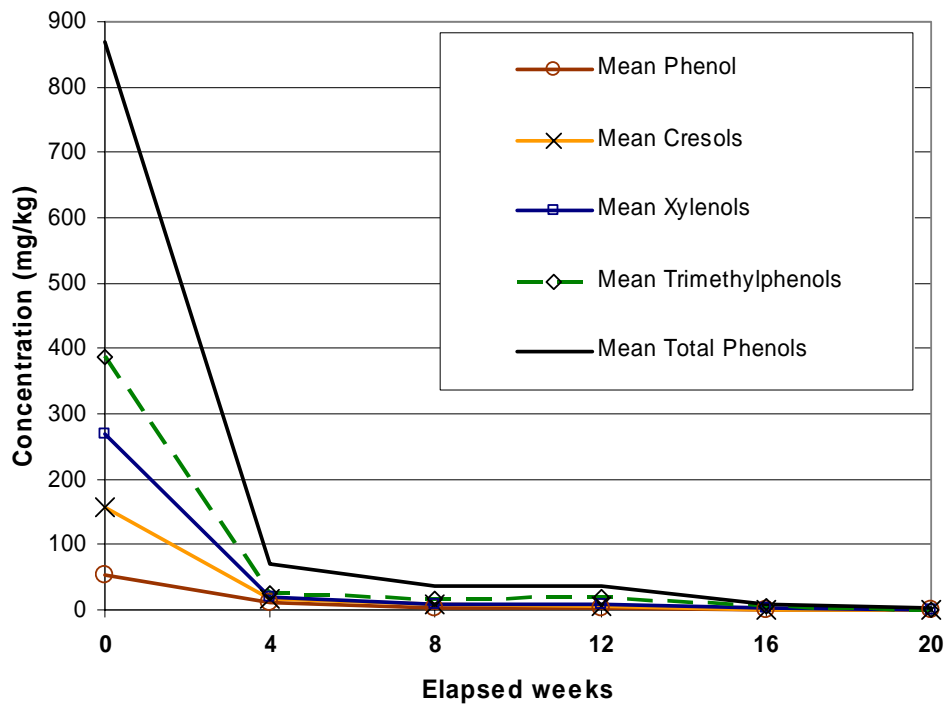
Figure 9.6: Mean concentration of compounds which comprise total phenols

9.2.4 BTEX COMPOUNDS

BTEX compounds are comprised of six different low molecular weight cyclic hydrocarbons: benzene, toluene, ethylbenzene and xylenes (ortho, meta and para). Figure 9.7 shows that these compounds display the same pattern in change in concentration over time as the other hydrocarbons included in the analysis and after 16 weeks have fallen below the acceptance criteria value of 100 μg/kg.
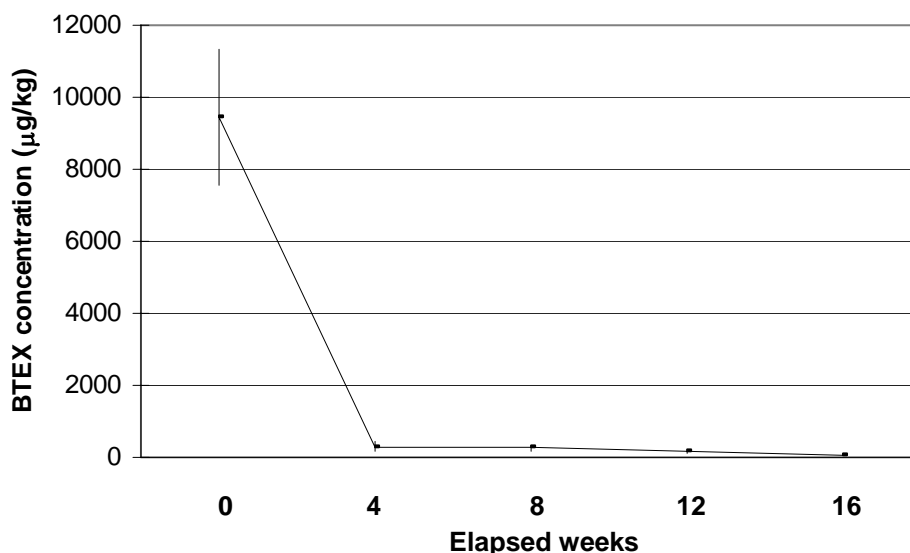
Figure 9.7: Mean BTEX concentrations over time (vertical bars represent the standard error based on 22 samples)

It is often assumed that the BTEX compounds are volatilised during bioremediation processes. However, analysis of the gas monitoring data (included in section 9.3) suggests that this has not occurred to the extent which would explain the marked reduction in concentration shown by the soil analysis results. The similarity of the degradation rate of the BTEX compounds with the TPH suggests that the removal process is similar and not separate and that biological degradation has indeed taken place.

9.2.5 MACRONUTRIENTS

There were two sources of macronutrients within the biopiles, the custom blend fertilizer and the composted sewage sludge (TCSS), both of which were added to the contaminated material during the formation works. The principal macronutrients that are discussed further below are ammonia, nitrate and orthophosphate and the change in their concentrations with time are shown in Figure 9.8.

