TECHNOLOGY DEMONSTRATION PROJECT REPORT: TDP4

SLURRY-PHASE BIOREACTOR TRIAL

CONTAMINATED LAND: APPLICATIONS IN REAL ENVIRONMENTS

CL:AIRE

WHAT IS CL:AIRE?

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)

October 2004

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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 slurry-phase bioremediation technology based on specific site conditions at a SecondSite Property Holdings Ltd site in the northwest of England. It is not a definitive guide to the application of slurry-phase bioremediation technology. CL:AIRE strongly recommends that individuals/organisations interested in using this technology retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

SecondSite Property Holdings Ltd (SPH), formerly Lattice Property Holdings, commissioned Parsons Brinckerhoff Ltd (PB) to undertake the project management of a slurry-phase bioreactor remediation trial at a former gasworks site in the northwest of England. The trial was designed to demonstrate and further verify the effectiveness of slurry-phase bioremediation at commercial-scale. The project was funded by The Onyx Environmental Trust and SPH, and was carried out as part of the Contaminated Land: Applications in Real Environments (CL:AIRE) programme of technology demonstration projects.

Slurry-phase bioremediation is the most intensive form of biological treatment available for the degradation of organic compounds. The bioreactor has been developed from laboratory and pilot trials to a commercial-scale test vessel. The vessel was first tested on a former gasworks in northern England. The results of that trial indicated that the technology worked at a field-scale. However, there were some issues that needed to be addressed with the material handling and production of foam, before the unit could be commercialised further. As part of this project several modifications were made to the plant, including upgrading the pump, changing the loading system and the installation of a remote monitoring system.

The purpose of this trial was to test the technology on a concentrated mixture of coal tar and fill material, as part of the main remediation works being undertaken at the site. Tar from a tar and liquor tank was mixed with contaminated soil in a 1:3 ratio to form the feedstock for the trial. Three full trials were completed. A fourth trial was started but terminated due to technical difficulties with the pump.

Despite encountering some difficulties during the trials in operating the bioreactor, the results of this work are promising. The results for Trial 2 in particular indicate significant levels of contaminant degradation, especially with respect to polycyclic aromatic hydrocarbons (PAH). Lighter end PAHs were degraded by up to 95 %. However, the most promising results were associated with the high molecular weight PAHs such as benzo(a)pyrene, which was reduced by 68 %. These results indicate how successful slurry-phase bioremediation can be in treating such contaminants in a short time-frame.

Trials 1 and 3 showed similar patterns of degradation, but not to the same degree as in Trial 2. It is thought that the difficulties with recirculation of the slurry during these trials may have contributed to the lower rates of degradation. In addition, the system needs to be made more robust, to be able to cope with changes in material size and density, loading weights and water volume. At the moment, labour input at the front end is too intensive for a commercial-scale process.

The current slurry-phase bioreactor system is suitable for certain applications. These might include a treatment process for fines produced from soil washing processes and contaminated dredgings (fines) or for any material contaminated with biodegradable contaminants that can be easily suspended in water.

In order to overcome the difficulties encountered in treating the type of heterogeneous made-ground material encountered in these trials and capitalise on the scientific basis of Trial 2, there are two main options for future development:

- Complete design change
- Further improvements and upgrades to the existing bioreactor

From the time and cost assessments detailed in this report, it is apparent that even with multiple reactors (of the design used in this project) operated in tandem, the treatment volume is not high enough to be commercially viable and, due to the low batch volume, the treatment time for the average site would still be too long. However, it must be emphasised that although this technology is in its infancy, these trials prove that this treatment option is still much quicker than conventional solid-phase bioremediation and treats a greater range of organic contamination more effectively.

It is recommended that development of the bioreactor now moves on to a period of redesign, using all the lessons learned from these trials. The ultimate goal must be to produce a tank or vessel that can rapidly treat the largest batch volume possible, with greatly improved loading and unloading capacity, in order to become commercially viable. Currently, thermal treatment is likely to be the only other process that would

adequately deal with these materials. It is recommended that costs and options for redesign are sought from specialist process engineers, in order to assist in the decision making process.

It is considered that, despite the difficulties that were encountered, the results of this work are very positive, as they have shown that slurry-phase bioremediation can be used to degrade contaminants commonly found on gasworks sites, both to acceptable levels and rapidly. With further improvements to design, the performance should be improved further.

ACKNOWLEDGEMENTS

CL:AIRE would like to acknowledge the financial support of The Onyx Environmental Trust and SecondSite Property Holdings Ltd, without whom this project would not have proceeded; the contribution of Russell Thomas and Denise Hughes of Parsons Brinckerhoff Ltd, and Catherine Sykes of Edmund Nuttall Ltd (formerly of Parsons Brinckerhoff Ltd) who prepared the original validation report and early drafts of this report and the support of Steve Wallace and Paddy Daly of SecondSite Property Holdings Ltd, who provided technical input and a suitable site where the trial could take place, is also acknowledged.

The bioreactor project team consisted of SecondSite Property Holdings Ltd; The Onyx Environmental Trust; Parsons Brinckerhoff Ltd; VHE Ltd; Edmund Nuttall Ltd; Davis Langdon and PCM Ltd.

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ABBREVIATIONS

AAS	Atomic Absorption Spectroscopy
ACEC	Aggressive Chemical Environment for Concrete
B(a)P	Benzo(a)Pyrene
BRE	Buildings Research Establishment
BTEX	Benzene, Toluene, Ethylbenzene and Xylene
CE	Cerniglia
CFM	Cubic Feet Minute
CFU	Colony Forming Unit
CL:AIRE	Contaminated Land: Applications in Real Environments
COSHH	Control Of Substances Hazardous to Health
CWG	Carburetted Water Gas
DCM	Dichloromethane
DPD	N-N-diethyl-phenylenediamine
DNA	Deoxyribonucleic Acid
DO	Dissolved Oxygen
EA	Environment Agency
EMS	Environmental Management System
EPS	Extracellular Polysaccharide
EU	European Union
GC	Gas Chromatography
GC FID	Gas Chromatography fitted with a Flame Ionisation Detector
GC MS	Gas Chromatography coupled with Mass Spectrometry
HCl	Hydrochloric Acid
HPLC	High Performance Liquid Chromatography
ICP MS	Inductively Coupled Plasma Mass Spectrometry
IVCO	Intermittent Vertical Chamber Oven
ISO14001	International Standards Organisation certification for environmental management systems
KW	Kilo Watt
LC	Liquid Chromatography
MTBE	Methyl Tertiary Butyl Ether
MNA	Monitored Natural Attenuation
NA	Nutrient Agar
NAPL	Non Aqueous Phase Liquid
NCBI	National Center for Biotechnology Information
PAH	Polycyclic Aromatic Hydrocarbons
PB	Parsons Brinckerhoff
PCB	Polychlorinated Biphenyls
PCR	Polymerase Chain Reaction
PFD	Petroleum Fuel Distillate
pH	*pondus hydrogenii* (degree of acidity / alkalinity of aqueous solutions)
PHBV	beta- hydroxybutyrate-co-beta-hydroxyvalerate
PRB	Permeable Reactive Barriers
PSD	Particle Size Distribution
PTFE	Polytetrafluoroethylene

RNA	Ribonucleic Acid
RPM	Revolutions Per Minute
SPA	Special Protection Area
SPH	SecondSite Property Holdings Limited
SSSI	Site of Special Scientific Interest
TOC	Total Organic Carbon
TP	Trial Pit
TPH	Total Petroleum Hydrocarbons
USEPA	United States Environmental Protection Agency
WAC	Waste Acceptance Criteria

1. INTRODUCTION

1.1 BACKGROUND

Parsons Brinckerhoff (PB) was commissioned by SecondSite Property Holdings Ltd (SPH) to undertake the project management of a slurry-phase bioreactor trial at a former gasworks in the northwest of England. The trial was undertaken to demonstrate the effectiveness of the process at commercial-scale. The project was funded by The Onyx Environmental Trust and SPH, and was carried out as part of the Contaminated Land: Applications in Real Environments (CL:AIRE) programme of technology demonstration projects.

Slurry-phase bioremediation is the most intensive form of biological treatment available for soils containing organic contaminants. The soils are mixed with water and fluidised in the bioreactor vessel, so that they are maintained as a suspension. This allows the contamination maximum opportunity to dissolve into the aqueous phase, where microorganisms can degrade the contaminants. Conditions in the bioreactor such as the pH, temperature and oxygen concentrations are kept at optimum levels to promote contaminant degradation.

A gasworks site in northwest England was planned for remediation as part of the SPH site remediation programme. This site had suitable types of contamination for the demonstration of the slurry-phase bioreactor. It was therefore decided to set up a field trial of the bioreactor on the site, to run concurrently with the main remediation works. This would allow demonstration of the bioreactor in a realistic environment.

The bioreactor underwent a previous site trial at a former gasworks in northern England approximately two years ago. Information gained from the previous trial was used to modify and improve a range of different aspects of the reactor operation prior to its use in this project. The bioreactor was thought to be particularly applicable for use at this former gasworks site due to the heavily hydrocarbon-contaminated materials present.

The previous trial had shown that the slurry-phase bioreactor is capable of efficiently treating soils contaminated with coal tar. In addition to this, slurry-phase trials carried out in the USA on former wood preserving facilities had also proven effective on a similar type of contamination. The trial described in this report has taken this concept one stage further, by mixing contaminated fill-material with the highest possible ratio of coal tar in order to still be mixable using slurry-phase technology in a contained process. Though the level of development achieved has not been sufficient to operate the process commercially on this particular feedstock, it is proof of concept for a complex process at field-scale.

1.2 PURPOSE AND PROJECT OBJECTIVES

The purpose of the trial was to meet the objectives of the CL:AIRE technology demonstration programme by demonstrating the ability of the bioreactor to treat hydrocarbon-contaminated material. This was in order to provide a cost effective and sustainable solution to the treatment of sites contaminated with coal tar and other hazardous hydrocarbons.

Specific remediation targets were not set for the bioreactor trial, though site-specific targets were agreed for the main remediation work between the site consultant (ENTEC UK Ltd), the Local Authority and Environment Agency. The objective was to achieve the best possible reduction in contaminant load in the time constraints. The ultimate aim was to render the material suitable for reuse elsewhere on the site.

1.3 THE NEED FOR SLURRY-PHASE BIOREACTOR TECHNOLOGY

Conventional remediation processes focus on the removal of contaminated soil from sites for disposal in landfill. That option will decrease due to the implementation of the European Union (EU) Landfill Directive, which bans the co-disposal of non hazardous and hazardous wastes in landfills, and also bans corrosive, flammable and liquid waste from landfill, properties which coal tar contaminated materials may possess. In addition Waste Acceptance Criteria (WAC) preclude

many hydrocarbon wastes from being disposed of to landfill due to their Total Organic Carbon (TOC) content being above 6 %. This has led to a significantly increased cost for the disposal of hazardous waste and increased distance travelled to a suitable landfill, increasing transport costs.

In addition landfill tax, decreasing availability, suitability of local landfill capacity and adverse public opinion will lead to changing waste management practices. In recent years, remediation technologies such as bioremediation have started being used as alternatives to landfill.

The bioreactor was developed as one such alternative technology for the remediation of coal tar wastes, in particular to deal with the problematic issues associated with 5- to 6-ring polycyclic aromatic hydrocarbons (PAH). These 5- to 6- ring PAHs are more recalcitrant to biodegradation than the 2- to 4-ring PAHs (Thomas *et al*., 2000, Thomas and Jones, 1998, Morris and Jones, 1998). Another technology, landfarming, has proven to be effective for degrading 2- to 4-ring PAH (Morris and Jones, 1998), although the technology has proven ineffective for degrading 5- to 6-ring PAH (Thomas *et al.*, 2000; Thomas and Jones, 1998; Morris and Jones, 1998; Cerniglia, 1981; and Cerniglia, 1992). The 5- to 6-ring PAHs and in particular benzo(a)pyrene pose the greatest health risk due to their high toxicity and carcinogenicity, so these PAHs need to be degraded in order to reduce the health risk posed. Slurry-phase bioreactor technology has previously been shown to be effective against 5- to 6-ring PAH and was therefore investigated as a potential method for the treatment of coal tar (Brown, 1993; USEPA, 1993 and Mahaffrey, 1993). Another benefit of slurry-phase bioreactor technology was the short treatment times which could be achieved; bioremediation of hydrocarbons which are more recalcitrant to biodegradation (e.g. PAH) could be achieved in 7 to 10 days and readily degradable compounds such as benzene or phenol could be degraded in about 2 days. The development of the bioreactor is discussed further in Chapter 2.

The slurry-phase bioreactor degrades hydrocarbon contamination in a batch process that utilises indigenous bacteria from either the soil feedstock being treated, or cultured from other gasworks. The bacteria use hydrocarbon contaminants in the feedstock as a carbon source and degrade the compounds to release energy. If fully mineralised, the hydrocarbon contaminants are converted into carbon dioxide and water. Contaminated soils are loaded into the bioreactor with water in order to produce homogeneous slurry. After treatment, the slurry is removed and dewatered to separate the treated soil from the aqueous phase, which can then be reused for further treatment.

1.4 CONTRACT TEAM

For this demonstration project, SPH were the site landowners and the client for the overall site remediation. The main remediation works were designed and managed by ENTEC UK Ltd. PB was only responsible for project managing and providing technical management of the slurry-phase bioreactor project in a designated area of the site.

Two sets of contractors were involved in the project. VHE Shepley was responsible for the fabrication, construction and installation of the bioreactor, and installation of associated monitoring probes and telemetry. Edmund Nuttall Ltd was the Principal Contractor for the main remediation works and therefore responsible for site health and safety. With respect to the bioreactor, they were also responsible for site preparation, fabrication of bunds and concrete bases, and operation and ongoing maintenance of the reactor under the direction of PB. They also supplied the ancillary items for the reactor such as the generator, compressor and centrifuge/shaker, and assisted with the sampling.

1.5 REPORT ORGANISATION

This report provides a brief summary description of the site history, geology and hydrogeology of the former gasworks where the trials were undertaken, together with the nature and extent of contamination. This report concentrates in particular on the classification and chemical composition of the materials sourced from the site for the bioreactor trial and describes the laboratory trials used to assess the feasibility of carrying out a field-scale trial at the site, and the results achieved.

The field trial is then described in detail, from initial site preparation to construction, operation, demobilisation and materials disposal. The technology demonstration support issues such as

contract agreements, insurance, regulatory approval, health and safety, and security are also discussed.

The results of the trial are assessed, and are presented in both tabular and graphical form. A discussion of contaminant mass balance is made and pathways of potential contaminant loss are highlighted. Difficulties with the technology are discussed, and its limitations identified. Possible improvements and other design issues are suggested. The lessons learned during the trial are also presented.

A discussion of the cost of the trial is made, and the cost is compared to the cost of disposal to landfill. The economic viability of this treatment process is then assessed.

2. BACKGROUND TO THE DEVELOPMENT OF THE SLURRY-PHASE BIOREACTOR

2.1 INTRODUCTION TO BIOREMEDIATION

A slurry-phase bioreactor is a form of bioremediation. Bioremediation covers a range of processes that attenuate hazardous compounds. Bioremediation is defined by the American Academy of Microbiology as: 'the use of living organisms to reduce or eliminate environmental hazards resulting from accumulations of toxic chemicals or other hazardous wastes' (Gibson and Sayler, 1992).

Bioremediation includes biodegradation (degradation of compounds) and bioaccumulation (accumulation of compounds, in particular metals) though other methods also exist.

The slurry-phase bioreactor uses the process of biodegradation. Biodegradation harnesses the ability of microorganisms (and some plants) to use compounds present in the environment as nutrient sources, compounds rich in carbon (e.g. sugars, starch and hydrocarbons) or containing nitrogen, phosphorus and certain trace elements.

In particular, the use of biodegradation for bioremediation takes advantage of the fact that some microorganisms can utilise compounds deemed contaminants by humans as nutrients, the most common examples of which are oils. In the well-known case of the Exxon Valdez oil spill near the Prince William Sound in Alaska in 1989, enhanced biodegradation was used to degrade the oil, which washed up on the beaches. The enhanced rate of biodegradation was achieved by the addition of nutrients whose natural availability was limited.

This ability means that many organic contaminants such as phenol, naphthalene and benzene can be biodegraded by microorganisms. Inorganic substances such as ammonia and phosphate can also be remediated provided that other nutrients are present.

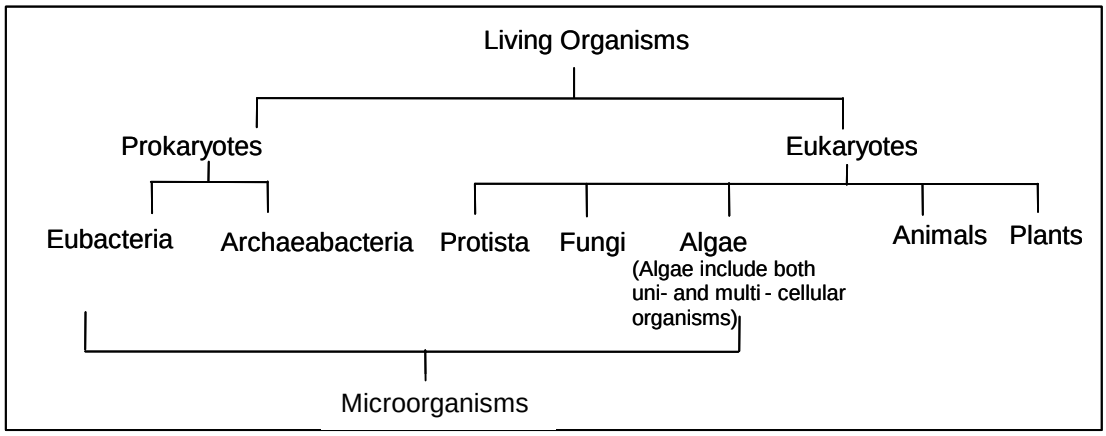


Figure 2.1: Phylogenetic tree of living organisms

As a matter of introduction, it should be pointed out that the microorganisms of interest to bioremediation processes include microorganisms either belonging to the prokaryotes or the eukaryotes (Figure 2.1) and include bacteria (also known as eubacteria), archaea (also known as archaebacteria) and fungi. Bacteria and archaea are both prokaryotes, fungi are more complex and belong to the eukaryotes, along with plants and animals (for simplicity, viruses, viroids and prions are not discussed).