One of the principal macronutrients that was used was ammonia, since the ammonium ion is used preferentially as a nitrogen source for aerobic bacteria. The ammonia concentration fell from a mean of 120 mg/kg at the start to 51 mg/kg after 4 weeks of treatment and demonstrates a similar trend of reduction to that shown by the contaminant hydrocarbons such as TPH. Following the initial decline, the ammonia concentration continues to decrease steadily over the remaining treatment period and the final data set contain a mean concentration of 11 mg/kg ammonia.
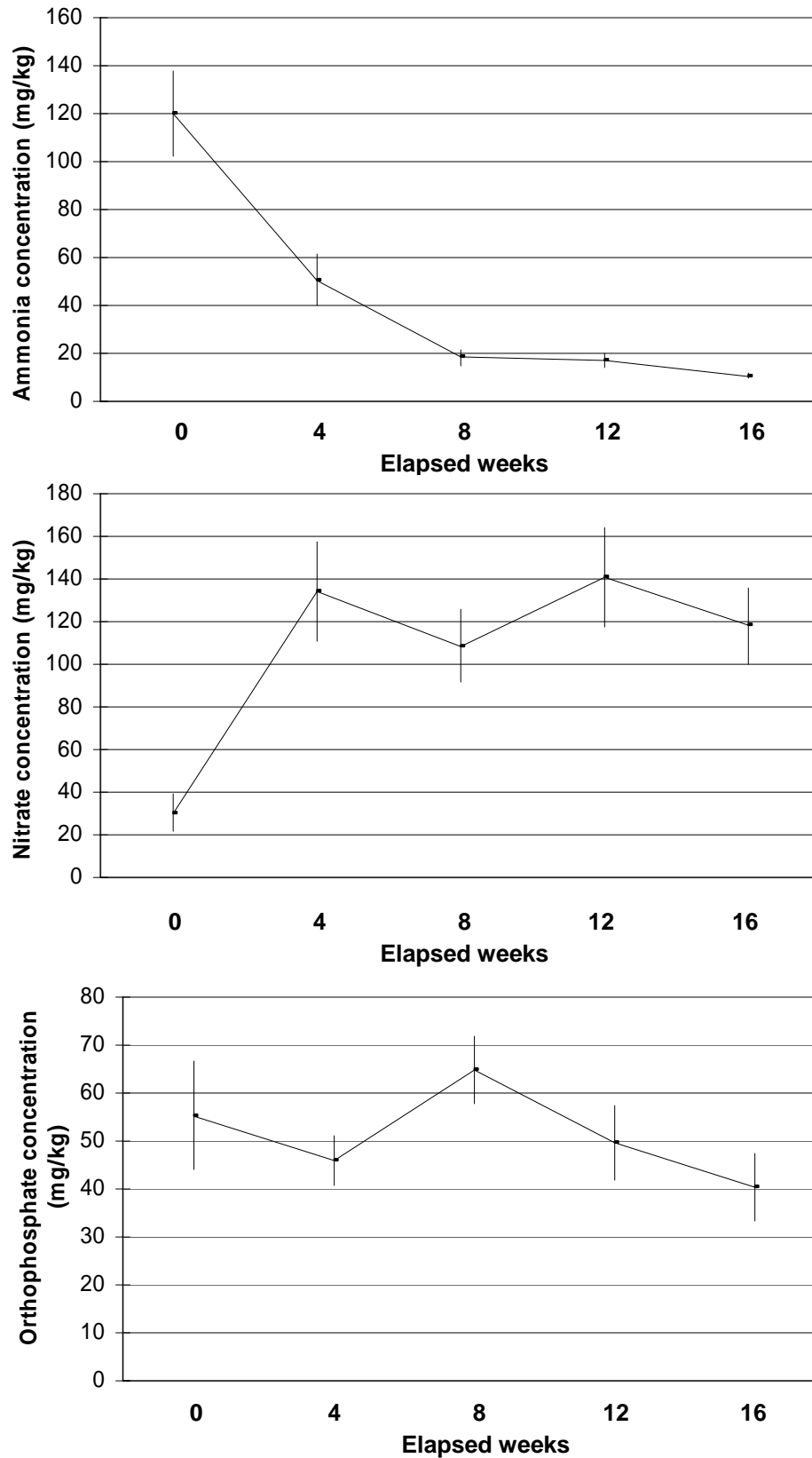
Figure 9.8: Mean concentrations of ammonia, nitrate and orthophosphate (vertical bars represent the standard error based on 22 samples)

Ammonia can be oxidised chemically to nitrate in an aerobic environment without the action of bacteria and the data for the concentration of nitrate show that this may have occurred to

a proportion of the ammonia within the biopiles. The nitrate concentration displays an initial rise over the first four weeks of a similar proportion of the decline in the ammonia concentration from 34 mg/kg up to 134 mg/kg mean, however, following this initial rise the concentration of nitrate does not follow the change in the concentration of ammonia but falls to 109 mg/kg mean and then increases to 141 mg/kg again, with 118 mg/kg being the final mean value. It is possible that, rather than the initial rise in the concentration being due to the oxidation of the ammonia within the biopiles, the change in the concentration of the nitrate is simply due to the action of the slow release nature of the fertilizer which was added during the formation works.

The concentration of phosphate within the biopiles displays a minor reduction over time although the variation in the data could be due to sampling and analysis error within the data. The amount of phosphorus which is utilised by bacterial action is significantly lower than the quantity of nitrogen which is utilised by bacteria and the fact that the two parameters do not display the same trend suggest that the nutrients were not washed out of the biopiles and that the nitrogen was utilised whereas only a small proportion of the phosphorus was utilised due to the lower requirement for bacterial growth. An alternative explanation is that the orthophosphate component of the fertilizer was released at a slower rate than the ammonium component giving a steady supply of phosphorus over the whole project rather than a large release at the beginning.

9.3   GAS MEASUREMENTS

Gas concentrations within, and released from, the biopile were measured using a Geotechnical Instruments GA2000 landfill gas analyser which is capable of measuring O_2, CH_4, CO_2, CO and H_2S concentrations, either as a percentage of the total or in parts per million (ppm) in the case of CO and H_2S.

Volatile organic compounds (VOCs) were measured using a MiniRae 2000 hand-held photoionisation detector (PID) which gives a quantitative measurement of volatile compounds expressed as a single gas. The instrument was calibrated against 100 ppm isobutylene and the readings are therefore expressed as isobutylene equivalents.

9.3.1   OXYGEN AND CARBON DIOXIDE

Figure 9.9 shows the mean O_2 and CO_2 concentrations over time. During the first half of the treatment period the concentration of these gases changed as would be expected. The O_2 concentration declined steadily until it became low enough as to become a limiting factor to aerobic biodegradation. The CO_2 content of the biopiles increased steadily over the first half of the treatment period as the aerobic bacteria utilised the O_2 and produced CO_2.