There are many differences between the cell structure of eukaryotic fungi and prokaryotic bacteria and archaea. Whereas eukaryotes have a defined nucleus containing several DNA molecules (chromosomes), surrounded by a nuclear membrane, prokaryotes have a simple nucleoid containing one molecule of DNA. Eukaryotes also contain a number of other membrane bound

structures, the most important being mitochondria. Prokaryotes also have a cell wall around the cell membrane and may also have a protective capsule formed from polysaccharides (composed of multiple bonded sugar compounds) around the cell wall. These differences are graphically represented in Figure 2.2.

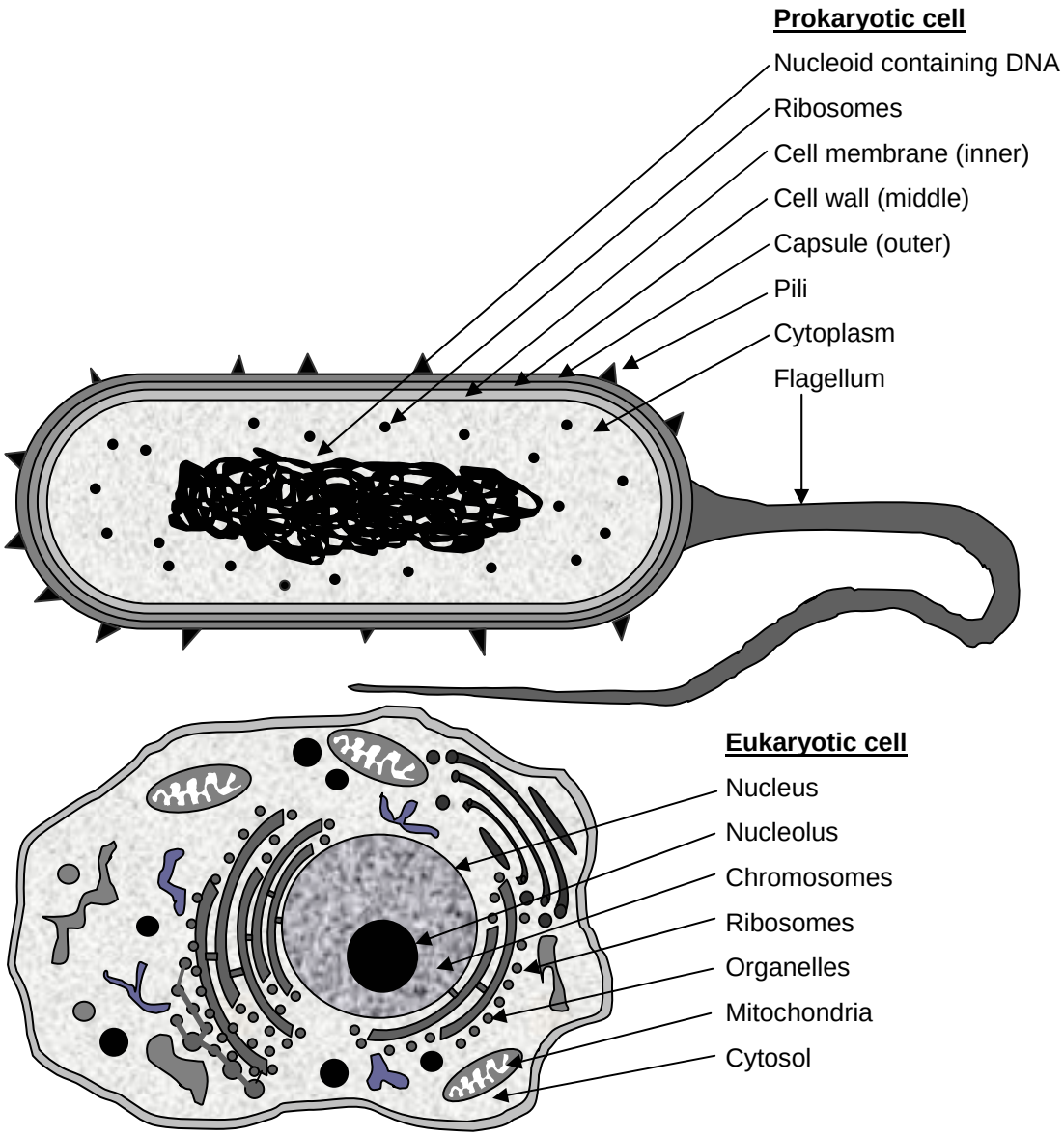


Figure 2.2. Simple structural schematic of prokaryotic and eukaryotic cells

Bacteria and archaea include only unicellular microorganisms, whereas fungi are both uni- and multi-cellular. Many fungi produce hyphae, which are long thin, multiply-branched, protrusions. The complex structure of these hyphae gives the fungi a delicate form that is not robust enough to survive in an environment where high shear forces exist.

Archaea differ from bacteria in many aspects including the composition of their cell walls and a range of biochemical processes. Both archaea and bacteria are important to *in situ* bioremediation processes. However, the archaea are more important in anaerobic processes, especially those in extreme environments, such as high salinity (halophiles) and acidity (acidophiles). In terms of aerobic slurry-phase bioremediation, archaea do not play a significant role. It has been observed previously that if the process is operated under anaerobic, sulphate-reducing conditions, then archaea were found to be active in the slurry (Thomas *et al.*, 2000).

When operated under aerobic conditions bacteria are the dominant microorganisms present in the slurry-phase bioreactor process. However, if the slurry-phase bioreactor is operated under anaerobic conditions, both archaea and anaerobic bacteria will be present in the slurry. The high rates of attrition produced by mixing in the slurry reactor do not suit the growth of most fungi, as the high shear forces produced damage their filamentous hyphae. (In low shear processes such as composting and landfarming, fungi are fundamentally important in the biodegradation processes). In terms of slurry-phase bioremediation systems, bacteria are the most important microorganisms, as they adapt better to these systems. Bacteria can grow and reproduce much faster than fungi, which mean that rates of degradation are greater.

In the slurry-phase bioreactor the microorganisms generally exist in a planktonic state in the water. On surfaces, microorganisms may also form a complex structure called a biofilm, which can provide an advantage to the microorganisms, as it allows them to form a localized microenvironment that buffers against some of the more hazardous conditions which occur in the water phase. Biofilms contain a diverse range of different microorganisms both prokaryotic and eukaryotic.

Microorganisms use enzymes to breakdown the organic compounds. Enzymes are biological catalysts that promote chemical reactions; they are usually proteins and have complex structures. The enzyme promotes a chemical reaction by reducing the amount of activation energy required for the reaction to occur. The activation energy is the amount of energy required to break bonds in the molecule, allowing the conversion to take place.

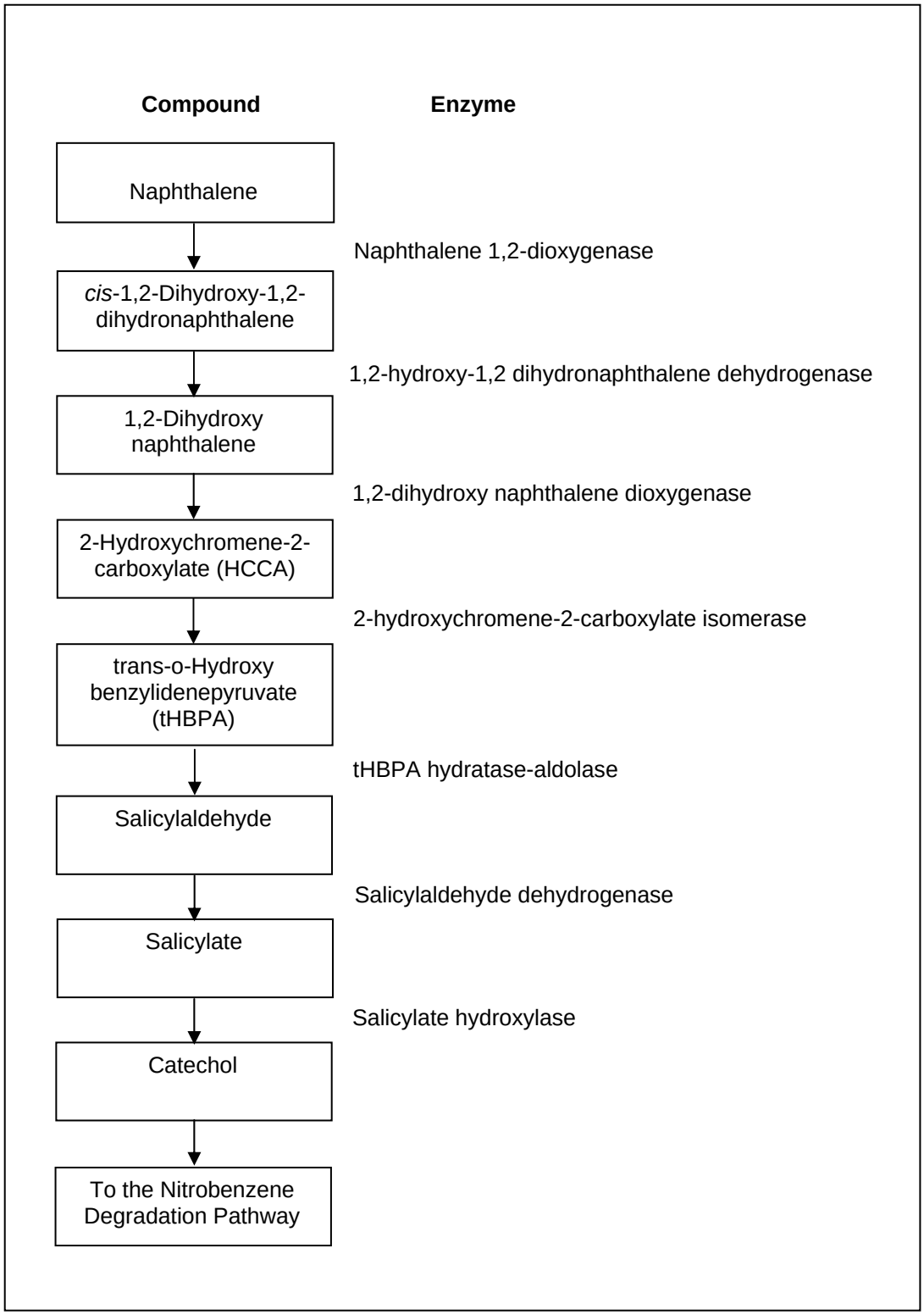
There are thousands of different microorganisms that have been identified as being active in bioremediation processes. The most regularly isolated organisms in bioremediation processes are of the genus *Pseudomonas*, including species such as *Pseudomonas fluorescens* and *Pseudomonas putida*. Bacteria of the genus *Bacillus, Acidovorax, Alcaligenes, Arthrobacter,* and *Rhodococcus* have also regularly been associated with bioremediation (Mueller *et al.,* 1989; Mueller *et al.,* 1990; Eweis *et al*., 1998; Thomas *et al*., 2000; Thomas and Gustavsen, 2000; Cerniglia, 1992; and Pothuluri, 1995).

For the full degradation of complex hydrocarbons, several enzymes are required and this either releases stored energy, which is utilised by the microorganism, or allows the biotransformation to another compound required by the organism. The series of reactions, enzymes and intermediate compounds through which compounds are metabolised comprise what are called biodegradation pathways, an example of which can be seen in Figure 2.3. These complex pathways are often interlinked with other metabolic pathways allowing the organism the ability to convert the compounds into a wide range of other compounds as required.

A compound can have numerous different degradation pathways, depending on the organisms and whether the degradation is aerobic or anaerobic. Many of the commonly identified hydrocarbon contaminants such as naphthalene, phenol, benzene, phenanthrene and nitrobenzene have interrelated degradation pathways, e.g. the degradation product of the naphthalene degradation pathway enters the nitrobenzene degradation pathway.

2.2 BIOREMEDIATION PROCESSES

Bioremediation processes are generally either *in situ* processes (the remediation is carried out in the ground without excavation of the material) or *ex situ* (the material is excavated and then treated). *In situ* remediation processes include, amongst others, enhanced monitored natural attenuation (MNA), biological permeable reactive barriers (PRB) and air sparging processes. Enhanced MNA uses amendments (e.g. oxygen-releasing compounds) to increase the rate of biodegradation in the dissolved phase of a contaminant plume. PRBs intercept groundwater plumes using a biologically active medium to attenuate the groundwater contamination. Air sparging increases the rate of biodegradation by increasing the amount of oxygen available for aerobic biodegradation.



Source: Resnick *et al.*, (1996)

Figure 2.3: Biodegradation pathway of naphthalene by *Pseudomonas sp.* NCIB 9816-4, G7.

Ex situ bioremediation includes, amongst others, landfarming, composting and slurry-phase bioremediation. Landfarming and composting both involve the excavation and stockpiling of contaminated soils in windrows (long heaps of soil); nutrients and water are added as required and the material is mixed regularly. Each time the soil is mixed it becomes more homogeneous, therefore representative sampling of the material is much harder at the start of the process than the end, because its starting composition is more variable.

With composting, approximately an extra 10 % of compost is added to the material, to provide the composting microorganisms (fungi). The compost can improve the quality of poor soils, especially those with high proportions of clay or silt, allowing more air into the soil and increasing the rate of oxygen diffusion into the soil. Slurry-phase bioremediation would be used where processes such as landfarming and composting are either too slow or unable to degrade the contaminants. Slurry-phase bioremediation is described in the following sections.

2.3 WHAT IS A SLURRY-PHASE BIOREACTOR?

A bioreactor is an engineered system that is designed to optimise conditions for a biological process to take place. In the brewing industry, the bioreactor (vat) is used for the production of beer; at a water treatment works the sludge digesters are bioreactors; in slurry-phase bioremediation, the main vessel is the bioreactor.

A slurry-phase bioreactor is a piece of engineering plant that degrades hydrocarbon contamination, by bioremediation, in a batch process. The process can utilise indigenous bacteria found either in the feedstock being treated, or cultured from other, similar sites which have suitable microorganisms. The bacteria use hydrocarbon contaminants in the feedstock as a carbon source and degrade those compounds to release energy. If fully mineralised, they are converted into carbon dioxide and water. Contaminated soils are loaded into the bioreactor with water in order to produce a homogeneous slurry. After treatment, the slurry is removed and dewatered to separate the treated soil from the water, which can then be reused for further treatment.

2.4 DEVELOPMENT OF THE SLURRY-PHASE BIOREACTOR

2.4.1 BACKGROUND

Advantica Technologies Ltd (formerly the Research and Development Section of British Gas) investigated the bioremediation of polycyclic aromatic hydrocarbon (PAH)-containing materials from former gasworks, in conjunction with the former Lattice Property Holdings Ltd (now SecondSite Property Holdings Ltd). Advantica tested the use of bioremediation using landfarms at two other former gasworks (see Plate 2.1). Although successful at degrading 2- to 4-ring PAHs, it was found to be less effective against 5-ring PAHs such as benzo(a)pyrene (B(a)P). As the concentration of B(a)P was thought to be a very significant future regulatory driver for remediating former gasworks, Advantica and Lattice Property Holdings developed the slurry-phase bioreactor as a more intensive form of treatment.

Plate 2.1: A mobile landfarm being operated at a gasworks in northern England.

All aerobic biotreatment methods tested and reported in journals to date, although successful at degrading low molecular weight PAHs, have been ineffective against the higher molecular weight multiple-ring PAHs, which is consistent with the findings of the bioremediation research carried out at two former gasworks (Morris and Jones, 1998 and Thomas *et al.,* 2000). The net result is that the total PAH concentration decreased significantly, but the toxicity (and carcinogenicity) with respect to B(a)P and the other 5- and 6-ring PAHs, did not. However, though landfarming and composting may not eliminate the hazard, the mobility and bioavailability of the contamination is likely to have been significantly reduced. The benefits of using slurry-phase bioreactor technology are that both the total PAH and the B(a)P concentrations can be decreased significantly in a short period of time (Thomas *et al.,* 2000 and Thomas and Gustavsen, 2000).

A small number of American companies have developed pilot-scale bioreactor processes to treat PAH contamination. The majority of these have not been developed any further as they proved too complex and uneconomic for commercial-scale operation. Teckno Associates developed a multistage slurry reactor, which did not progress beyond 60 litres operational capacity. The system had a sound scientific basis, using both biological and chemical oxidation. The system developed by the ECOVA Corporation demonstrated effective treatment of wood preserving wastes containing PAH, with a 90 % reduction in two weeks at a 50 litre scale. The OHM Corporation (a major US bioremediation company) has installed a full-scale slurry-phase bioreactor for treating PAH, at a wood preserving site in North Carolina (Mahaffrey, 1993; USEPA, 1993; Brown, 1993; and Woodhull and Jerger, 1994).

2.4.2 PREVIOUS TREATABILITY STUDIES

The bioreactor is a significant advancement on the landfarm concept, as it provides optimum conditions for the growth of microorganisms by heating, mixing, aeration, nutrient supply and pH control. Advantica assessed the use of slurry-phase bioreactors for the treatment of a variety of different types of tar-contaminated soils at laboratory (1 litre to 10 litre), bench (50 litre) and pilot-scale (1 tonne). Material contaminated with PAHs was taken from a variety of sites for analysis. This summary focuses on the work completed on contaminated soils from a former gasworks in northern England, as an example.

The medium used for all the trials was either Cerniglia (CE) or BG. CE medium was developed by Dr Carl Cerniglia and co-workers for investigating the biodegradation of PAH (Cerniglia, 1992). The BG medium was adapted from the CE medium by Russell Thomas formerly at Advantica, now at Parsons Brinckerhoff. BG medium was adapted by increasing the phosphorus to nitrogen ratio by using ammonium phosphate. This medium had been developed for the growth of PAH-degrading bacteria and it had been shown to provide improved rates and extent of biodegradation over CE medium in laboratory trials (Thomas *et al.,* 2000).

The laboratory test vessels were all glass fermentation vessels, with motorised stirrers that operated at up to 1400 revolutions per minute (rpm). The units provided pH and temperature control, in order to provide optimum conditions for biodegradation. Dissolved oxygen was also measured to assess the growth of bacteria. Pressurised air was injected, and exhaust gases removed.