During the first half of the treatment period the vacuum blower was not operating at its full potential which enabled the amount of volatilisation of contaminants to be kept to a minimum. However, at week 12 the mean concentration of O_2 dropped below 5 % and it became necessary to increase the rate of aeration by placing the vacuum blower on full power (suction rate >7000 m^3 per hour). Prior to week 12 the vacuum blower was operating at approximately 50 % power.
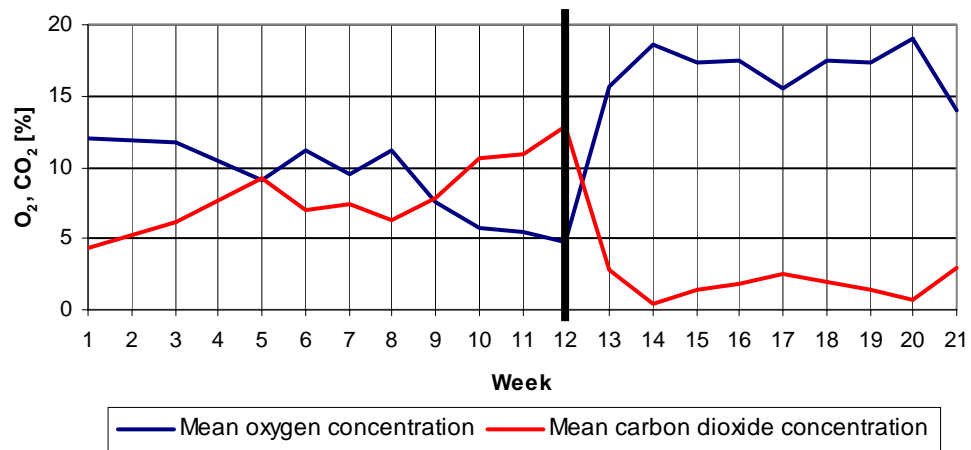
Figure 9.9: Mean oxygen and carbon dioxide concentrations over time (the vertical line indicates when the vacuum blower was used at full power)

The result of altering the flow rate of the vacuum blower is clearly illustrated in Figure 9.9, the O_2 levels within the biopiles increased to over 15 % and the CO_2 was reduced to below 5 % in one week. It is possible that the increase in the O_2 content during week 12 of the treatment allowed the biological degradation of the contaminants to continue at a faster rate and produce the change in TPH concentration seen between weeks 12 and 16 (see Table 9.1 and Figure 9.1).

9.3.2   VOLATILE ORGANIC COMPOUNDS

Figure 9.10 shows the mean VOC concentrations over time. The VOCs within the soil in each lot of the biopiles show an increase in concentration over the first four weeks of operation followed by a decline over the following 11 weeks. The point at which the VOCs reach their highest concentration is two weeks after an increase in temperature of the biopiles (see section 9.4), which shows that there was a two week lag before the volatile compounds evaporated into the pores spaces in the soil. From this point on, the VOC concentration declines within the soil pore spaces. This could be due to dissolution into the pore water and subsequent biodegradation or it could be the case that the VOCs were removed from the soil by the vacuum extraction system and ejected into the atmosphere, however, the latter of these is not entirely plausible due to the fact that the outlet from the vacuum blower did not exceed 10 ppm throughout the duration of the project. The mean concentration of VOCs in the exhaust from the vacuum blower was 8 ppm which assuming an average compound type of isobutylene gives an actual concentration of 18.7 mg/m^3 or approximately 3 kg per day at the full power of the vacuum blower (1 ppm of isobutylene is equal to 2.32 mg/m^3 at 20°C).
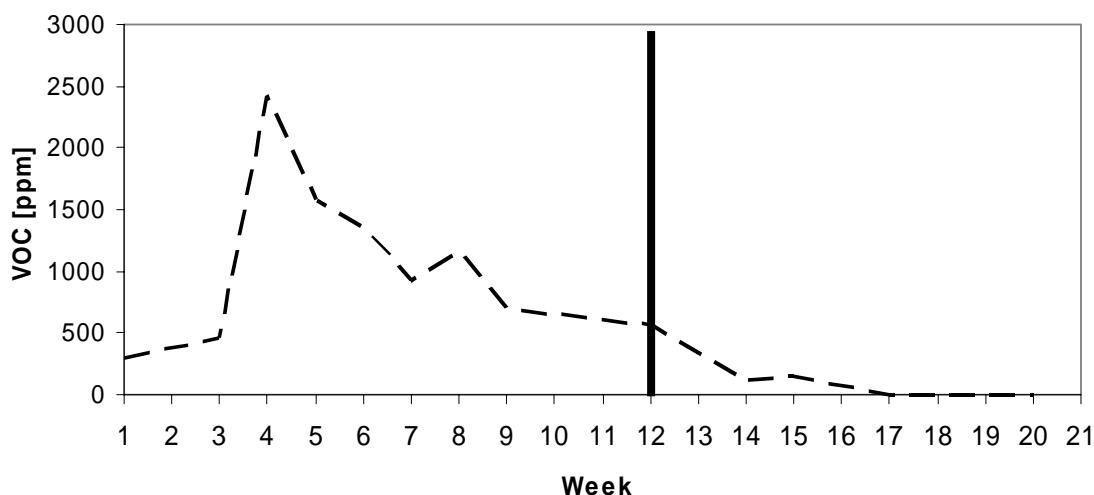
Figure 9.10: Mean VOC concentration over time (the vertical line indicates when the vacuum blower was used at full power)

Had the concentration in the exhaust of the vacuum blower been the same as the concentration in the pore spaces within the biopiles an approximate weight of 580 kg of hydrocarbons per day could have been volatilised. This would have resulted in the certain requirement for a VOC abatement system to be fitted to the exhaust of the vacuum blower and it is highly likely that a serious odour problem would have been apparent at the site during the treatment. Malodour was not noticed during the treatment and measurements of VOCs from the exhaust of the vacuum blower were undertaken in the presence of the local authority environmental health officer.

It was expected that an increase in the amount of volatilisation would have occurred following the increase in the power of the vacuum blower from approximately 50 % to 100 % at week 12, however this did not occur and it is possible that the VOCs had been effectively remediated within the initial 12 week period.

9.3.3   OTHER GASES

Other gases which were measured and monitored included CO, CH_4 and H_2S, all of which are associated with various species of anaerobic bacteria. CO and CH_4 reached maximum concentrations at week 12 of 0.3 % CH_4 and 12.2 ppm CO; H_2S was not detected during the remediation process. Following the alteration in the aeration rate, the concentration of these gases dropped to zero or the minimum detection limit. Although theses gases had built up over the first 12 weeks of operation the fact that they did not reach particularly high levels in the biopiles suggests that an anaerobic bacterial population did not become prevalent and that the availability of O_2 did not become a limiting factor.

9.3.4   RESPIRATION TESTS

During the remediation project a number of respiration tests were undertaken by switching the vacuum blower off line and monitoring the O_2 and CO_2 over a period of hours.

The respiration tests showed a mean reduction in the O_2 concentration in the soil from 18 % to 14 % of the total gas over 5 hours and an increase in CO_2 from 0.3 % to 2.4 % of the total gas in the same time frame. One test was conducted over a period of 24 hours and produced a reduction in the O_2 concentration from 18.7 % down to 5.8 % and an increase in the CO_2 concentration from 0.7 % to 6.4 % in the same 24 hours.

The respiration tests that were undertaken clearly show that an active aerobic bacterial population was present in the biopiles.

9.4 TEMPERATURE MEASUREMENTS

The soil temperatures recorded within each lot at Askern reached a maximum of 33.7 °C, a minimum of 17.7 °C and a mean of 24.4 °C. The temperature of the biopiles at Askern increased from a mean of 13 °C at the first data point to 23.2 °C two weeks later. The mean temperature of the lots ranged between 23.2 °C and 25.9 °C during the whole treatment period of 20 weeks, declining to 22.8 °C during the final week.

The ambient temperature on site during the treatment period ranged between 10 °C and 31 °C with the highest temperatures during the middle of the treatment period in June and July. The highest ambient temperature was recorded during week 8, in July. The trend in ambient temperature does not follow the trend in the temperature in the biopiles, which remained much more constant and increased to above 20 °C when the ambient temperature remained at 12 °C and 14 °C.

Many of the lots showed peaks of temperature followed by a decline, and the timings of the peaks are not equal, this suggests that sub-systems existed within the biopiles and that the degradation in each lot progressed at varying rates. However, this is to be expected with 22,000 m^3 of heterogeneous material. The decline in temperature is to be expected after the bioremediation reaches the limit of its carbon source and the bacterial population begins to decline.

The use of temperature has shown that it is possible to undertake indicative monitoring of the biopiles quickly and easily, and is a parameter that could be used on a daily basis to gauge the health of the biological population.

9.5 LEACHATE MEASUREMENTS AND MASS BALANCE

The leachate was sampled and analysed four times during the project and gave relatively consistent results. The leachate was analysed for TPH, phenols and ammonia.

Table 9.2: Leachate data

Date	TPH (mg/L)	Total phenols (mg/L)	Ammonia (mg/L)
20/08/2002	8.8	<0.1	127
13/09/2002	3.8	<0.1	87.8
01/10/2002	5.5	<0.1	73.6
14/10/2002	5.6	<0.1	85.3

The data for the concentration of phenols in the leachate was not expected, it was thought before the project that a large amount of the phenol would be washed out of the biopiles and into the leachate, however, this was not the case.

A total of 697 m^3 of leachate were disposed of from the remediation process, containing a mean of 6.74 mg/L TPH, which equates to a total of 4.7 kg of hydrocarbons. Based upon a mean concentration at the start of treatment, it was calculated that the biopiles contained a total of 538 tonnes of TPH at the start of the treatment.

An indicative mass balance calculation shows that from this total of 538 tonnes of TPH in the original 22,000 m^3, 420 kg of TPH (0.08 %) were lost to atmosphere and 4.7 kg of TPH (0.0009 %) were lost to leachate. In terms of total phenols, of a total of 1,800 kg of phenols in the original 22,000 m^3, 238 grams (0.01 %) were lost to leachate.

10.   ECONOMIC CONSIDERATIONS

Bioremediation is now accepted as a viable alternative to landfill as a method for the removal of environmental and human health risk from contaminated sites. The economic advantages do not just extend to the value of the method of disposal but also the cost of returning the site in question to its original levels, which can involve the importation of large quantities of material to replace the material that was landfilled.

In a broader scenario, the use of bioremediation to treat contaminated material on site does not add to the burden of the existence of contaminated landfill sites which must be maintained and monitored for very long periods of time, whereas material which conforms to a site-specific quantitative risk assessment through bioremediation does not involve the same long term economic liability as a contaminated landfill.

The operation of a remediation project such as the one undertaken at Askern Colliery involves many individual items of expenditure. The actual bioremediation of the material may not constitute the majority of these costs and most of them will be incurred anyway if the waste material is landfilled or treated with another system of remediation. For example, waste material totalling 25,000 m^3 would still require excavation, sorting and screening prior to landfill so that the hazardous waste can be separated from the controlled waste and the material not requiring remediation can be effectively removed from the waste and re-used at the site so as to reduce the volume of material that is landfilled. This process of excavation and sorting is also required for bioremediation to be successful, so the two systems for remediation of contaminated land involve the same costly groundwork.

The bioremediation cost for the material that was treated at Askern Colliery equated to approximately £8.50 per m^3. This cost is at the low end of the scale which should be expected from bioremediation as it was only possible because of the economies of scale allowed by treating a large volume of material. The bioremediation cost included the treatment plant and equipment, aeration pipework, maintenance and monitoring of the bioremediation system for 20 weeks.

The costs associated with the earthworks were;
- £0.80 to £1.00 per m^3 for excavation.
- £4.00 to £5.00 per m^3 for screening and crushing.
- £0.40 to £0.50 per m^3 for placement.

The process of excavation and groundwork undertaken at Askern (see section 6) was able to reduce the original estimated volume of material requiring treatment or disposal from 52,000 m^3 to 24,000 m^3. This shows that large savings can be made from well planned excavation and sorting methods. The contamination mapping exercise cost £85,000 and created a volume reduction of 28,000 m^3. The saving produced with reduced treatment alone was therefore £238,000 (£8.50 x 28,000). In addition, there would be an absolute minimum cost of £0.50 per m^3 for handling that material (as it required some movement and crushing) which equates to £14,000. Therefore, the overall saving of undertaking the contamination mapping exercise and methodical excavation and sorting was at least £165,000.