The inoculum for all the laboratory scale work was taken from the former gasworks in northern England, added to 100 mL of CE medium and shaken for 7 days. The inoculum was then added to 180 mL of soil and a further 900 mL of CE medium in a 1 litre test vessel. For scale-up work at 2 litres to 10 litres, working volumes of 1.5 litres and 7 litres were used respectively. Slurry concentrations of 10 %, 20 % and 40 % by weight were tested. Previous studies had indicated that 40 % by weight is the maximum possible solid to liquid ratio for a stable biologically active slurry. When slurries exceed 40 % by weight to volume, slurries then become uneconomical to mix.

A number of different tests were carried out with a variety of variables, in order to determine the effects of mixing, particle size, temperature, co-solvents, benzoic acid, hydrogen peroxide and the use of water from a tar sealed gasholder, on PAH degradation. The general conclusion of the studies was that a 70 % decrease in the PAH content of the contaminated material in 10 days was achievable and that no benefit was noted from any of the amendments added (e.g. co-solvents). Compounds with a linear structure of 2 and 3 benzene rings appeared to degrade first, whilst compounds with more rings, and those that were non-linear, degraded more slowly. The non-linear

compounds are likely to have less hydrogen available for reaction. It was also found that above a mixing rate of 50 rpm, biodegradation is independent of agitation. The results of these initial tests indicated that further increases in scale could be made.

For the bench scale tests, coal tar contaminated soil was dried for 2 days, ground using a ball mill and sieved to 3 mm. To this BG medium was added. The 50 litre capacity bioreactor was made from a steel fermenter and had a motorised stirrer capable of 1,000 rpm. The feedstock material contained approximately 2,700 mg/kg of total PAH, which reduced to approximately 1,000 mg/kg after 8 days (60 % reduction). The individual degradation of B(a)P, pyrene and chrysene was 44 %, 66 % and 60 % respectively.

For the 1 tonne pilot vessel, additional heat was supplied using internal heating elements. All other factors were similar to the smaller vessels, but increased in scale. The fines showed a 46 % reduction in total PAH concentration, whilst a mixture of both coarse and fines showed a 67 % reduction. B(a)P, pyrene and chrysene were individually degraded by 47 %, 57 % and 52 %. After 16 days, the coarse and fine mixture was reduced to 1180 mg/kg total PAH.

The technology, scaled up after the pilot-scale trial to produce the 45 tonne capacity reactor, was first tested at a former gasworks in northern England. The reactor was designed by WS Atkins and VHE Shepley Engineering Ltd. It was constructed by VHE at their Shafton premises in conjunction with Advantica and on behalf of Lattice Property Holdings (project sponsor). The original bioreactor can be seen in Plate 2.2.

Plate 2.2: The slurry-phase bioreactor after the first trials on a gasworks in northern England

Due to the size of the reactor, the design had to be fundamentally different to the pilot-scale version, particularly with respect to materials mixing. The field-scale vessel did not have a paddle stirring mechanism, as the size of the vessel precluded the use of this technology.

Three batches of tar-contaminated soil were treated at the gasworks. The starting concentrations of the fill material were in the range 2,300 mg/kg to 5,500 mg/kg total PAH. Speciated and total PAH were monitored on a daily basis. With the larger more robust reactor design, it was anticipated that soil loading of up to 40 % by weight could be achieved without compromising biodegradation performance. The first trial used 20 % solids (approximately 5.5 tonnes), and analysis showed a decrease in total PAH from approximately 5,000 mg/kg to 1,300 mg/kg (73 %) in 8 days. A significant reduction in B(a)P of 69 % also occurred. Four, 5- and 6- ring PAHs all showed similar percentage degradation of about 81 % over the 8 days. However, 3-ring PAHs were only degraded by 72 %. As the contaminated material contained weathered tar, only very low concentrations of the 2-ring PAH, naphthalene, were detected relative to the other PAHs, so the validity of this data was uncertain, as with the other PAHs. The percentage of each PAH remaining at the end of Trial 1 is shown in Figure 2.4 and for naphthalene the percentage shown reflects the increase in concentration from 2 mg/kg in the feedstock to 3 mg/kg at the end of the trial.

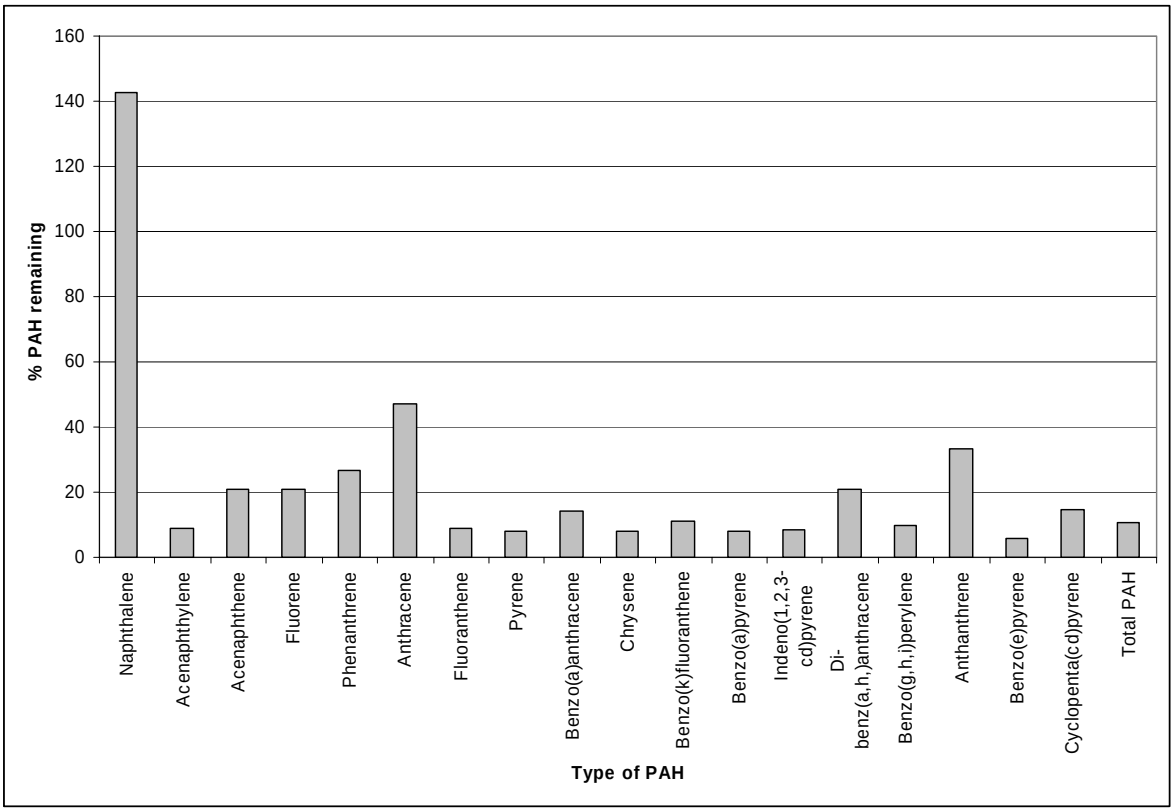


Figure 2.4: Percentage of each PAH remaining at the end of Trial 1

The second trial was also loaded with 20 % solids, and inoculated with 1 tonne of material left over from the first trial. After 11 days the reactor contents were pumped to a dewatering pen, with the exception of 5 tonnes left for the next trial. Sample analysis from the second trial indicated a decrease in total PAH from 2,400 mg/kg to 900 mg/kg, a reduction of 62 % in 8 days. The B(a)P concentration decreased by 44 %. The results from Trial 2 are shown in Figure 2.5.

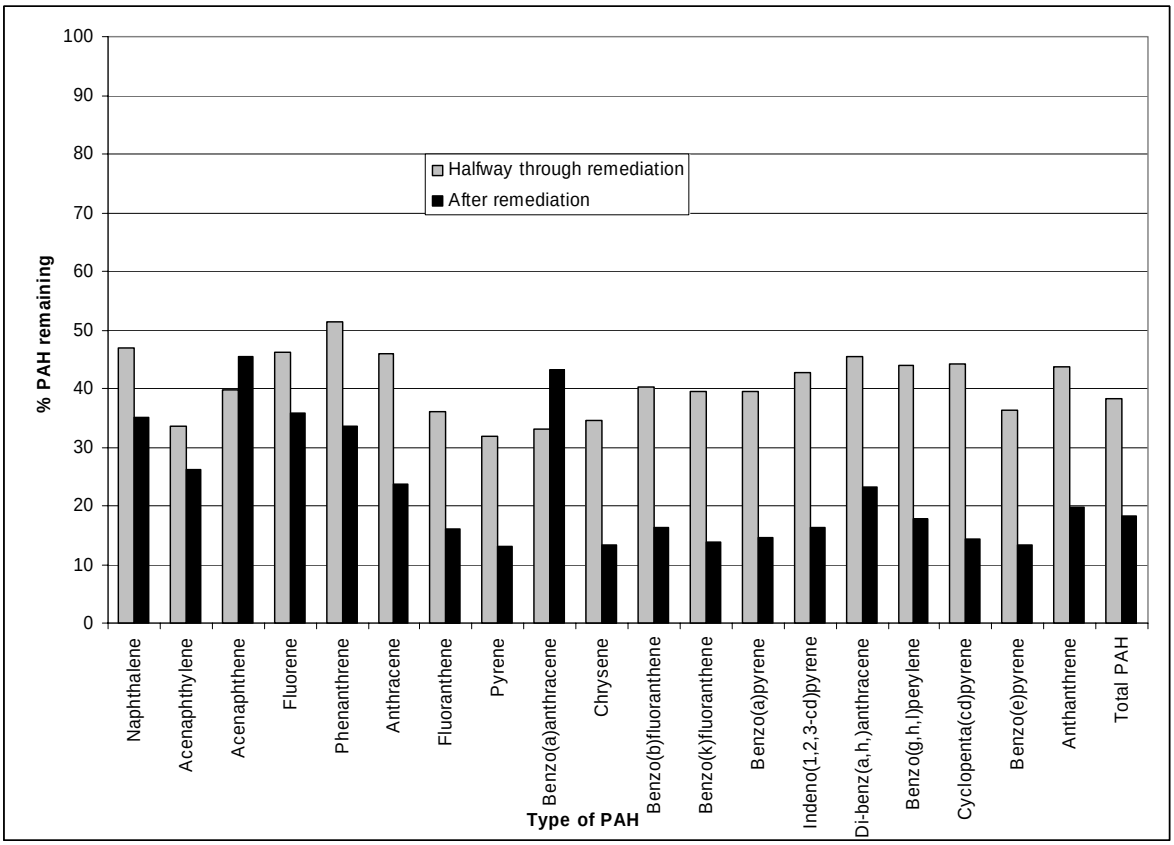


Figure 2.5: Percentage of each PAH remaining at the end of Trial 2

The third trial was loaded with 40 % solids. Operational difficulties were encountered with this trial, and the reactor had to be stopped twice. Excluding the down-time, the reactor was run for 16 days, though no significant further degradation occurred after day 12. The total PAH degradation was 82 %, resulting in a final concentration of 266.2 mg/kg. The final B(a)P concentration was 19.2 mg/kg (86 % degradation). The biodegradation performance of the process is displayed in Figure 2.6; the data are displayed as PAH grouped according to the number of ring structures they contain. The extent of degradation is similar between each group of PAH, though the 2-ring PAHs showed less degradation, however this was in part due to the relatively low concentration of the 2-ring PAHs by comparison to the other PAHs.

The results of the trials at the former gasworks in northern England confirmed that there was no detrimental effect in scaling up to the 45 tonne scale, and the treatment was capable of remediating difficult PAHs such as B(a)P. The results also showed that for the contaminated fill used, the rate of biodegradation was independent of initial concentration, material type and percentage of soil loaded. The results of this trial are included for reference, in Appendix A.

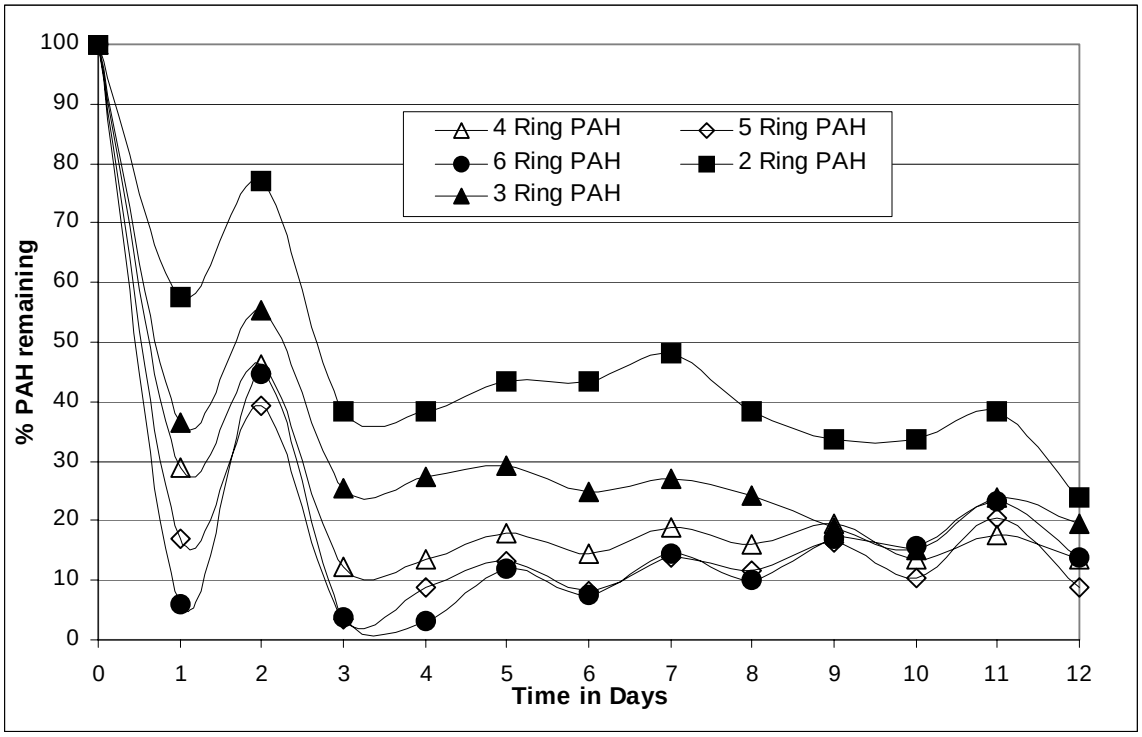


Figure 2.6: Percentage of each group of PAH (according to number of benzene rings) remaining at the end of the remediation Trial 3

2.4.3 CONCLUSIONS

It was found that further developments would have to be made to the process engineering of the field-scale reactor, as the following problems were encountered during the limited trials:

- A large amount of foam was generated and it could only be controlled by manual addition of antifoam at the top of the bioreactor.
- The discharge of treated material was problematic, with the pipework at the base of the reactor becoming blocked.
- The plastic pipework on the reactor became blocked easily and could not handle the pressure exerted by the weight of the slurry.
- A water pump had been used for the bioreactor and the seals had not been sufficient to handle the slurry.
- It was considered that the pumping regime was not adequate for the load required of it.
- The system had to be run manually, with nutrients and additives such as antifoam administered manually. A 24-hour operational presence was therefore required.
- Dewatering of the slurry was problematic as it was very slow.

After its use in northern England, the bioreactor was stored at the VHE premises in Shafton, Barnsley until it was decided to use it again for this demonstration project. Before bringing it to site a number of design changes were made as part of the CL:AIRE project, and these are listed below:

- The loading hatch was moved from the side of the vessel to the top, to enable the vessel to be filled to a greater extent.
- The recirculation pipework was moved and constructed of steel, rather than flexible hose.

- A specialist slurry pump with a higher pumping capacity was specified.

- The original trace heating (trace heating is a low-power electrical heating system consisting of a long, cable-like, heating element that is attached to the item to be heated) on the cone section was removed and replaced by a much more intensive and robust trace heating system at the base of the reactor, to maintain vessel temperature effectively.

- Telemetry was added to control acid, alkali and antifoam addition and removed the requirement for 24-hour supervision.

2.5 SUMMARY OF THEORY

The principal of slurry-phase bioremediation is simple; biodegradation is generally limited by the rate at which contaminants diffuse into the microorganisms. This process is much faster in the aqueous phase. By mixing soils in the aqueous phase, the rate of diffusion from the contaminants on the slurry particle surface, through the water phase, into the microorganism, is increased significantly over that observed with landfarming.

Additionally, the bioreactor provides optimum conditions for the growth of microorganisms by allowing control of heating, mixing, aeration, nutrient supply and pH control. The provision of heating ensures that the optimum conditions of between 25 °C and 30 °C are maintained, allowing the microorganisms to operate at their optimum metabolic rate. The installation of a pH control system also ensures maximum metabolic activity and the addition of nutrients and aeration ensures that the process is not nutrient- or oxygen-limited.

2.6 PERFORMANCE ASSESSMENT CRITERIA

The performance of the slurry-phase bioreactor in this trial was assessed primarily on its ability to biodegrade the target hydrocarbon compounds, namely PAH, phenolic compounds, BTEX compounds (benzene, toluene, ethylbenzene and xylene) and petroleum hydrocarbons. However, process improvements were also sought to overcome problems faced in the previous trial.

Specific remediation targets were not set for the bioreactor trial, though for the main remediation work site-specific targets were agreed between the site consultant (ENTEC UK Ltd) and the Environment Agency. The objective was to achieve the best possible reduction in contaminant load in the time constraints. The ultimate aim was to render the material suitable for reuse as fill material in the main works being carried out elsewhere on the site.

3. TECHNOLOGY SUPPORT ISSUES

3.1 REGULATORY APPROVAL

In the planning stages of the trial, the Environment Agency (EA) was approached to determine its requirements with respect to licensing issues. As the volume of material to be treated was below 1,000 m^3, the process was exempt from Waste Management Licensing requirements. However, a method statement was required, explaining the process in detail, and including risk assessments and Control of Substances Hazardous to Health (COSHH) details for the chemicals used. The method statement was submitted at the beginning of August 2002, approximately two weeks before commencement of the work. The EA had no comments to make on the application, but indicated that they would visit the trial once in progress.