Many economic considerations are site specific and can have a large impact upon the final cost of the project. For example, at Askern Colliery, the availability of colliery spoils with high clay content meant that the treatment area could be constructed from materials present at the site, thereby producing a significant saving. One aspect of the costs incurred, which was difficult to predict prior to the project, was vandalism. During the bioremediation project vandalism caused several significant delays and theft of materials, particularly the biopile covers, caused adverse financial implications such as the necessity to employ full time site-wide security where security of the site compound would usually suffice.

11.   CONCLUSIONS

The biopiles that were designed, constructed and operated by Ecologia Environmental Solutions Ltd at Askern Colliery were designed to conform to the basic principals of removal of limiting factors while retaining control of the process. The data contained in this report show that it is possible to monitor the system in various inexpensive ways, such as temperature and gas monitoring, so that potential problems can be identified and the process can be studied. When the monitoring is coupled with the standard chemical analysis of the contaminants it is possible to demonstrate the bioremediation of the hydrocarbons. For instance, combining process monitoring of gases with chemical analysis of the soil will demonstrate the fate of the VOCs. The implementation of a vacuum aeration system allows the amount of VOCs to be quantified. The system which Ecologia built in-house allowed the airflow to be kept to a minimum thus reducing the volatilisation. The biopile system also allows the implementation of a VOC abatement system, as all the exhaust is emitted from a single pipe, therefore, off gases can be easily passed through a biofilter.

The analysis of the gases within the biopile enabled Ecologia to undertake respiration tests to assess the level of biological activity. The tests showed that there was a rapid production of carbon dioxide and utilisation of oxygen, consistent with an active aerobic bacterial population.

Although the project demonstrated that it is possible to achieve the effective bioremediation of contaminated soils through careful monitoring of the process, it did not conclusively show that bioremediation is an effective remediation option for the removal of PAHs. Although the PAH concentrations declined during the treatment, they were already below the target concentrations at the start of the project.

Other problems which became apparent during the project were the weather and vandalism, both of which had a large cost implication. One problem which was identified following the first heavy rainfall event was that the bio-treatment area of the site did not have adequate drainage for surface water. On several occasions the treatment system had to be switched off due to flooding, the main concern of which was the contact of the surface water with the contaminated soil, thereby contaminating it. On several occasions high winds caused some of the covers to be blown off the biopiles which left the soil beneath exposed to the rain. Extensive damage caused by vandalism and theft was encountered during the biopile formation works that necessitated the employment of night time security.

Overall the project has shown that successful bioremediation is possible given the correct planning and design. An important part of this design is a good system of excavation and sorting of the contaminated material. This is especially important at sites such as former coking works where non-biodegradable material such as coal tars exist. The fact that the majority of the material selected for bioremediation at Askern Colliery contained relatively few PAHs is testament to the success of the excavation programme implemented by Mowlem, which was in turn vital to the success of the bioremediation, as the inclusion of material which is not biodegradable leads to the failure of bioremediation. This was experienced to a certain extent at Askern in the cases of Lots G and H, which did not reach the target concentration for TPH and required special risk assessment, and subsequent agreement from the Environment Agency before the material included in these lots could be incorporated into the earthworks programme at the site. With the exception of Lots G and H the bioremediation at Askern was successful and the monitoring programme implemented by Ecologia has shown that it is possible to monitor large bioremediation projects using inexpensive, quick methods that do not require a large amount of laboratory analysis.

12.   LESSONS LEARNED

1.   The excavation programme is vital to the success of the bioremediation programme. A poor excavation programme with no planning or material segregation will lead to non-biodegradable material, such as coal tars, being included in the material due for treatment, and ultimately the failure of the treatment system.

2.   Inexpensive and rapid monitoring of the temperature and gases allow the bioremediation to be monitored on a daily basis which can predict problems, identify the end point and provide data to verify the process.

3.   Bioremediation using biopiles allows the control of potentially polluting effects of bioremediation such as leachate formation and VOC loss to atmosphere to be effectively monitored and controlled.

4.   The waste management licensing system can be used effectively. It was possible to gain approval of a site-specific licence within one month of submission through pre-planning and a good understanding of what is required in a site-specific licence document.

5.   Severe problems can arise from adverse weather conditions. Adequate systems for the collection and removal of large amounts of rainwater are required and this should be included in the pre-project planning.   A site may require discharge consents to be sought from the Environment Agency in the case of a discharge to a controlled water or the local water company in the case of discharge to foul sewer.

GLOSSARY OF TERMS

Aerobic
A descriptive term for a process that can proceed only in the presence of oxygen or organisms that require the presence of oxygen to live.

Aliphatic hydrocarbons
A straight or branched chain hydrocarbon (i.e. without a benzene ring).

Anaerobic
A descriptive term for a process, such as fermentation, that can proceed only in the absence of oxygen, or a living thing that can survive only in the absence of oxygen.

Aromatic hydrocarbons
Hydrocarbons containing one or more benzene rings (C_6H_6).

Catabolic
A metabolic process in which complex molecules are broken down into simple ones, often resulting in a release of energy.

Chemoheterotrophs
A heterotroph that exploits chemical forms of energy. Most microorganisms used in bioremediation are chemoheterotrophs.

Enzymes
Biological catalysts that promote chemical reactions by reducing the amount of activation energy required for the reaction to occur.

Exogenous
From outside the system. For example, non-indigenous microorganisms added to a biopile to augment the biodegradation.

Fermentation
A process in which an agent causes an organic substance to break down into simpler substances; especially, the anaerobic breakdown of sugar into alcohol.

Fill materials
Materials that have been brought together from a number of sources such as brick rubble, concrete etc and used to raise the natural ground level.

Heterotrophs
A heterotroph is an organism that requires organic substrates to get its carbon for growth and development.

Macronutrients
Macronutrients are nutrients that are needed in large amounts.

Made ground
Manmade soil that is lying on top of the natural ground and often consist of natural soil mixed with clinker, ash, concrete and brick.

Metabolic
The chemical processes that occur in living organisms, resulting in growth, production of energy, and elimination of waste.

Micronutrients
Micronutrients are needed in very small amounts. Micronutrients are also known as trace elements.