3.2 HEALTH AND SAFETY

As Principal Contractor for the main remediation works, Edmund Nuttall Ltd (Nuttalls) was responsible for health and safety on the site. As Project Managers of the bioreactor trials, PB provided a method statement and risk assessment for the works, which was included in the Construction Health and Safety plan produced by Nuttalls. VHE Shepley Engineering Ltd (VHE) also submitted a method statement and risk assessment both approved by Nuttalls, for the lifting, construction and removal of the bioreactor.

Health and safety aspects of the work were also checked and approved by PCM Ltd, the Planning Supervisor appointed on behalf of SecondSite Property Holdings Ltd (SPH). Nuttalls carried out daily ambient air monitoring for volatile compounds at strategic monitoring locations around the site, including near the bioreactor. Daily samples were taken and tested at a laboratory for naphthalene, phenol, cresols, xylenols and asbestos.

3.3 ENVIRONMENTAL MANAGEMENT

SPH operate an ISO14001 accredited Environmental Management System (EMS), with which all work must comply. The site works were designed and managed in accordance with best practice and the requirements of their accreditation.

PB carried out an environmental risk assessment, covering all the potential environmental risks from the works, which was incorporated into the method statement for the works. Nuttalls also carried out environmental aspects checks throughout the works as part of the EMS operated for the site. These checks included a daily inspection and monitoring of site equipment, particularly drum/fuel storage, hoses, bunding, storage area and waste management areas.

A purpose-built concrete slab surrounded by an impermeable bund was constructed in order to prevent any deleterious environmental impact should any spills occur from the bioreactor. The layout of this compound is provided in Section 6.2. All hazardous chemicals were stored in a taped area of this compound, and their presence indicated by hazard warning signs.

In order to minimise water consumption, water was reused in the subsequent trials of the bioreactor system; any water that was not reused was treated in the on-site water treatment centre prior to disposal. When plant and equipment were not being used, they were turned off completely in order to reduce energy consumption. Dust was minimised by Nuttalls, who used a roadsweeping vehicle to clean the access roads around the site. Where possible, waste was prevented or minimised, predominantly by reuse of packaging materials and by the use of washable protective clothing rather than disposable items.

All pipework and valves that could release contaminated water were locked shut at night to prevent vandalism. Any loss of water caused by a leakage or other release from the system would also trigger an automatic telemetry system to alert the engineer to inspect the site.

3.4 INSURANCE

The plant and equipment were insured by SPH.

3.5 SECURITY

A 24-hour security presence was maintained on site by a sub-contractor of Nuttalls. The bioreactor had ladder protectors that were put in place at night to prevent unauthorized access. Security lighting was also fitted to the reactor for security purposes and for night visits, if required.

3.6 SAMPLING AND LABORATORY PROTOCOLS

3.6.1 INTRODUCTION

The sampling protocol for the trial is described in general in the following paragraphs, and described in further detail in Section 7 (Field Trial Operation). Sampling was in accordance with the Code of Practice for Investigation of Potentially Contaminated Sites (BSI 10175:2001).

Soil samples were stored in sealed and labelled plastic containers with snap lids. For volatile organic compound (VOC) analysis glass jars (filled to result in no headspace above the soil) were used. Any groundwater encountered was sampled and preserved using an approved method.

For water samples the following sampling protocols were applied. For the analysis of organic compounds, glass bottles, thoroughly washed and rinsed in acetone, were used. Samples taken for the analysis of benzene, toluene, ethylbenzene and xylene (BTEX) compounds were placed in screw-cap containers (no headspace), fitted with polytetrafluoroethylene (PTFE)-faced silicone discs. Samples taken for metals analysis were placed in a washed and acid-rinsed polythene bottle containing trace metal grade nitric acid, 50:50 (v/v). For other inorganic chemical analysis, glass bottles, washed and then rinsed with de-ionised water, were used. All samples not dispatched to the laboratory on the same day were stored at below 4ºC until dispatch.

3.6.2 LABORATORY ANALYSIS

The soils or dewatered slurry samples were scheduled for analysis for the standard SPH suite of tests for soils from former gasworks that comprises:

1. % Loss on Ignition, Moisture Content, % Stones
2. Phenols, Cresols, Xylenols, Ethylphenols, Catechol, Trimethylphenol
3. Speciated and total PAH and TPH (aliphatic/aromatic split and carbon banding)
4. Cyanides (easily liberable, complex and total), Thiocyanate
5. Water soluble Sulphate and Chloride
6. Ammonium
7. Nitrate
8. BTEX
9. Arsenic
10. Cadmium
11. Chromium
12. Lead
13. Mercury
14. Selenium

15. Boron
16. Copper
17. Nickel
18. Zinc

Analysis was undertaken in accordance with standard SPH analytical protocols for each of the suites of analytes, brief details of these are included below:

Table 3.1: Analytical protocols used for slurry-phase bioreactor project

Analyte	Analytical Protocol Details
pH	pH meter.
Moisture content	Weight before and after drying at 30°C.
Polycyclic Aromatic Hydrocarbons (PAH)	Soil samples are Soxhlet extracted with dichloromethane (DCM). The PAH content is determined by gas chromatography using mass spectroscopy (GC-MS). PAH were extracted from unfiltered water samples using DCM, and concentrated into acetonitrile. Analysis was by reversed-phase high pressure liquid chromatography (HPLC) with fluorescence detection.
Total Petroleum Hydrocarbons (TPH)	Soil samples are Soxhlet extracted with a mixed solvent of acetone and n-heptane and determined by gas chromatography using flame ionisation detection (GC-FID).
Benzene, Toluene, Ethylbenzene and Xylene	The determination of BTEX by headspace GC-MS for both soils and water.
Phenols	Samples containing phenols were either extracted into a methanol/water matrix or aqueous samples were filtered and directly injected into an HPLC with determination by electrochemical detection.
Total Metals	Extraction of metals into an *aqua regia* matrix (or direct injection of acidified and filtered water samples) and their subsequent determination by atomic absorption spectrometry (AAS) or inductively coupled plasma mass spectroscopy (ICP-MS).
Cyanide	Easily liberated cyanide is liberated at pH 4, and then complex cyanides are dissociated and liberated from the same sample using orthophosphoric acid under reflux conditions. The hydrogen cyanide from each step is absorbed in separate sodium hydroxide solutions and analysed by electrochemical detection.
Elemental Sulphur	DCM extraction then analysis by HPLC
Water Soluble Sulphate and Chloride	Chloride and sulphate are extracted into de-ionised water and detected by ion chromatography with conductivity detection.
Sulphide in water	Samples are buffered to prevent oxidation, and the sulphide concentration is determined colourimetrically after reaction with N-N-diethyl-phenylenediamine (DPD) to form Ethylene Blue.
Exchangeable Ammonium	Soil is treated with potassium chloride solution and magnesium oxide, distilled and the ammonia evolved driven into boric acid and determined by titration with a standard acid solution.
Sulphate, Chloride and Nitrate in Waters	Anions analysed in the aqueous samples by ion chromatography.
Ammonia in waters	Determination of ammonia in solution by ion selective electrode.

A single additional sample, produced by combining the feedstock samples, was taken for microbial analysis (by direct plate counting method and detection via 16S Ribonucleic Acid (RNA) analysis, see Section 3.4). These samples were placed in 20 mL sterile plastic vials, and refrigerated prior to transport.

3.6.3 PRE-TREATMENT SAMPLING

Sampling of the soil feedstock was carried out prior to each batch entering the bioreactor. At least 6 samples, each of at least 1 kg, were taken randomly from the area of the feedstock stockpile that was to be excavated and moved to the bioreactor.

3.6.4 SAMPLING DURING TREATMENT

During each treatment cycle, 4 slurry samples of 1 litre were taken every other day over the period of treatment. As the soil was mixed with water, the samples were in slurry form, and could be collected through the sampling port on the side of the reactor. This was facilitated by attaching a 1 litre plastic bottle to the sample port repeatedly until the required volume was achieved.

The slurry sample was then centrifuged to dewater it, using a standard laboratory scale centrifuge. This process was time consuming as only a small amount of sample could be processed per batch (the sample volume was too small for the full size centrifuge/shaker to be used). When the liquid and solids had been separated, the solids were transferred to 1 kg jars and the liquids to appropriate bottles for despatch to the laboratory to be analysed for the SPH suite. If despatch to the laboratory on the same day could not be achieved, the samples were refrigerated.

At the same sampling frequency, samples were taken for microbiological analysis. The microbiological samples were left in slurry form for testing.

3.6.5 POST-TREATMENT SAMPLING

Post-treatment sampling of each batch was carried out in a similar manner to the pre-treatment sampling. The material coming out of the centrifuge/shaker was divided into a coarse and a fine fraction. The sampling was therefore divided equally between the fractions. At least 6 samples were taken; sometimes more were taken when treatment efficiency altered, or changes were made to the process. A combined sample was also taken for microbiological testing.

In addition to the soils analysis, 3 samples of water were taken from the bioreactor from the beginning and end of each trial.

The sampling was carried out between PB and Nuttalls, with PB undertaking the centrifuging and preparation of soil samples. Two testing laboratories were responsible for the chemical testing; City Analytical Services (CAS), which analysed for the entire SPH suite with the exception of TPH, which was analysed for by Severn Trent Laboratories. This arrangement was put in place to take advantage of the best cost rates for testing at each laboratory. Both laboratories were on the SPH approved list.

Sampling for the purpose of geotechnical testing was undertaken on the treated soils for trials 1 and 2. Eight bulk samples were taken from each product, and sent to Exploration Associates for testing of particle size distribution, moisture content, Atterberg Limits, 4.5 kg compaction and acid- and water-soluble sulphate.

3.7 QUALITY ASSURANCE AND QUALITY CONTROL

The sampling programme detailed above was designed such that sufficient samples were taken to ensure that the results would be statistically representative. When sampling feedstock and product, the stockpiled material was divided up into representative areas and sampled accordingly (6 random samples were taken from the feedstock and at least 6 random samples were taken from the product). Daily sampling of the bioreactor slurry was particularly problematic as the samples had to be centrifuged manually, so the amount of slurry sample recovered each day was limited. Details of the samples taken are found in Section 7.

Full records were kept on site of the number of samples, their nature, sampling and despatch dates. On receipt of the results, the data were appraised to ensure that all the work had been carried out, and to bring any potential errors to the attention of the laboratory.

SPH operates a laboratory proficiency-testing scheme, which meets the requirements of the Environment Agency's policy on analysis of contaminated soil (effective 1st October 2000). The policy requires all methods to conform to specified performance criteria, including participation in a relevant proficiency-testing scheme. The SPH scheme evaluates the performance of laboratories in the analysis of contaminated material associated with the coal carbonisation process. The scheme comprises soil and water based 'standard reference samples'. The laboratories used for this work participate in the SPH scheme, and provided Certificates of Analysis for the testing carried out.

A representative of CL:AIRE made two visits to site to watch sampling from the reactor and the subsequent handling of the samples prior to dispatch to the laboratory.

3.8 METHODOLOGY FOR MICROBIAL ANALYSIS OF FIELD SAMPLES

3.8.1 CULTURE-BASED ENUMERATION

One gram of well-homogenised soil or sludge was taken from each sample and mixed well in 10 mL of sterile distilled water. Serial dilutions were made down to 10^{-5} in order to establish an optimal counting range for microbial enumeration. One hundred microlitres of each dilution was plated out onto duplicate agar plates (nutrient agar plates incubated at 25 °C and 37 °C and Burks agar medium incubated at 25 °C). Burks agar is a mineral based, minimal-type medium well suited to the recovery of microorganisms from environmental samples. Colony growth on all media was checked daily and a full colony count was generally possible after 5 days. Colony forming units per millilitre (cfu/mL) of initial suspension were then calculated from mean data derived from duplicate plate counts and, from this, cfu/g soil or sludge was calculated. This approach, as far as was possible, provided a microbial count for a truly representative portion of each sample.

3.8.2 DNA-BASED ANALYSIS

One hundred microlitres of the same soil suspension used for the culture-based enumerations were also used for Deoxyribonucleic Acid (DNA) extraction using the Qiagen DNA extraction system (the same system as used by the Health and Safety Laboratories (HSL) for environmental samples). Following initial extraction, the DNA was further cleaned using Pharmacia Sephacryl spin columns (S300 type). Approximately 520 base pairs of the 16S DNA were then amplified, and products were analysed by gel electrophoresis using ethidium bromide to indicate band generation. Those samples chosen for more detailed cloning analysis required good 16S ribosomal Ribonucleic Acid (rRNA) Polymerase Chain Reaction (PCR) products, and because of the chemical contamination of these soils, some degree of PCR repetition was necessary for certain samples in order to achieve satisfactory PCR results. PCR cloning was performed to determine the individual components of these general 16S rRNA amplifications. Cloning was undertaken using a published approach (Beswick *et al.*, 1999). Briefly, sub-clone colonies were recovered on Luria agar with added tetracycline and ampicillin, and cloned inserts were screened for using in a secondary PCR step. Following clean up of cloned PCR products, clone DNA was sequenced by Alta Biosciences, University of Birmingham. The sequences generated were analysed using the Blast interface of the USA National Center for Biotechnology Information (NCBI), and the most closely related sequence was sought in each case.

The results of this microbial analysis are discussed in Section 9.

4. SITE DESCRIPTION

4.1 LOCATION

The site is located in the northwest of England and covers an area of approximately 6 ha, the majority of which is owned by SPH. Transco owns approximately 1.2 ha.

The area owned by Transco is operational and used as a gasholder station and service depot. It is contained in its own secure area, and comprises two gasholders, a gas conditioning unit and a pressure reducing station. The remainder of the site is disused. The site is generally flat with only a slight slope from east to west.

4.2 HISTORICAL BACKGROUND

This section largely describes the general development of gas production from coal and oil and provides a historical context for the types of contamination found at former gasworks.

4.2.1 GAS PRODUCTION PROCESSES

Town gas was produced for domestic and industrial use from the early 1800s until the mid-1970s at approximately 3,000-10,000 gasworks sites across the UK.

Town gas was produced by the thermal decomposition of coal or oil. This process has been, and still is, used for the production of coke, but now to a much more limited extent. The typical town gas manufacturing process operated on a gasworks is shown in Figure 4.1. The process operated as follows:

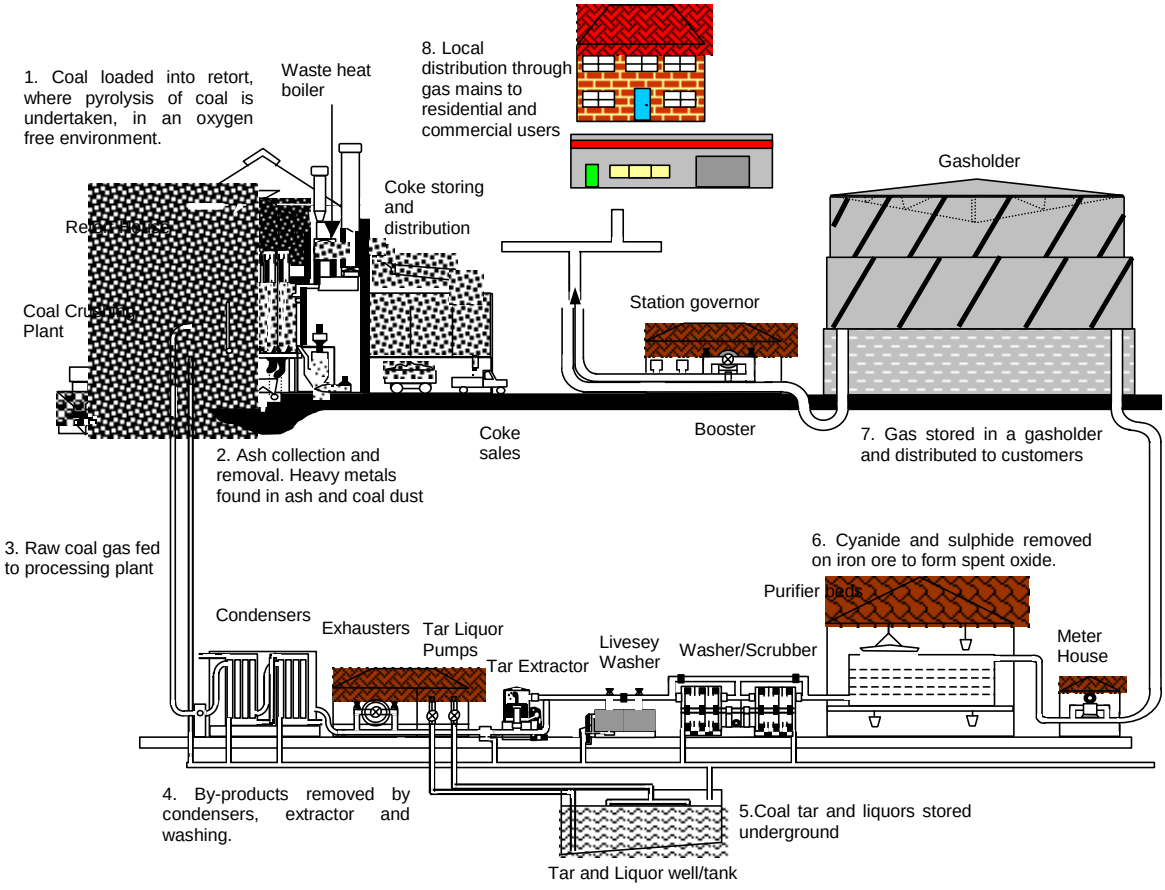


Figure 4.1: Schematic showing the coal gas manufacturing process.

1. Coal was transferred from barges, trains and lorries into the retort via a conveyor system.

2. Once inside the retort the coal was heated in an oxygen free environment, volatilising off hydrocarbon compounds and impurities such as ammonia, cyanide and sulphur.

3. Gas was drawn off the retort by exhauster pumps; it contained hydrogen, carbon dioxide, hydrocarbons and impurities.

4. The gas was cooled by the condensers to remove less volatile hydrocarbons such as bitumen and pitch.

5. Further coal tar was removed by the tar extractor, which removed tar fog, which was always difficult to remove from the cooled gas.

6. The lighter hydrocarbons such as phenol and ammonia were removed by washer/scrubbers, including the Livesey washer. These processes depended on creating a mist of water (in order to increase the surface area of the water), which would dissolve the aforementioned by-products.

7. The final stage of processing was purification; this is where the impure coal gas passed through purifier beds filled with iron oxide. The iron oxide reacted with the hydrogen sulphide and hydrogen cyanide in the gas, precipitating iron sulphide and iron cyanide compounds and making the gas much purer and safer.

8. The gas was then pumped into a gasholder, which then maintained a pressured supply of gas for local distribution.

The yield, quality and composition of the town gas and its by-products varied according to the design of the process operated and the type of coal used as a feedstock. The useful by-products from gas manufacturing included:

- Coke – Used in the manufacture of steel
- Coal tar and Phenol – Used in the manufacture of organic chemicals
- Spent Oxide – Used for the manufacture of sulphuric acid, due to its sulphur content.
- Ammonia – Used for the manufacture of fertilizers
- Benzol – Motor fuel

Coal tars are highly variable compounds that contain a range of different hydrocarbons, with the predominant type being aromatic hydrocarbons such as benzene and polycyclic aromatic hydrocarbons (PAHs), which are toxic and can also be carcinogenic. The coal tar was generally stored in underground tanks, on site.

PAHs are a large group of compounds containing two or more benzene rings fused to each other, or to other hydrocarbon rings. Their toxicity varies with their structure. Naphthalene poses the lowest health risk, whereas benzo(a)pyrene (B(a)P), a 5-ring PAH poses the greatest risk from carcinogenicity.

B(a)P is carcinogenic due to the ability of its degradation product BP-diol epoxide 2 (anti) to bind with deoxyribonucleic acid (DNA). As DNA is the genetic code of organisms, alteration of it can be harmful or fatal. Where binding has occurred between DNA and BP-diol epoxide 2 (anti), further cell replication will result in mutation, which can lead to cell death or tumour development. As PAHs increase in size, their solubility decreases, therefore the less harmful PAH are more mobile in groundwater than the carcinogenic PAHs such as B(a)P, which has a very low solubility in water.

All the other by-products mentioned previously, along with the waste ash, are all common contaminants of gasworks sites. The main risk from spent oxide is that in addition to sulphur, it also contains cyanide, mainly as the stable iron ferricyanide complex. The ash may contain elevated concentrations of heavy metals, in particular arsenic and lead. Phenol and benzol both pose a risk from their toxicity and ammonia poses a risk of eutrophicating surface waters or toxifying groundwater used for drinking water.

These toxic and/or carcinogenic contaminants may migrate through the soil and contaminate ground and surface waters and so they are a potential source of environmental liability to site owners.

4.3 SUMMARY OF GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

The majority of the site is directly underlain by Sherwood Sandstone bedrock, with a limited occurrence of glacial drift in the eastern part of the site. The bedrock occurs beneath the majority of the site at from ground level to 10 m below ground level. The bedrock dips to the southwest at an angle of 15 degrees and a north-northwest to south-southeast trending fault is shown running through the northeastern part of the site.

The Sherwood Sandstone is classified by the Environment Agency as a Major Aquifer. The overlying soils are classified as being of 'high leaching potential', indicating that they have little potential for the attenuation of pollutants and hence a low level of protection to the aquifer. The drift deposits present in the east of the site are classified as a Minor Aquifer.

The material used for the trials was composed of contaminated made ground, which was predominantly a gravelly sand containing brick fragments, mixed with coal tar excavated from the former tar tank on the site.

4.4 HISTORICAL INFORMATION

The gasworks was developed in the early 1890s and started gas production in 1894. It initially produced gas by the carburetted water gas (CWG) process, and was owned by the local Gas Company.

The CWG plant was located at the north of the site. Coal to supply the plant was delivered to the site by rail and oil was supplied via a pipeline from a nearby dock to a group of four oil storage tanks located at the northwest of the site.

Gas production using a horizontal retort house commenced at the site around 1892. This retort house was located in the north of the site, to the east of the CWG plant.

A third phase of development occurred around 1938 when a vertical retort house was built, located immediately north of the original retort house. Several other gas process structures were also built at this time. The vertical retort house was extended around 1943.

Further phases of development occurred in the 1950s and 1960s, including the construction, around 1958, of a large 'Intermittent Vertical Chamber Oven' (IVCO) retort house in the south of the site and the introduction of Petroleum Fuel Distillate (PFD) plant towards the end of the 1960s.

At the maximum extent of the gasworks, gas production/process buildings and other structures were located on land across the entire site and extended onto the adjacent land to the east. Gas production ceased at the site in 1975, following which the majority of the above ground structures were demolished to ground level. Gas storage/distribution structures remained.

4.5 NATURE AND EXTENT OF CONTAMINATION

Detailed site investigations were carried out at the site by ENTEC UK Ltd. In summary, the site investigations indicated generally low levels of contamination in the made ground (composed of gravely sand with fragments of brick, iron and concrete) throughout the majority of the site. Gasworks materials such as spent oxide and foul lime were encountered in only a few locations.

The remaining underground structures had been infilled, largely with demolition rubble. Six large below ground tanks were encountered, comprising a tar and liquor tank, a relief holder tank and four tar settling tanks. The tar and liquor tank was found to contain tar during the ground investigation, and it was suspected that tarry sludges could be present in the bases of the other tanks. This was confirmed during the remediation works. A description of sampling from the tar and liquor tank for the purpose of the bioreactor trial is included in Section 3.

The tar and liquor tank was the most significant contamination source in the site. The principal contaminants present in the tank were PAHs, phenols, BTEX, TPH and ammonium. Detailed chemical analysis of the tar and other contaminated soil used as feedstock in the bioreactor trial is discussed in Section 7 and presented in full in Appendix B. A summary of the feedstock material for the trials is shown in Table 4.1. From this table it can be seen that PAHs are the main contaminants. The layout of the trial area can be seen in Figure 6.1.

Table 4.1: Mean data for the feedstock (contaminant concentrations are given in mg/kg)

Determinand	Mean value	Determinand	Mean value
pH	7.7	Anthanthrene	20.8
% Loss on ignition	10.0	Benzo(e)pyrene	57.3
% Moisture	14.4	Cyclopenta(cd)pyrene	6.5
% Stones	29.7	Total PAH	2988.9
Xylenols and ethylphenols	26.3	Easily-liberable cyanide	0.9
Cresols	14.3	Complex cyanide	16.9
Catechol	0.4	Total cyanide	17.1
Phenol	6.2	Elemental sulphur	90.4
Trimethylphenol	13.8	Water soluble sulphate as SO_4	2026.7
Total Phenols	60.8	Water soluble chloride	51.9
Naphthalene	631.7	Exchangeable ammonium	85.1
Acenaphthylene	193.7	Nitrate	7.7
Acenaphthene	42.1	Arsenic	62.8
Fluorene	168.3	Cadmium	1.1
Phenanthrene	506.7	Chromium	40.4
Anthracene	154.8	Lead	462.2
Fluoranthene	333.9	Mercury	2.2
Pyrene	310.6	Selenium	1.1
Benzo(a)anthracene	114.7	Copper	67.8
Chrysene	100.7	Nickel	36.2
Benzo(b)fluoranthene	69.9	Zinc	523.9
Benzo(k)fluoranthene	68.3	Boron	1.5
Benzo(a)pyrene	86.2	Benzene	3.6
Indeno(1,2,3-cd)pyrene	45.4	Toluene	2.6
Di-benzo(a,h,)anthracene	12.9	Ethylbenzene	0.3
Benzo(g,h,i)perylene	50.8	Xylenes	2.6

5. LABORATORY TRIALS

5.1 INTRODUCTION

In January 2002, during the ground investigation being carried out by ENTEC UK Ltd, PB collected samples from trial pits (TPs) excavated into the underground tar and liquor tank. The tar tank was found to contain demolition material, including bricks, concrete, ash, sand and gravel and waste metals. Free phase tar was encountered below 2.5 mbgl, with perched groundwater at approximately 1.5 mbgl.

Samples of free phase tar and sandy made ground (sieved to <8 mm particle size) were taken for use as feedstock in the laboratory trials. The samples were sent for laboratory-scale treatability testing at the laboratories of Advantica in Loughborough. Samples requiring microbiological analysis were sent to the microbiology department of the Health and Safety Laboratories (HSL) in Sheffield. The tar to soil ratio used during the laboratory trials was 1:10. The treatability trials were undertaken according to protocols used on other similar Advantica projects.

5.2 MICROBIOLOGICAL TESTING

The nutrient medium used to culture the microorganisms for microbiological testing was BG medium (meaning Better Growth medium, the composition of which is given in Table 5.1). BG medium had been developed to give a very good biodegradation performance as a minimal nutrient medium during previous studies carried out by Advantica. The medium had been modified from one previously developed by Carl Cerniglia (Cerniglia *et al.,* 1992*)* by replacement of the nitrogen and phosphate sources by ammonium dihydrogen phosphate and diammonium hydrogen phosphate, as detailed in Table 5.1.

Table 5.1: Composition of BG medium

Mineral components	Concentration (g/L)	Trace metal solutions	Concentration (μg/L)
$NH_4H_2PO_4$	1.1	$CuSO_4.5H_2O$	80
LiCl	0.02	$ZnSO_4.7H_2O$	100
$(NH_4)_2HPO_4$	1.1	KBr	30
$MgSO_4.7H_20$	0.15	KI	30
NaCl	0.3	$MnCl_2.2H_2O$	600
		$SnCl_2.2H_2O$	40
		$FeSO_4.7H_2O$	300

The microorganisms used were those intrinsically found in the soil from the gasworks. To identify the soil microcosm, two methods were used; direct culturing of microorganisms and direct amplification of 16S ribosomal Ribonucleic Acid (rRNA) from microorganisms in the soil.

The methods of microbial enumeration and identification were as follows:

- Enumeration of microorganisms was undertaken on viable colonies, using standard serial dilution plating procedures using 20 μL of each dilution on solid media consisting of nutrient agar or minimal agar (CE medium with 15 g/L agar noble) with naphthalene (1 g) supplied as a carbon source (placed on the inside of the petri dish lid and the plate inverted).

- A 16S rRNA Polymerase Chain Reaction (PCR)-based method was used to identify predominant colonies of microorganisms on the petri dishes. These represented the most commonly seen colony types worthy of further investigation. Sterile pipette tips were used to lift discrete colonies from isolation plates, and these were then suspended in 5 μL of sterile water prior to amplification of the 16S rRNA gene of each bacterial isolate. All samples were run in duplicate. Of the 9 colony types identified using this technique, all gave PCR products. The 9 PCR products identified were cleaned using Pharmacia Sephacryl S400 columns, and were sent off for sequencing with a standard 16S primer.

The 16S rRNA analysis of the bacterial colonies involved amplification and analysis of the first third of the 16S rRNA gene. This region of 16S rRNA (16S base positions 1 to 530) contains three valuable 'hyper-variable' regions that differ between different bacterial species. By comparing the DNA sequences of this region to a large database over 10,000 of other 16S sequences, genetic analysis allows a genus level to be determined with accuracy and a species level to be determined with some confidence, providing the DNA sequence match is >95 % with known species.

All sequence data were aligned on the Internet using 'Advanced BLAST', through the USA National Center for Biotechnology Information.

5.3 TREATABILITY TESTING

Particle size analysis was undertaken on the sandy made ground excavated from the tar tank. The material was pre-screened to below 8 mm and separated using Endicott sieves.

Five treatability trials were undertaken in 10 L bioreactors at the Advantica laboratories. For all five trials, the following conditions were adhered to:

- The stirring rate was set at 500 rpm (sufficient to maintain the material in suspension);
- The rate of aeration of the vessels was 2 L of air per minute and the temperature was 25 °C;
- The pH control on the microprocessor was set to trigger a dose of acid if the pH exceeded 7.5 and to dose alkali if the pH fell below 6.9;
- The reagents used were:

    a) 1 M hydrochloric acid

    b) 1 M sodium hydroxide

    c) PennWhite Ltd Foamdoctor G2000 silicone based antifoam

For each trial approximately 2.8 kg of contaminated feedstock was mixed with 6.65 L of BG medium and 0.35 L of inoculum, as detailed in Table 5.2. The inoculum used during Trial 1 comprised tarry water sampled from the tar tank at the gasworks. The inoculum used in Trials 2 to 5 was water recovered from the previous trial (i.e. Trial 2 used water recovered from Trial 1).

5.4 SAMPLING

The following samples were taken for chemical and microbiological analysis:

- Two 100 g samples of feedstock;
- A 50 mL sample of slurry taken from the laboratory scale bioreactors on a daily basis (samples were drained and dried at 30 ºC prior to testing);
- Two 100 g samples of solid product taken at the end of each trial.

Table 5.2: Bioreactor conditions

Trial	Start Date	End Date	Composition of Feedstock	Inoculum/Nutrients Used
1	25/02/02	06/03/02	a) 2,800 g sandy made ground from TP1 b) 254 g free phase tar from TP1	350 mL water from tar tank used as an inoculum, plus 6.65 litres of BG medium
2	11/03/02	20/03/02	a) 2,728 g sandy made ground from TP2 b) 272 g free phase tar from TP2	350 mL water from Trial 1 used as an inoculum, plus 6.65 litres of BG medium
3	08/04/02	17/04/02	a) 2,755 g sandy made ground from TP2 b) 245 g free phase tar from TP2	350 mL water from Trial 2 used as an inoculum, plus 6.65 litres of BG medium
4	22/04/02	01/05/02	a) 2,746 g sandy made ground from TP2 b) 245 g free phase tar from TP2	350 mL water from Trial 3 used as an inoculum, plus 6.65 litres of BG medium
5	13/05/02	22/05/02	a) 2,753 g sandy made ground from TP2 b) 247 g free phase tar from TP2	350 mL water from Trial 4 used as an inoculum, plus 6.65 litres of BG medium

Note 1 The material excavated from Trial Pit 1 (TP1) was notably drier than that from Trial Pit 2 (TP2)

5.5 RESULTS AND DISCUSSION

The following paragraphs summarise and discuss the results of the laboratory trials. References cited can be found in the References section at the back of the document.

From the microbiological analysis, the organisms that were cultured have been compared to known rRNA sequences, and the sequences that match them most closely have been tabulated in Appendix B.

It should be noted that the rRNA reference information for the cultured organisms must be approached with care. The reference information identifies where and how similar sequences have been identified before, but this does not mean that the sequence may not be found elsewhere. For example, one of the isolates matches a previously uncultured, cloned isolate that has been identified in human mouths. This does not mean that it occurs only as an oral bacterium. A broader view needs to be taken because many of these microorganisms have a wide distribution.

5.5.1 COMPOSITION OF THE MADE GROUND

Microbial analysis of the made ground from the tar tank, before it was subjected to any treatability tests, identified two types of microorganism: *Azorhizobium sp*. and *Acidovorax sp*. (refer to Table 5.3); each is a nitrogen-fixing bacterium and both are commonly associated with the rhizomes of nitrogen-fixing plants. These organisms may have been associated with plants growing on the surface of the made ground, prior to excavation of the tar tank.

Acidovorax sp. is able to mineralise compounds with quaternary carbon atoms such as benzene and methyl tertiary butyl ether (MTBE) and have also been implicated in the denitrification of dimethylmalonate (Morse *et al.*, 2002). Since *Acidovorax sp.* is an anaerobic bacterium it is likely that this population was located deeper than 0.5 mbgl, in the anaerobic zone.

Table 5.3: Microbial composition of the made ground in the tar tank

Genus/species	Similarity (%)	Source of microorganism	Previous information known about isolate
Azorhizobium sp.	97	Tarry soil	Nitrogen-fixing bacterium
Acidovorax sp.	94	Tarry soil	Anaerobic mineralization of quaternary carbon atoms: isolation of denitrifying bacteria on dimethylmalonate
Acidovorax sp.	96	Tarry soil	Anaerobic mineralization of quaternary carbon atoms: isolation of denitrifying bacteria on dimethylmalonate
Uncultured bacterium FukuS36.	91	Water from tar tank	Comparative 16S rRNA analysis of lake bacterioplankton reveals globally distributed phylogenetic clusters including an abundant group of actinobacteria
Uncultured eubacterium.	95	Water from tar tank	Dependence of wastewater treatment efficiencies on treatment system and its bacterial community composition
Poor sequence – unknown	n/a	Water from tar tank	n/a
Sphingopyxis witflariensis.	98	Water from tar tank	*Sphingopyxis witflariensis sp.* nov., isolated from activated sludge
Pseudomonas sp.	99	Water from tar tank	Peptide nucleic acid-mediated PCR clamping as a useful supplement in the determination of microbial diversity
Sphingopyxis witflariensis.	98	Water from tar tank	*Sphingopyxis witflariensis sp.* nov., isolated from activated sludge
Pseudomonas sp. PsI.	97	Water from tar tank	Phylogeny, ribosomal RNA gene typing and relative abundance of new Pseudomonas species (*sensu stricto*) isolated from two pinyon-juniper woodland soils of the arid southwest U.S
Uncultured bacterium.	90	Water from tar tank	Phylogenetic composition of bacterioplankton assemblages from the Arctic Ocean

Some of the microorganisms isolated from the water contained in the tar tank were uncommon and the 16S rRNA identification method was incapable of identifying many of the organisms to either genus or species level.

The only organisms identified with a high degree of confidence were:

- *Sphingopyxis witflariensis,* an uncommon bacterium, previously identified in activated sludge treatment processes.
- *Pseudomonas sp*: Pseudomonads are commonly found in contaminated environments and are associated with the degradation of a wide range of organic compounds including phenol, PAH and BTEX compounds.

The particle size distribution (PSD) testing undertaken (See Table 5.4) indicated the sandy made ground material to have a relatively equal distribution of sand and gravel with a smaller proportion of silt/clay. The silt portion of the made ground provides the best surface area to volume ratio for

mixing with tar and is the easiest to mix as it suspends easily. However, it is also the hardest to dewater. The sand and gravel fractions require much more energy to keep them suspended and have a lower surface area to volume ratio for mixing with tar, but are much easier to dewater.