Polycyclic aromatic hydrocarbons
Hydrocarbon compounds with multiple benzene rings. PAH are typical components of tars, asphalts, fuels, oils and greases.

Respiration
The oxidative process occurring within living cells by which the chemical energy of organic molecules is released in a series of metabolic steps involving the consumption of oxygen and the liberation of carbon dioxide and water. Also, any of various analogous metabolic processes by which certain organisms, such as fungi and anaerobic bacteria, obtain energy from organic molecules.

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APPENDICES

Appendix 1: Analytical data for each of the biopile lots

APPENDIX 1: ANALYTICAL DATA FROM EACH OF THE BIOPILE LOTS

LOT A	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	1643	62	37	76	53
TPH (mg/kg)	14190	5490	2550	3280	625
Total phenols (mg/kg)	661	41.9	17.6	29.1	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	970	<10	<10	<10	<10
Ethylbenzene (µg/kg)	659	<10	<10	<10	<10
Xylenes (µg/kg)	4040	<20	<20	<20	<20
pH	9.3	10.1	8.1	9	8
Moisture content (%)	16.7	15.6	16.6	15.9	9.9
Ammonia (mg/kg)	56.1	15.8	11.5	18.6	10.2
Nitrate (mg/kg)	23	128	86	411	228
Orthophosphate (mg/kg)	10	49.7	48.1	50.4	36

LOT B	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	136	51	181	72	44
TPH (mg/kg)	17860	2680	2580	2510	398
Total phenols (mg/kg)	948	4.5	9.2	14.5	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	447	<10	<10	<10	<10
Ethylbenzene (µg/kg)	495	<10	<10	<10	<10
Xylenes (µg/kg)	2760	<20	<20	<20	<20
pH	7.9	7.7	7.9	8.1	8.2
Moisture content (%)	16.7	17.3	16.6	15	12.2
Ammonia (mg/kg)	73	125	24.9	9.8	7.4
Nitrate (mg/kg)	55	464	209	236	212
Orthophosphate (mg/kg)	39	66.8	48.1	33.6	25.6

LOT C	Elapsed weeks							
Determinand	**0**	**4**	**8**	**12**	**16**	**20**	**24**	**28**
Total PAHs (mg/kg)	249	117	140	191	134			
TPH (mg/kg)	44160	7690	10960	7950	1230			420
Total phenols (mg/kg)	1640	312	35	50.1	<2.4			<0.5
Benzene (µg/kg)	563	<10	<10	<10	<10			<0.1
Toluene (µg/kg)	3380	37	15	<10	<10			<0.1
Ethylbenzene (µg/kg)	1690	33	16	<10	<10			<0.1
Xylenes (µg/kg)	9530	113	36	<20	<20			<0.1
pH	8	7.8	8.2	8.7	8.2			
Moisture content (%)	12.7	20.7	22.5	25.5	14.9			
Ammonia (mg/kg)	32.6	37	14.9	13.3	7.2			
Nitrate (mg/kg)	15	337	184	107	315			
Orthophosphate (mg/kg)	39	66.8	48.1	33.6	25.6			

LOT D	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	261	101	128	182	53
TPH (mg/kg)	42410	16570	10000	10800	451
Total phenols (mg/kg)	1110	62.2	29.3	44.9	<1.2
Benzene (µg/kg)	1200	<10	<10	<10	<10
Toluene (µg/kg)	6390	12	<10	<10	<10
Ethylbenzene (µg/kg)	2610	<10	<10	<10	<10
Xylenes (µg/kg)	14700	54	<20	<20	<20
pH	8.3	11.1	7.8	8.4	7.9
Moisture content (%)	7.7	19.9	26.2	19.1	14
Ammonia (mg/kg)	68.9	7.5	14.2	68.8	12.7
Nitrate (mg/kg)	14	46	84	299	127
Orthophosphate (mg/kg)	23	12.3	72.2	55.1	58.1

LOT E	Elapsed weeks							
Determinand	**0**	**4**	**8**	**12**	**16**	**20**	**24**	**28**
Total PAHs (mg/kg)	150	103	75	83	97			
TPH (mg/kg)	17040	3530	11300	8350	912			360
Total phenols (mg/kg)	1010	265	44.7	33.5	<2.4			<0.5
Benzene (µg/kg)	2530	<10	<10	<10	<10			<0.1
Toluene (µg/kg)	11100	77	26	13	20			<0.1
Ethylbenzene (µg/kg)	3660	202	47	25	38			<0.1
Xylenes (µg/kg)	19890	1085	151	64	109			<0.1
pH	8.1	8	8.1	7.8	7.4			
Moisture content (%)	16.9	17.5	22.8	19.6	21.6			
Ammonia (mg/kg)	247	36.9	15.9	14.1	16.4			
Nitrate (mg/kg)	<5	73	7	188	257			
Orthophosphate (mg/kg)	131	41.5	49.7	74.6	108			

LOT F	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	102	117	227	82	92
TPH (mg/kg)	12840	6190	6610	4470	550
Total phenols (mg/kg)	292	104	27.9	30	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	760	23	12	50	<10
Ethylbenzene (µg/kg)	750	37	22	84	<10
Xylenes (µg/kg)	4140	108	75	396	<20
pH	8.4	7.7	8.1	7.8	7.7
Moisture content (%)	18.2	30.4	26.7	17.6	10.7
Ammonia (mg/kg)	324	98.4	18.7	12.5	6.8
Nitrate (mg/kg)	5	43	116	68	156
Orthophosphate (mg/kg)	176	38.3	114	54.2	30.1

LOT G	Elapsed weeks							
Determinand	**0**	**4**	**8**	**12**	**16**	**20**	**24**	**28**
Total PAHs (mg/kg)	45	102	113	107	346	58	230	
TPH (mg/kg)	4800	8140	20800	24800	2180	4400	6500	2600
Total phenols (mg/kg)	51.5	29.2	99.5	235.9	73.6	<0.5	<0.5	<0.5
Benzene (µg/kg)	<25	<10	<10	<10	<10	<0.1	<0.1	<0.1
Toluene (µg/kg)	57	29	126	56	27	<0.1	<0.1	<0.1
Ethylbenzene (µg/kg)	104	57	166	85	38	<0.1	<0.1	<0.1
Xylenes (µg/kg)	418	299	1100	450	108	<0.1	<0.1	<0.1
pH	8	7.5	7.8	8.6	7.9			
Moisture content (%)	10.7	24.2	22.2	20.7	12.5			
Ammonia (mg/kg)	78.7	220	37.9	22.3	10.4			
Nitrate (mg/kg)	21	307	46	15	22			
Orthophosphate (mg/kg)	30	24.1	34.8	25.6	5			