Table 5.4: Results of particle size distribution analysis

Particle size range	Weight in sample (g)	BS5930 definition	Percentage of sample
8.0 mm – 2.00 mm	87.0	Fine to medium gravel	43.50
2.0 mm – 600 µm	29.8	Coarse Sand	14.90
600 µm – 200 µm	31.2	Medium Sand	15.60
200 µm –150 µm	14.0	Fine Sand	7.00
<150 µm	41.5	Fine Sand – Silt	20.75

5.5.2 RESULTS OF THE TREATABILITY TRIALS

5.5.2.1 Trial 1

A comparison of the most common microorganisms isolated from the start and the end of the trial are shown in Table 5.5. The dominant microorganisms in the slurry changed from those identified as similar to a *Eubacterium sp.*, *Variovorax paradoxus* and *Acidovorax delafieldii*, to a mixture identified as similar to *Eubacterium sp.* and an unidentified bacterium or *Alcaligenes sp*.

Table 5.5: Microbial composition of the slurry at the start and end of Trial 1

Species	Similarity (%)	Source of Microorganism	Previous information about isolate
Eubacterium	90	Trial 1 Start	Common soil bacteria. Identified in petroleum hydrocarbons degrading microbial communities
Variovorax paradoxus	94	Trial 1 Start	Bacterial rhizosphere populations of black poplar and herbal plants to be used for phytoremediation of diesel.
Acidovorax delafieldii	95	Trial 1 Start	Microbial degradation of poly (beta-hydroxybutyrate-co-beta-hydroxyvalerate) PHBV.
Eubacterium	90	Trial 1, End	Combined use of 16S Ribosomal DNA and 16S rRNA to study the bacterial community of polychlorinated biphenyl-polluted soil. Identified in petroleum hydrocarbons degrading microbial communities
Unidentified bacterium or *Alcaligenes sp.*	92	Trial 1, End	An outbreak of non-flocculating catabolic populations caused the breakdown of a phenol-digesting activated-sludge process
Unidentified bacterium or *Alcaligenes sp*.	92	Trial 1, End	An outbreak of non-flocculating catabolic populations caused the breakdown of a phenol-digesting activated-sludge process

The predominant microorganisms found in the samples of feedstock are similar to those previously identified as capable of degrading complex organic compounds, including polychlorinated biphenyl

(PCB), benzene (Rooney-Vega *et al.*, 1999), phenol (Fires *et al.,* 1997) and petroleum hydrocarbons (Morse *et al.,* 2002; Mallard *et al.*, 1994; Rafii and Cerniglia, 1995). By the end of the trial the *Variovorax sp.* and *Acidovorax sp.* had been replaced by an unidentified bacterium. This unidentified bacterium was reported to be similar to a previously identified *Alicagenes sp.*

Eubacterium sp. was found in both the initial (feedstock) and final (product) samples and have previously been associated with the biodegradation of a range of complex hydrocarbons, which include 3-, 4- and 5-ring PAHs. *Eubacterium Sp.* have been reported to successfully reduce sulphur in anaerobic environments.

Contaminated tar-tank water (350 mL) was used as an inoculum for the first trial. Such water typically contains readily degradable organic compounds such as phenol, which due to their availability and high biodegradability boost microbial growth. Chemical analysis of the tar-tank water used in Trial 1 showed that the dissolved phase contamination was low and restricted almost entirely to phenol. A total phenol concentration of about 0.5 mg/L was present at the start of the trial. The phenol degraded rapidly during the trial with no detectable phenols present by the end of the trial (Figure 5.1).

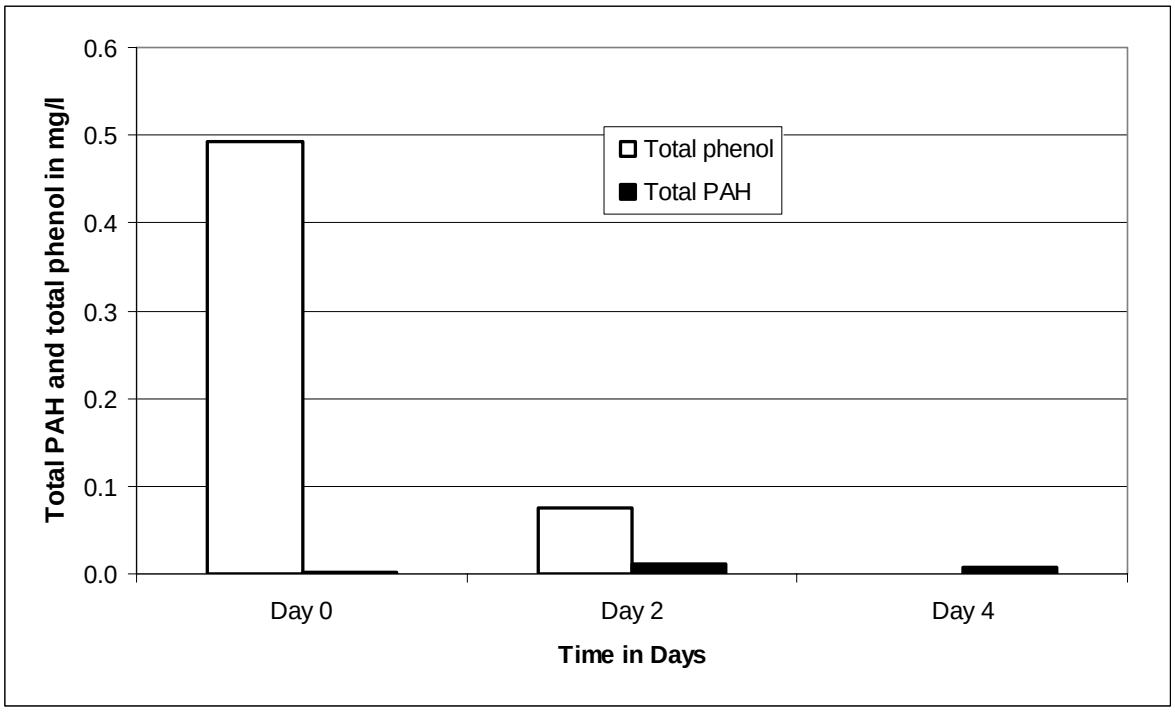


Figure 5.1: Concentration of total polycyclic aromatic hydrocarbons (tPAH) and total phenols in the aqueous medium of the slurry reactor during Trial 1

Dissolved oxygen levels dropped significantly at the start of the trial and remained low throughout. This suggests that aerobic microorganisms in the slurry were active throughout the trial, utilizing oxygen for the biodegradation of the hydrocarbons. The amount of dissolved oxygen in the slurry relates to aerobic microbial activity, fully aerated slurry should have a dissolved oxygen concentration of 100 %. When aerobic microbial activity occurs, such as biodegradation of coal tars, then oxygen is consumed and the amount of dissolved oxygen drops. This continues until oxygen becomes limiting, when the rate of metabolism is limited by the amount of oxygen entering the system. Once metabolic activities cease in the slurry then the amount of oxygen should recover to 100 %.

The pH gradually increased during the trial. This suggests that degradation of acidic organic compounds, such as phenol, occurred. The trial temperature was maintained at 25 °C throughout.

Chemical analysis showed that the composition of the tar had a significant bias towards low molecular weight PAHs. No significant concentration of the high molecular weight PAHs was detected. Historical information has shown that the tar tank contained a number of subdividing

compartments used for storing different tar products. A detailed description of which tar products were stored in which tanks is not available but the results of the trial suggest that the area in which TP1 was excavated contained a very light fraction of coal tar oil. With the exception of benzo(a)anthracene and naphthalene, the PAH were either 3- or 4-ring structures. The only phenolic compound present in a significant amount was catechol, which is a breakdown product of phenol and other aromatic compounds. Analysis of the speciated petroleum hydrocarbons showed that most of the hydrocarbons were aromatic, and were PAH compounds or their methylated derivatives.

The chemical analysis of the material before, during and after the first trial showed a significant reduction in the concentration of total phenols (99.27 %), total PAH (60.87 %) and total petroleum hydrocarbons (95.14 %) (see Figure 5.2). Apart from acenapthylene and fluorene, the degradation across the whole range of PAHs was about 60 %. The increase in the fluorene concentration was not significant, and probably attributable to analytical variation. However, the increase observed for acenapthylene was significant.

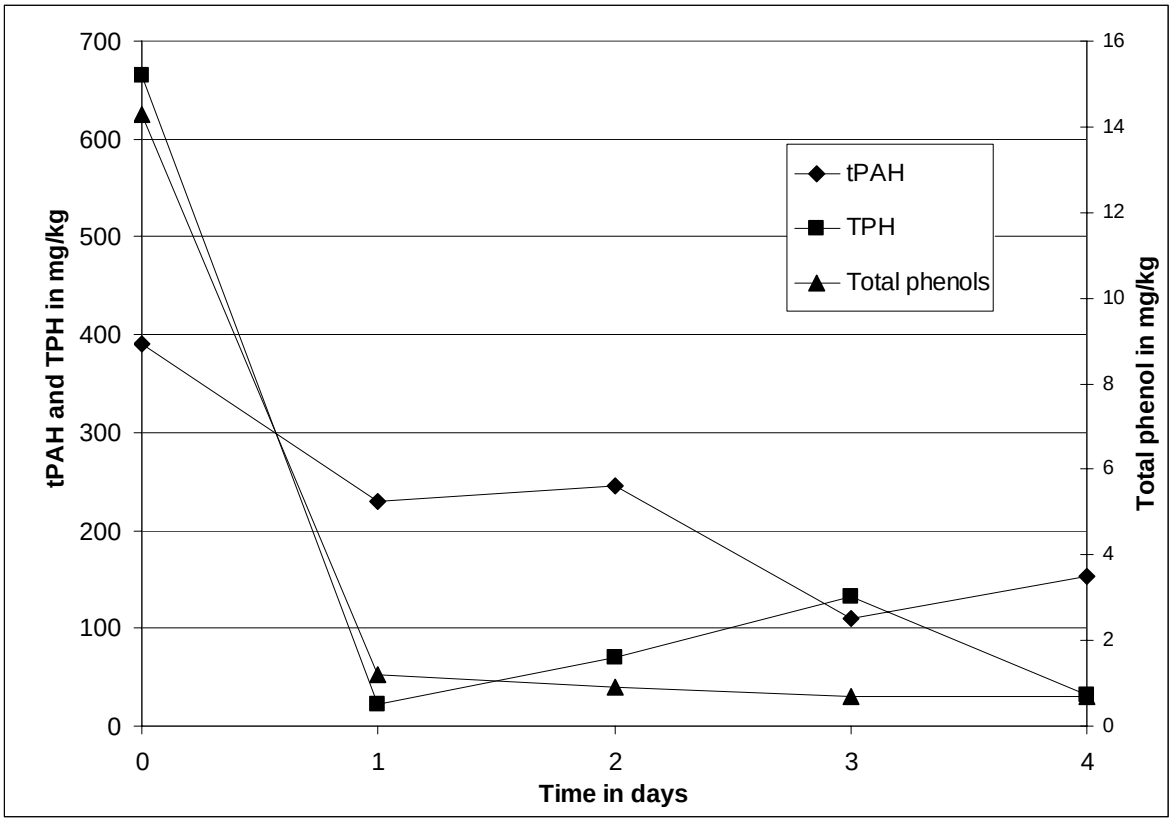


Figure 5.2: Concentrations of total polycyclic aromatic hydrocarbons (tPAH), total petroleum hydrocarbons (TPH) and total phenols in the solid phase during Trial 1

During previous laboratory and field-scale trials, acenapthylene had proven to be more recalcitrant than other, similar, PAHs, in particular the structurally similar acenaphthene. The reason for the increase in the concentration of acenapthylene is not clear; one possibility is that it may be due to a breakdown of more complex PAH into acenapthylene, though there are no scientific publications to support this theory. These results were in line with previous studies and suggested that the material from the gasworks site would be suitable for bioremediation using a slurry-phase bioreactor.

5.5.2.2 Trial 2

The second trial used 350 mL of inoculum from the first trial, with no addition of tar tank water from the site. Dissolved phase contamination included both phenolic compounds and PAHs, neither of which were present in particularly high concentrations. No detectable phenol or PAH remained by day 3 of the trial (Figure 5.3). This pattern would be expected, as contamination in the dissolved

phase is the most bioavailable, and therefore should be the most biodegradable. This trial used a 40 % slurry composed of tar mixed with sandy fill material from TP2.

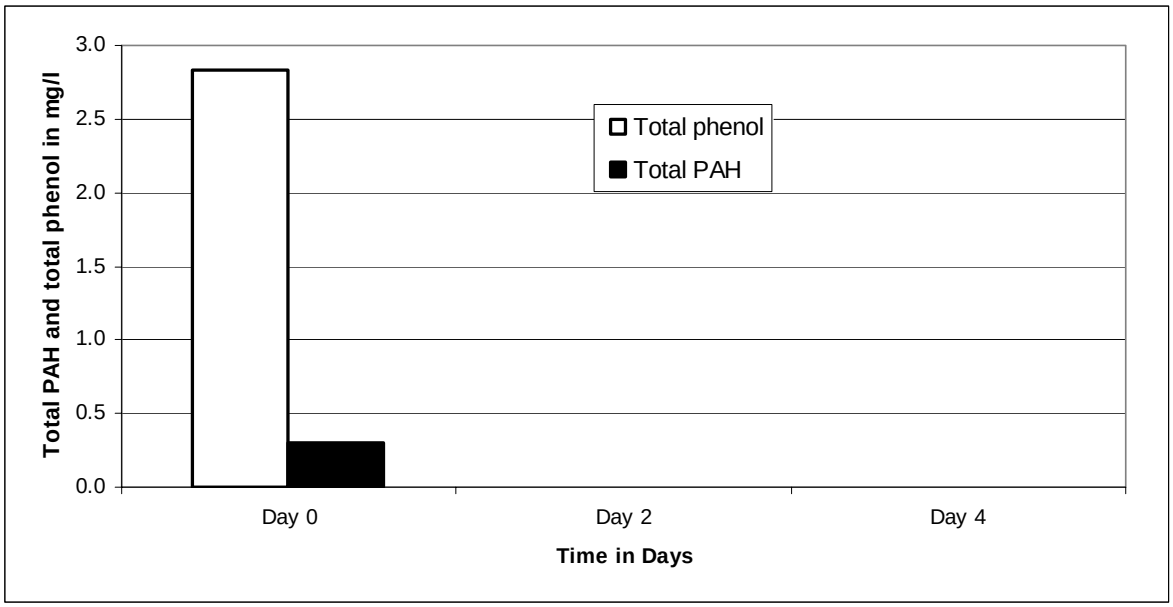


Figure 5.3: Concentration of total polycyclic aromatic hydrocarbons (tPAH) and total phenols in the aqueous medium of the slurry reactor during Trial 2.

A comparison of the most common microorganisms isolated from the start and the end of the trial are shown in Table 5.6. The dominant microorganisms in the slurry changed from a mixture identified as similar to *Afipia genosp.* and *Hydrogenophaga taeniospiralis*, to a mixture identified as similar to a *Sphingomonas paucimobilis* and unindentified bacterium.

Table 5.6: Microbial composition of the slurry at the start and end of Trial 2.

Species	**Similarity (%)**	**Source of microorganism**	**Previous information about isolate**
Afipia genosp. 9.	92	Trial 2, Start	This species was formally known as cat scratch fever bacillus; however, it has now been reclassified as *Afipia genosp. 9*.
Afipia genosp. 9 strain G8990	96	Trial 2, Start	See above
Hydrogenophaga taeniospiralis	98	Trial 2, Start	Geochemistry and microbial diversity of a trichloroethene-contaminated Superfund site undergoing intrinsic *in situ* reductive dechlorination
Uncultured bacterium	96	Trial 2, End	Bacterial 16S rRNA clones associated with carbon leader ore samples from deep within a gold mine, South Africa
Uncultured bacterium FukuS93	94	Trial 2, End	Comparative 16S rRNA analysis of lake bacterioplankton reveals globally distributed phylogenetic clusters including an abundant group of actinobacteria.
Sphingomonas paucimobilis	96	Trial 2, End	Phylogenetic and physiological comparisons of PAH-degrading bacteria from geographically diverse soils

The predominant microorganisms found in the initial feedstock samples are not commonly associated with the biodegradation of hydrocarbon or complex organic compounds. *Afipia* is commonly associated with a disease called 'cat scratch fever'. *Hydrogenophaga* sp. is known to degrade carboxysulphobenzene (Tan, 2001) and MTBE (Ramsden, 2000).

At the end of Trial 2, *Afipia genosp. and Hydrogenophaga taeniospiralis* had been replaced by two unidentified bacteria and a bacterium similar to *Sphingomonas paucimobilis.* One of the unidentified bacteria was similar to a bacterium previously identified 3.3 km below ground level in a South African goldmine, and the other was similar to *Acinetobacter sp.* associated with lake bacterioplankton. There is no documented evidence to suggest that either of these bacteria is able to biodegrade organic compounds. *Sphingomonas paucimobilis* has been documented to degrade haloalkanes (Oakley *et al.*, 2002), gamma-hexachlorocyclohexane (Oakley *et al.*, 2002), and PAHs (Lantz *et al.,* 1995 and Lantz *et al.,* 1997).

Dissolved oxygen dropped significantly at the start of the trial and remained low throughout, which suggests the microorganisms in the slurry were active throughout the trial (Appendix B, Figure B2).

The pH gradually increased through the trial until it triggered the acid pump, which dosed over 1700 mL of 1 M hydrochloric acid. The pH increase was equivalent to the addition of 1.7 g of hydrogen ions, which was required to neutralize the increasing pH as a result of the significant biodegradation of acidic compounds in the slurry. It is likely that considering the significant amount of hydrochloric acid required, not all of the compounds being degraded were detected during the analysis as this only targets specific compounds of interest. This pH consumption does suggest that significant biodegradation was occurring throughout the trial (Appendix B, Figure B2). Temperature throughout the process was maintained at 25 °C.

As with Trial 1, the composition of the tar had a significant bias towards low molecular weight PAHs. Of the high molecular weight PAHs, only benzo(a)anthracene was present in significant concentrations.

The tar used in the feedstock for Trial 2 was sampled from TP2, located in a different area of the tar tank to TP1 and so likely to be from a different compartment. The chemical analysis of this material suggested that this tar contained a slightly heavier fraction of coal tar oil than that in TP1 (some 5-ring PAHs were detected in a significant quantity). Phenolic compounds were present only in a very low concentration but were more varied than those found in TP1.