LOT H	Elapsed weeks							
Determinand	**0**	**4**	**8**	**12**	**16**	**20**	**24**	**28**
Total PAHs (mg/kg)	899	286	302	90	127	37	110	
TPH (mg/kg)	138530	17050	33900	21900	3340	3700	4000	1800
Total phenols (mg/kg)	6000	204	206	78.6	77.1	0.96	<0.5	<0.5
Benzene (µg/kg)	214	<10	<25	<10	<10	<0.1	<0.1	<0.1
Toluene (µg/kg)	1860	21	91	31	36	<0.1	<0.1	<0.1
Ethylbenzene (µg/kg)	1200	31	121	30	60	<0.1	<0.1	<0.1
Xylenes (µg/kg)	7300	113	993	144	162	<0.1	<0.1	<0.1
pH	8.3	8.1	8.8	8	7.8			
Moisture content (%)	18	21.2	21.3	17.5	17.8			
Ammonia (mg/kg)	177	102	79.4	36.5	31.2			
Nitrate (mg/kg)	<5	156	48	112	10			
Orthophosphate (mg/kg)	12	60.2	8.9	30.1	6.2			

LOT I	Elapsed weeks			
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	48	14	55	18	42
TPH (mg/kg)	1380	1320	9380	593	743
Total phenols (mg/kg)	212	16.9	75.6	10.9	<1.2
Benzene (µg/kg)	<10	<10	<10	<10	<10
Toluene (µg/kg)	53	<10	12	<10	<10
Ethylbenzene (µg/kg)	63	<10	34	<10	<10
Xylenes (µg/kg)	309	<20	141	<20	<20
pH	8.2	7.9	8.2	7.7	8
Moisture content (%)	12.5	15.9	23.1	15.1	9
Ammonia (mg/kg)	230	46.7	41.8	12	13.4
Nitrate (mg/kg)	19	151	89	152	106
Orthophosphate (mg/kg)	18	20.6	81.5	22.7	17.4

LOT J	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	42	9	30	22	33
TPH (mg/kg)	6490	1200	1000	514	332
Total phenols (mg/kg)	41	62.6	15.1	8	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	39	31	<10	<10	<10
Ethylbenzene (µg/kg)	40	37	<10	<10	<10
Xylenes (µg/kg)	176	113	<20	<20	<20
pH	8.1	8.1	7.7	7.9	7.7
Moisture content (%)	12.3	17.3	16.6	16.3	9.9
Ammonia (mg/kg)	25.5	94.5	17.1	11	11.4
Nitrate (mg/kg)	24	133	338	87	118
Orthophosphate (mg/kg)	22	7.6	58.3	53.7	32.4

LOT K	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	49	48	62	50	58
TPH (mg/kg)	3170	6890	4160	4050	817
Total phenols (mg/kg)	68.3	38.3	31.8	10.1	<1.2
Benzene (µg/kg)	546	<10	<10	<10	<10
Toluene (µg/kg)	756	<10	<10	12	<10
Ethylbenzene (µg/kg)	1389	<10	11	12	<10
Xylenes (µg/kg)	6110	<20	29	37	<20
pH	10.8	8.8	10.4	9.7	9.8
Moisture content (%)	17.2	16.7	13.8	19.2	11.4
Ammonia (mg/kg)	24.6	29.4	7	10.1	8.1
Nitrate (mg/kg)	57	17	39	89	42
Orthophosphate (mg/kg)	138	28.5	80.4	108	45.7

LOT L	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	77	70	19	37	133
TPH (mg/kg)	6120	4090	3520	1860	521
Total phenols (mg/kg)	518	35.4	8.6	15.4	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	1770	10	<10	10	<10
Ethylbenzene (µg/kg)	1200	12	<10	13	<10
Xylenes (µg/kg)	6370	<23	<20	36	<20
pH	8.2	10	10.3	9.8	9.2
Moisture content (%)	20.7	13.5	14.4	15.9	11
Ammonia (mg/kg)	218	15	6.8	8.4	8.3
Nitrate (mg/kg)	<5	99	199	81	113
Orthophosphate (mg/kg)	39	31	116	49.2	64.6

LOT M	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	51	55	39	56	183
TPH (mg/kg)	5210	4880	5120	1550	672
Total phenols (mg/kg)	100.1	40	72.8	10.5	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	2450	<10	<10	<10	<10
Ethylbenzene (µg/kg)	3080	12	<10	<10	<10
Xylenes (µg/kg)	16320	33	<20	<20	<20
pH	9.6	8.2	8.2	8.1	8.2
Moisture content (%)	12.1	19.4	15.7	14.2	12
Ammonia (mg/kg)	73	32.9	11.2	11	9.4
Nitrate (mg/kg)	102	40	126	137	62
Orthophosphate (mg/kg)	109	35.1	53.8	50.4	35.7

LOT N	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	64	58	40	78	63
TPH (mg/kg)	4270	3540	4320	3572	810
Total phenols (mg/kg)	186	22.1	11.6	22.5	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	1960	10	<10	<10	<10
Ethylbenzene (µg/kg)	2610	15	<10	<10	<10
Xylenes (µg/kg)	8680	27	<20	<20	<20
pH	8.6	10.7	10.3	9.9	9
Moisture content (%)	17.2	14.7	17.3	18	9.6
Ammonia (mg/kg)	163	19.3	5.3	8.2	9.4
Nitrate (mg/kg)	16	151	138	167	146
Orthophosphate (mg/kg)	165	66.2	64.9	56	36.9

LOT O	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	241	21	31	36	34
TPH (mg/kg)	31780	2690	2270	2160	374
Total phenols (mg/kg)	1620	38	8.9	98.4	<1.2
Benzene (µg/kg)	126	<10	<10	<10	<10
Toluene (µg/kg)	1280	<10	<10	<10	<10
Ethylbenzene (µg/kg)	1040	<10	<10	<10	<10
Xylenes (µg/kg)	6060	<20	<20	<20	<20
pH	9.3	9.1	8.9	9.2	8.7
Moisture content (%)	12.3	14.8	17.1	13.1	12.9
Ammonia (mg/kg)	99.4	19.8	7.2	6.2	5.8
Nitrate (mg/kg)	26	77	127	49	28
Orthophosphate (mg/kg)	8	69.7	130	11.2	44.5

LOT P	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	151	57	51	22	56
TPH (mg/kg)	12500	2620	1740	1280	746
Total phenols (mg/kg)	291	18	8.8	5	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	384	<10	<10	<10	<10
Ethylbenzene (µg/kg)	463	<10	<10	<10	<10
Xylenes (µg/kg)	2500	<20	<20	<20	<20
pH	8.4	9.4	8.3	10	8.2
Moisture content (%)	11.8	12.1	19.6	14.9	8.3
Ammonia (mg/kg)	214	16.2	9.4	2.7	9.1
Nitrate (mg/kg)	174	48	113	13	119
Orthophosphate (mg/kg)	52	45.9	129	31.2	20.9

LOT Q	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	180	61	84	142	56
TPH (mg/kg)	19710	5350	6770	3900	445
Total phenols (mg/kg)	1400	84.9	20.5	28	<1.2
Benzene (µg/kg)	72	<10	<10	<10	<10
Toluene (µg/kg)	1040	<10	<10	<10	<10
Ethylbenzene (µg/kg)	880	<10	<10	<10	<10
Xylenes (µg/kg)	5110	<20	<20	<20	<20
pH	8.6	10	9.1	9.9	8.3
Moisture content (%)	10.2	16	19.6	15.1	12.8
Ammonia (mg/kg)	69.1	14	7.4	25.4	12.6
Nitrate (mg/kg)	6	156	0	141	38
Orthophosphate (mg/kg)	38	42.7	40.8	52.8	30.1

LOT R	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	153	32	52	55	60
TPH (mg/kg)	14560	2800	5010	2850	955
Total phenols (mg/kg)	592	27.6	18.4	21.7	<1.2
Benzene (µg/kg)	107	<10	<10	<10	<10
Toluene (µg/kg)	1380	<10	<10	<10	<10
Ethylbenzene (µg/kg)	1180	<10	<10	<10	<10
Xylenes (µg/kg)	6520	<20	<20	<20	<20
pH	7.9	9.6	9.1	8.8	8.5
Moisture content (%)	11.9	12.3	17.1	17.1	11.7
Ammonia (mg/kg)	113	27.3	10.6	11.3	11.5
Nitrate (mg/kg)	5	214	177	149	81
Orthophosphate (mg/kg)	32	23.7	48.4	25.4	10.9

LOT S	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	108	40	45	29	39
TPH (mg/kg)	12640	2440	1560	1920	535
Total phenols (mg/kg)	294	33.9	20.3	33.1	<1.2
Benzene (µg/kg)	119	<10	<10	<10	<10
Toluene (µg/kg)	1490	100	23	89	11
Ethylbenzene (µg/kg)	990	489	158	144	17
Xylenes (µg/kg)	5670	2000	453	522	51
pH	8.3	9.3	9	9.3	9.4
Moisture content (%)	12.1	17.2	14.7	14	10.7
Ammonia (mg/kg)	102	33.4	32.8	8.6	8.8
Nitrate (mg/kg)	8	24	104	15	52
Orthophosphate (mg/kg)	41	63	51.9	5	24.8

LOT T	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	190	58	78	65	127
TPH (mg/kg)	11840	3750	2610	5070	1020
Total phenols (mg/kg)	272	72.4	13.7	27.5	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	303	37	41	<10	<10
Ethylbenzene (µg/kg)	257	88	197	<10	<10
Xylenes (µg/kg)	1500	258	851	<20	<20
pH	8.3	10.6	10.6	10.8	10.8
Moisture content (%)	10.3	14.1	16.7	13.6	10.5
Ammonia (mg/kg)	79.5	44.7	8.2	28.3	10.9
Nitrate (mg/kg)	9	29	51	402	181
Orthophosphate (mg/kg)	33	117	76.9	165	145

LOT U	Elapsed weeks				
Determinand	**0**	**4**	**8**	**12**	**16**
Total PAHs (mg/kg)	183	43	45	46	46
TPH (mg/kg)	17960	2170	1660	3900	486
Total phenols (mg/kg)	1710	43.8	12.3	10.3	<1.2
Benzene (µg/kg)	109	<10	<10	<10	<10
Toluene (µg/kg)	1880	42	<10	<10	<10
Ethylbenzene (µg/kg)	1230	125	10	<10	<10
Xylenes (µg/kg)	7450	269	40	<23	<20
pH	8.1	9.4	9.4	10.9	10.6
Moisture content (%)	22	14.9	15.4	11.5	5.9
Ammonia (mg/kg)	143	30.3	7.3	14.3	3.1
Nitrate (mg/kg)	10	150	97	119	170
Orthophosphate (mg/kg)	17	35.5	55.1	50.4	47.5

LOT V	Elapsed weeks				
Determinand	0	4	8	12	16
Total PAHs (mg/kg)	124	40	49	45	38
TPH (mg/kg)	16820	2860	2070	1640	569
Total phenols (mg/kg)	101.9	13.8	15.7	12.1	<1.2
Benzene (µg/kg)	<25	<10	<10	<10	<10
Toluene (µg/kg)	83	12	<10	12	<10
Ethylbenzene (µg/kg)	121	12	20	11	<10
Xylenes (µg/kg)	850	68	56	28	<20
pH	9.3	8.4	8.2	8	8
Moisture content (%)	23.2	16.9	15.3	16.1	7.9
Ammonia (mg/kg)	29.1	47.5	10	20.2	9.1
Nitrate (mg/kg)	65	114	14	60	17
Orthophosphate (mg/kg)	72	66.5	14.9	2	4.7