The chemical analysis of the material before and after the second trial showed a significant reduction in the concentration of total phenols (95.24 %), total PAH (63.85 %) and TPH (52.31 %), see Figure 5.4. The degradation of PAHs was biased towards the 3-ring compounds. The 4- and 5-ring PAHs showed reductions in concentration of 42.8 % and 45.8 % respectively. Degradation of the 2-ring PAH, naphthalene, was low at only 17 %, the reason for this is unclear. It is possible that some larger PAH molecules were being broken down into naphthalene, replacing the concentrations of naphthalene that were being biodegraded. However, known pathways for the biodegradation of, for example, phenanthrene, would not support this theory, as naphthalene is not known to be an intermediate of phenanthrene degradation. However, it is possible that other high molecular weight PAHs may be degraded with naphthalene as an intermediate.

The results of Trial 2 were less successful than had been noted in previous studies undertaken at Advantica (Thomas *et al.*, 2000; Thomas and Gustavsen, 2000), suggesting that something could be retarding degradation of the PAH compounds. However, the results still suggest that the process would be effective at remediating material at the gasworks.

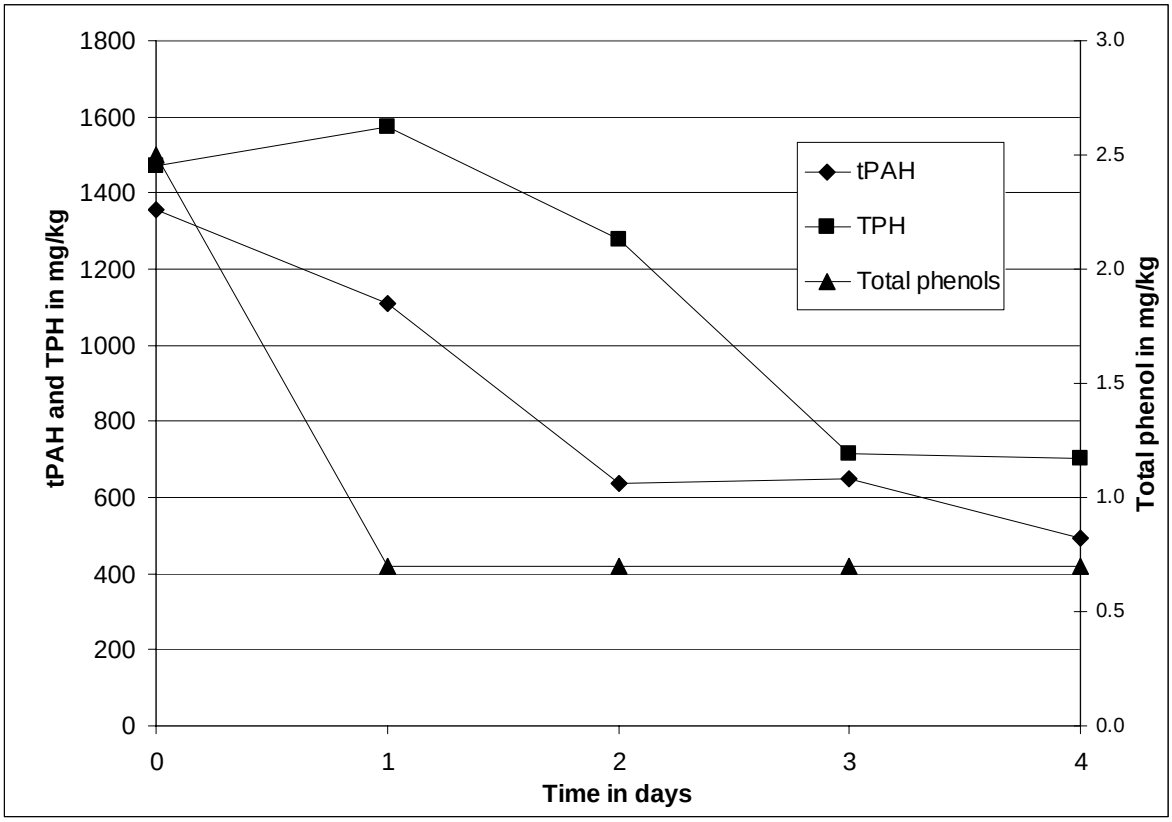


Figure 5.4: Concentrations of total polycyclic aromatic hydrocarbons (tPAH), total petroleum hydrocarbons (TPH) and total phenols in the solid phase during Trial 2

5.5.2.3 Trial 3

The last three trials were undertaken using the same conditions. The soil feedstock comprised 245 g wet weight tarry soil from TP2 and 2,546 g of sandy made ground, also sampled from TP2. In each case 350 mL of liquid from the previous trial was used as the inoculum.

Dissolved phase contamination included both phenolic compounds and PAH. The PAH was present in fairly low concentrations (0.5 mg/L) and the phenol was present at a significant concentration (2.75 mg/L). No detectable phenol or PAH remained by day 3 of the trial (Figure 5.5).

A comparison of the most common microorganisms isolated from the start and the end of Trial 3 are shown in Table 5.7. The dominant microorganisms in the slurry changed from a mixture of those identified as similar to *Stenotrophomonas maltophilia, Sphingomonas sp.,* and Bromate-reducing bacterium to a mixture identified as similar to *Sphingomonas sp. Pseudomonas sp.* and an unknown bacterium. *Stenotrophomonas maltophilia* and *Sphingomonas sp.,* which were found in the initial feedstock samples (and the *Sphingomonas sp.* identified in the final product samples), are similar to those previously identified as degrading PAHs, pentachlorophenol, dioxin and dibenzofuran compounds (Oakley *et al.,* 2002; Lantz *et al.,* 1995; Lantz *et al.,* 1997). It is well documented that *Sphingomonas sp.* has been found to be important in biodegradation of xenobiotic compounds (Oakley *et al.,* 2002; Lantz *et al.,* 1995; Lantz *et al.,* 1997).

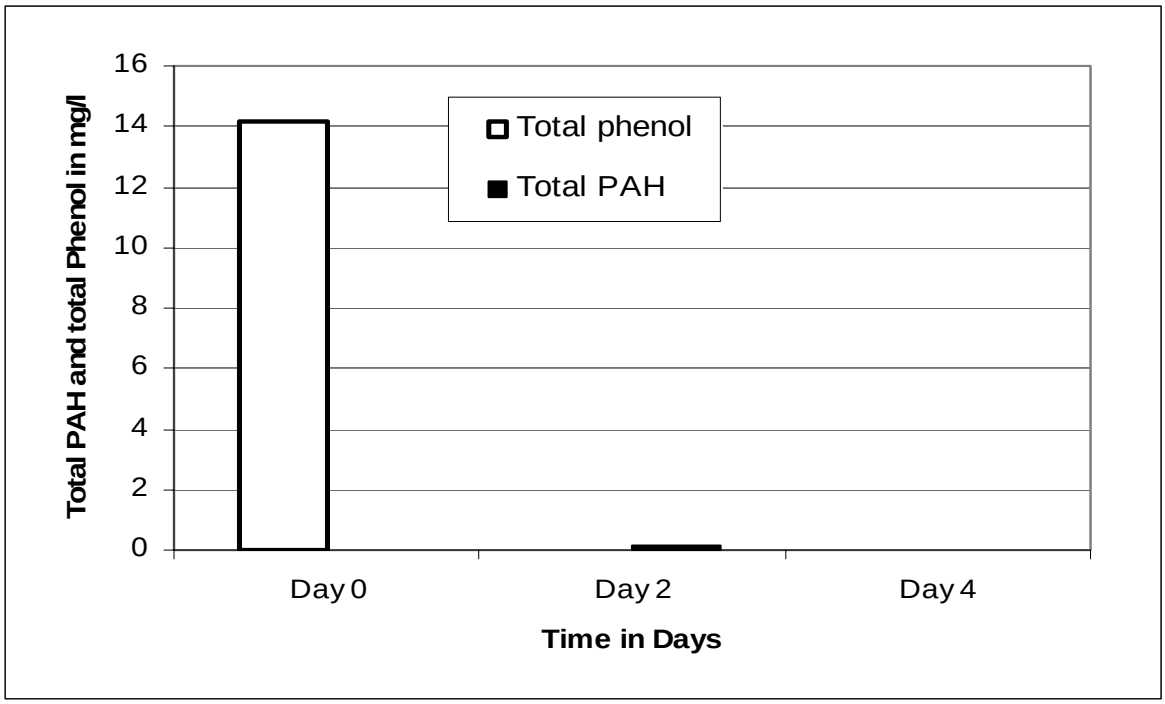


Figure 5.5. Concentration of total polycyclic aromatic hydrocarbons (tPAH) and total phenols in the aqueous medium of the slurry reactor during Trial 3.

Table 5.7: Microbial composition of the slurry at the start and end of Trial 3.

Species	**Similarity (%)**	**Source of microorganism**	**Previous information about isolate**
Stenotrophomonas maltophilia	96	Trial 3, Start	Molecular typing of gram-negative bacterial soil isolates from a PAH-contaminated site in Melbourne Australia
Bromate-reducing bacterium	98	Trial 3, Start	Unique bacterial diversity in subseafloor habitats associated with a deep-sea volcanic eruption
Sphingomonas sp.	93	Trial 3, Start	Found in several studies including Evolution of bacterial diversity during enrichment of PCP-degrading activated soils
Unknown bad sequence		Trial 3, End	n/a
Pseudomonas sp.	92	Trial 3, End	Diversity and ubiquity of bacteria capable of utilizing humic substances as electron donors for anaerobic respiration
Sphingomonas sp.	96	Trial 3, End	Dominant marine bacterioplankton species found among colony-forming bacteria

The bacterium identified in the initial feedstock samples was similar to a previously identified bromate-reducing bacterium, unique to sub-seafloor habitats associated with deep-sea volcanic eruptions. These habitats are highly specialized anaerobic environments where the organisms thrive under extreme conditions, namely barophilic (exist under high pressure), thermophilic (exist

under high temperature) and halophilic (exist in very salty environments). Though these conditions are very different from a gasworks, a gasworks still poses a range of extreme and hostile environments for life from a contamination perspective. It should therefore be expected that that types of organism identified on a gasworks would be related to extremophiles.

At the end of Trial 3 *Sphingomonas sp.* was still present but the *Stenotrophomonas maltophilia* and the bromate-reducing bacteria had been replaced by *Pseudomonas sp.* and an unidentifiable organism. The identification of Pseudomonas species on contaminated sites is very common, since they are probably the most regularly identified microorganisms implicated in the biodegradation of organic compounds (Kastner *et al.,* 1998; Kastner and Mahro, 1998; Mahaffey *et al.,* 1988; Stringfellow and Aitkin, 1994; Grimberg *et al.*, 1996; Stringfellow and Aitkin, 1998; Eaton *et al.*, 1994; and Eaton *et al.*, 1996).

Dissolved oxygen levels remained low during the trial, which suggests the microorganisms in the slurry were active throughout this period (Appendix B, Figure B3). The pH rose only slightly, which suggests the rate of degradation was lower than Trials 1 and 2. Temperature was kept at a steady 25 ºC throughout the trial.

The tar used in production of the feedstock for Trial 3 comprised mainly light-end PAHs but was also found to have a significant concentration of three types of 5-ring PAHs (Appendix B, Table B3). The only phenolic compound present in detectable levels in the tar was catechol.

Chemical analysis of the material before, during and after Trial 3 showed a significant reduction in the concentration of total PAH (51.46 %) and TPH (90.18 %), see Figure 5.6.

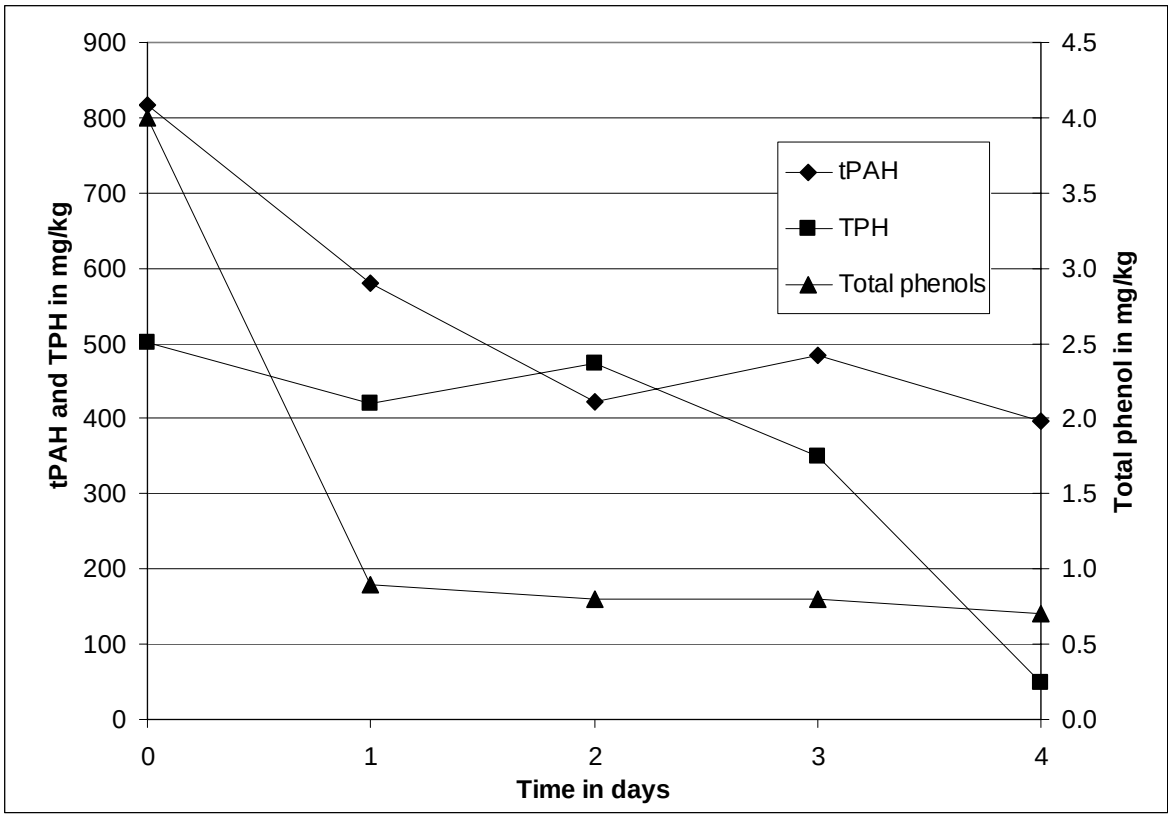


Figure 5.6: Concentrations of total polycyclic aromatic hydrocarbons (tPAH), total petroleum hydrocarbons (TPH) and total phenols in the solid phase during Trial 3

With the exception of benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, naphthalene and anthracene, the degradation of PAH was between 60 % and 70 %. Naphthalene concentrations increased during the trial. The reasons for this increase may be due to a breakdown of more complex PAHs into naphthalene, though it is more likely that it is due to the variability of this heterogeneous material and the low concentration of naphthalene, which would

make slight changes in concentration look more significant when interpreted as percentage changes. This, coupled with the heterogeneous material, makes anomalous data look more significant than it actually may be. For anthracene and benzo(a)pyrene, degradation was less than 60 %. Benzo(b)fluoranthene and benzo(k)fluoranthene increased in concentration, possibly for similar reasons to the increase in naphthalene.

5.5.2.4 Trial 4

Dissolved phase contamination included both phenolic compounds and PAHs. The PAHs were not detectable, apart from a low concentration detected on day 3. Phenol was present at a significant concentration (14 mg/L) on day 1, but no detectable phenol or PAH remained by day 5 of the trial (Figure 5.7).

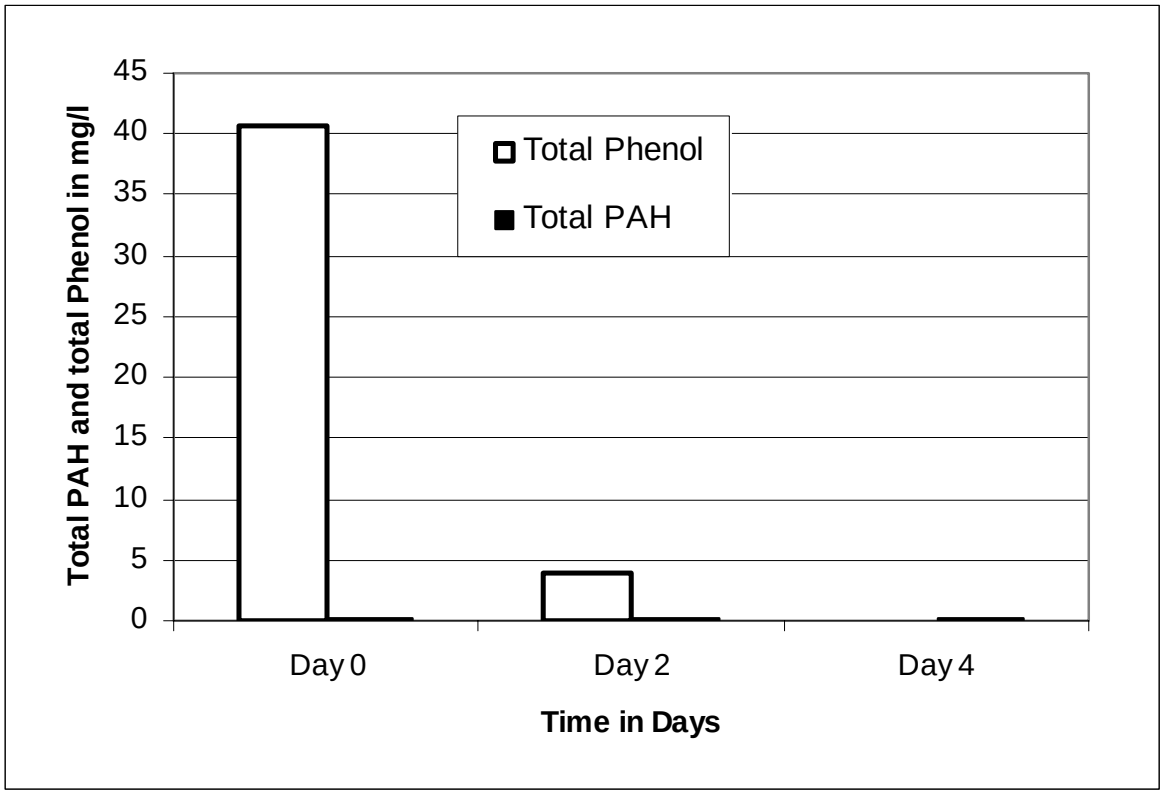


Figure 5.7: Concentration of total polycyclic aromatic hydrocarbons (tPAH) and total phenols in the aqueous medium of the slurry reactor during Trial 4

A comparison of the most common microorganisms isolated from the start and end of Trial 4 are shown in Table 5.8. The dominant microorganisms in the slurry changed from a mixture of those identified as similar to a bromate-reducing bacterium, and to *Pseudomonas sp*., to a mixture containing microorganisms identified as similar to a *Sphingomonas sp, Bordetella sp*. and an alpha proteobacterium (Table 5.8).

Table 5.8: Microbial composition of the slurry at the start and end of Trial 4.

Species	Similarity (%)	Source of microorganism	Previous information about isolate
Bromate-reducing bacterium B7.	97	Trial 4, Start	Unique bacterial diversity in sub-seafloor habitats associated with a deep-sea volcanic eruption
Pseudomonas sp.	98	Trial 4, Start	Bacterial diversity in water samples of Monticello mill tailings site, the water used was from uranium mining waste. Also a common environmental bacteria
Pseudomonas gessardii	98	Trial 4, Start	*Pseudomonas gessardii sp*. and *Pseudomonas migulae sp*. two new species isolated from natural mineral waters
Sphingomonas sp.	96	Trial 4, End	Plasmid-mediated mineralization of carbofuran by Sphingomonas sp.
Bordetella sp.	92	Trial 4, End	Microflora for efficient degradation of cellulolytic substrate
Alpha proteobacterium	96	Trial 4, End	Composition of marine bacterial communities utilizing dissolved organic matter

Sphingomonas sp. are similar to microorganisms previously identified as capable of degrading PAHs, pentachlorophenol, dioxin and dibenzofuran compounds (Oakley *et al.,* 2002; Lantz *et al.,* 1995 and Lantz *et al.,* 1997). It is well documented that *Sphingomonas sp.* is important in biodegradation of xenobiotic compounds (Oakley *et al.,* 2002; Lantz *et al.,* 1995; and Lantz *et al.,* 1997).

Bordetella sp. is known primarily as pathogenic organisms. It is unlikely that human pathogens would survive in this slurry. The particular species of *Bordetella* identified is similar to those known to degrade cellulose.

Alpha proteobacteria include the genera *Rhodospirillum, Rhodobacter, Rickettsia* and *Agrobacterium*. This group includes a diverse range of bacteria which can fix nitrogen and cause human disease. Many Alpha proteobacteria are common soil bacteria (such as *Agrobacterium*) and so it is not surprising to find them in the slurry.

Dissolved oxygen levels remained low during the trial, which suggests the microorganisms in the slurry were active throughout. The pH levels changed only slightly during Trial 3, suggesting the rate of degradation was low. Temperature was maintained at 25 ºC throughout the trial.

The composition of the tar was the same as reported for Trial 2, with a bias towards light-end PAHs, but with a significant concentration of benzo(a)anthracene (Appendix B, Table B4). The only phenolic compound present in detectable levels was catechol, which was present in a significant concentration of 177 mg/kg.

The chemical analysis of the material before, during and after the first trial showed a significant reduction in the concentration of total phenol (99.15 %) total PAH (71.26 %) and total petroleum hydrocarbons (94.44 %), see Figure 5.8. With the exception of anthracene the average degradation of PAH for 3-, 4- and 5-ring structures was 70.3 %, 75.57 % and 99.15 %, respectively. The degradation of the 3 and 4-ring PAHs did not significantly differ from one another. However, the results for the 5-ring structure PAH were skewed by there only being one 5-ring PAH detected (benzo(a)anthracene), the degradation of which was unusually high at 99.5 %. Whether this is significant is unclear, though it does suggest that the biodegradation achieved during this trial was better than had been expected from the results of the previous trials. The naphthalene

concentration was undetectable at the start of the trials with a low concentration measured at the end.

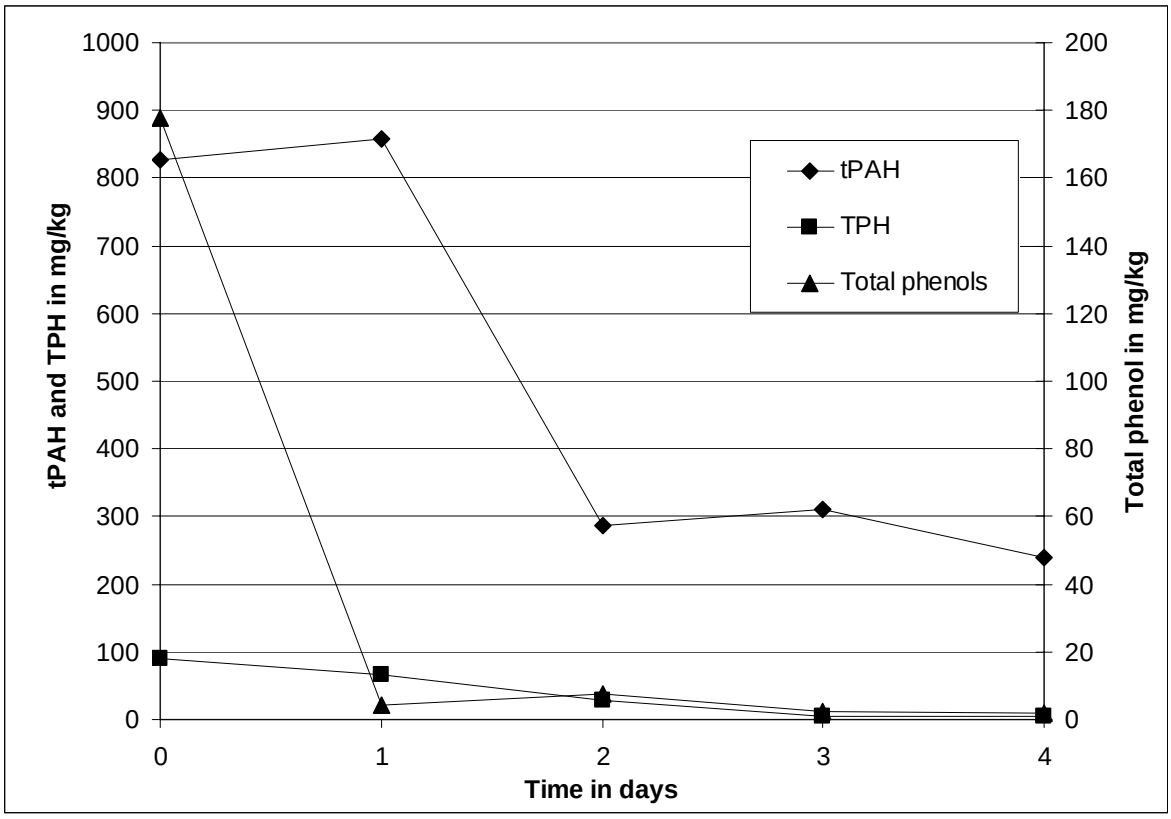


Figure 5.8: Concentrations of total polycyclic aromatic hydrocarbons (tPAH), total petroleum hydrocarbons (TPH) and total phenols in the solid phase during Trial 4.

5.5.2.5 Trial 5

The fifth trial used 350 mL of slurry from Trial 4 to act as an inoculum. Other conditions remained the same as those for Trials 3 and 4.

Dissolved phase contamination included the whole spectrum of phenolic compounds (40 mg/L) and the PAH acenaphthylene (0.24 mg/L). No detectable phenol remained by the end of the trial, the residual PAH concentration had decreased to 0.17 mg/L, see Figure 5.9.

A comparison of the most common microorganisms isolated from the start and the end of the trial are shown in Table 5.9. The dominant microorganisms in the slurry changed from a mixture of those identified as similar to *Pseudomonas marginalis* and *Pseudomonas sp*., to a mixture identified as similar to a *Sphingomonas sp., Eubacterium sp*. and an organism similar to a blackwater bacterium BW6.

As previously mentioned, *Eubacterium sp*. has been associated with the biodegradation of petroleum hydrocarbons and the biodegradation of a range of complex hydrocarbons (Morse *et al.,* 2002; Mallard *et al.,* 1994; and Rafii and Cerniglia, 1995). Eubacteria have been reported to successfully exist anaerobically, degrading hydrocarbons and reducing sulphur (Finster *et al.,* 1997). *Sphingomonas sp.*, which was identified in the product from Trial 5, is one of the most commonly isolated bacteria in the trials, having also been identified in Trials 2, 3 and 4.

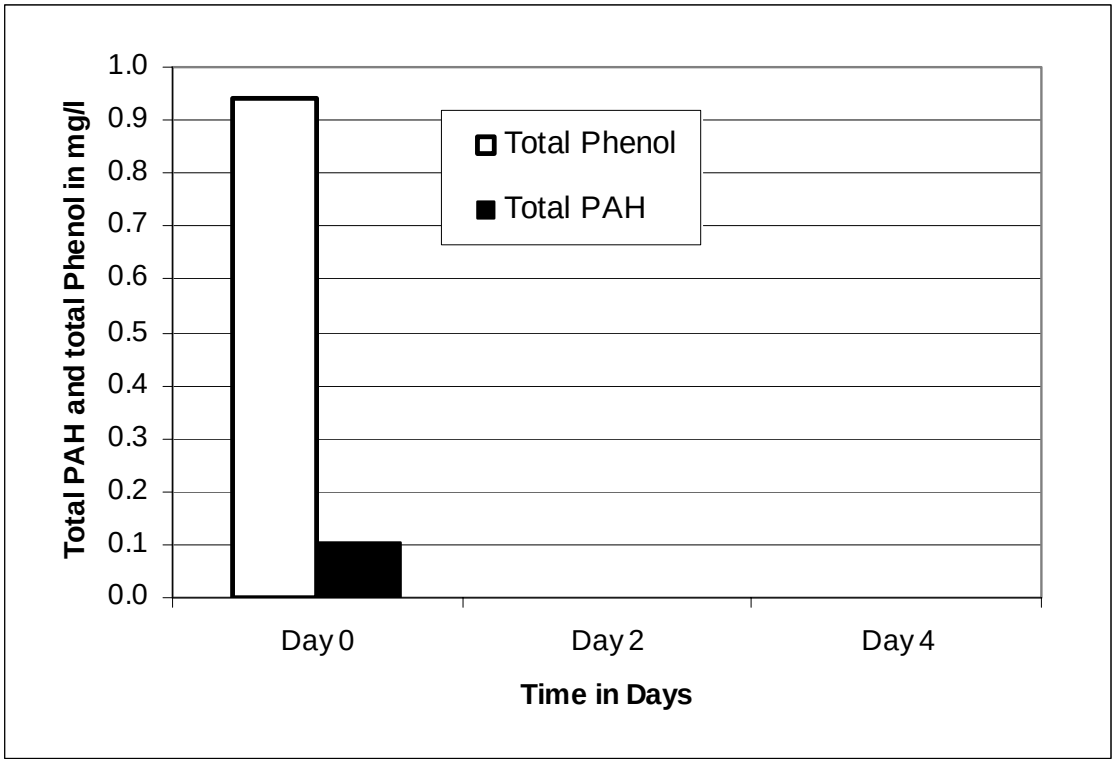


Figure 5.9: Concentration of total polycyclic aromatic hydrocarbons (tPAH) and total phenols in the aqueous medium of the slurry reactor during Trial 5

Table 5.9: Microbial composition of the slurry at the start and end of Trial 5

Species	Similarity (%)	Source of microorganism	Previous information about isolate
Pseudomonas marginalis	99	Trial 5, Start	Identification of *Pseudomonas viridiflava* and *Pseudomonas marginalis* isolates causative of carrot post harvest bacterial soft rot during refrigerated export from New Zealand
Pseudomonas marginalis	92	Trial 5, Start	Spatial distribution of total, ammonia-oxidizing, and denitrifying bacteria in biological wastewater treatment reactors for bioregenerative life support.
Pseudomonas sp.	97	Trial 5, Start	Rhizosphere microbial community of gluphosinate-tolerant and wildtype oilseed rape
Blackwater bioreactor bacterium BW6	96	Trial 5, End	Analysis of microbial activity based on 16S rDNA and 16S rRNA by denaturing gradient gel electrophoresis
Uncultured eubacterium WR8151	96	Trial 5, End	Combined Use of 16S Ribosomal DNA and 16S rRNA To Study the Bacterial Community of Polychlorinated Biphenyl-Polluted Soil
Sphingomonas sp.	95	Trial 5, End	Phylogenetic and physiological comparisons of PAH-degrading bacteria from geographically diverse soils

Dissolved oxygen levels remained low throughout the trial, which suggests the microorganisms in the slurry were active throughout (Appendix B, Figure B5).

The pH changed only slightly (Appendix B, Figure B5), which suggests the rate of degradation was similar to Trial 3 and Trial 4 but lower than Trial 1 and Trial 2. Temperature was maintained steadily at 25 ºC throughout the trial.

The consistency of the tar was similar to that reported in Trial 3 and had a bias towards light-end PAHs, but with a significant concentration of four types of 5-ring PAHs (Appendix B, Table B5). The only phenolic compound present at detectable levels was catechol, which was present at the significant concentration of 88.7 mg/kg.

Chemical analysis of the material before and after Trial 5 showed that there was a significant reduction in the concentration of total phenol (96.66 %), total PAH (53.25 %) and TPH (99.99 %, below detection limit), see Figure 5.10. With the exception of naphthalene, fluoranthene and pyrene the degradation of PAH was near or above 60 %. This was noted throughout the 3, 4 and 5-ring structure PAHs. The naphthalene concentration increased significantly by the end of the trial.

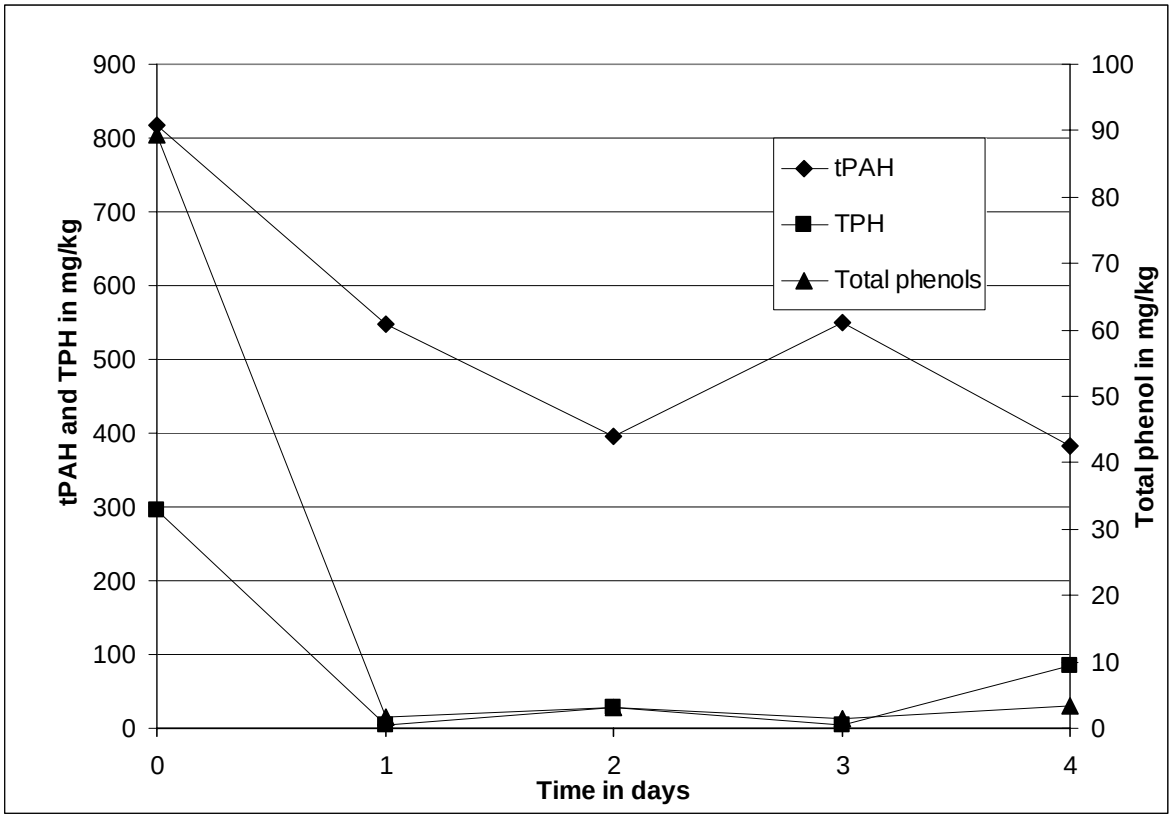


Figure 5.10: Concentrations of total polycyclic aromatic hydrocarbons (tPAH), total petroleum hydrocarbons (TPH) and total phenols in the solid phase during Trial 5

5.6 SUMMARY

Although the microorganisms *Sphingomonas sp.* and *Pseudomonas sp.* were found to predominate during the trials, the general microbial composition of the slurry was found to vary and never reached a consistent composition (see Figure 5.11).

Most of the organisms (one exception) were from the Phylum proteobacteria, these included the *alpha, beta* and *gamma* subgroups. The predominance of the proteobacteria is shown clearly in the phylogenetic tree in Figure 5.12.

The two most common genera isolated through the trials were *Sphingomonas* and *Pseudomonas*. Both of these organisms have been regularly implicated in the biodegradation of petroleum hydrocarbons, PAHs, pentachlorophenol, dioxin and dibenzofuran compounds. It is well documented that they have both been found to be important in biodegradation of xenobiotic compounds. The other organism identified was a eubacterium from the phylum Firmicutes (previously *Eubacterium sp.),* which have been associated with the biodegradation of a range of complex hydrocarbons (Morse *et al.,* 2002; Mallard *et al.,* 1994; Rafii and Cerniglia, 1995).

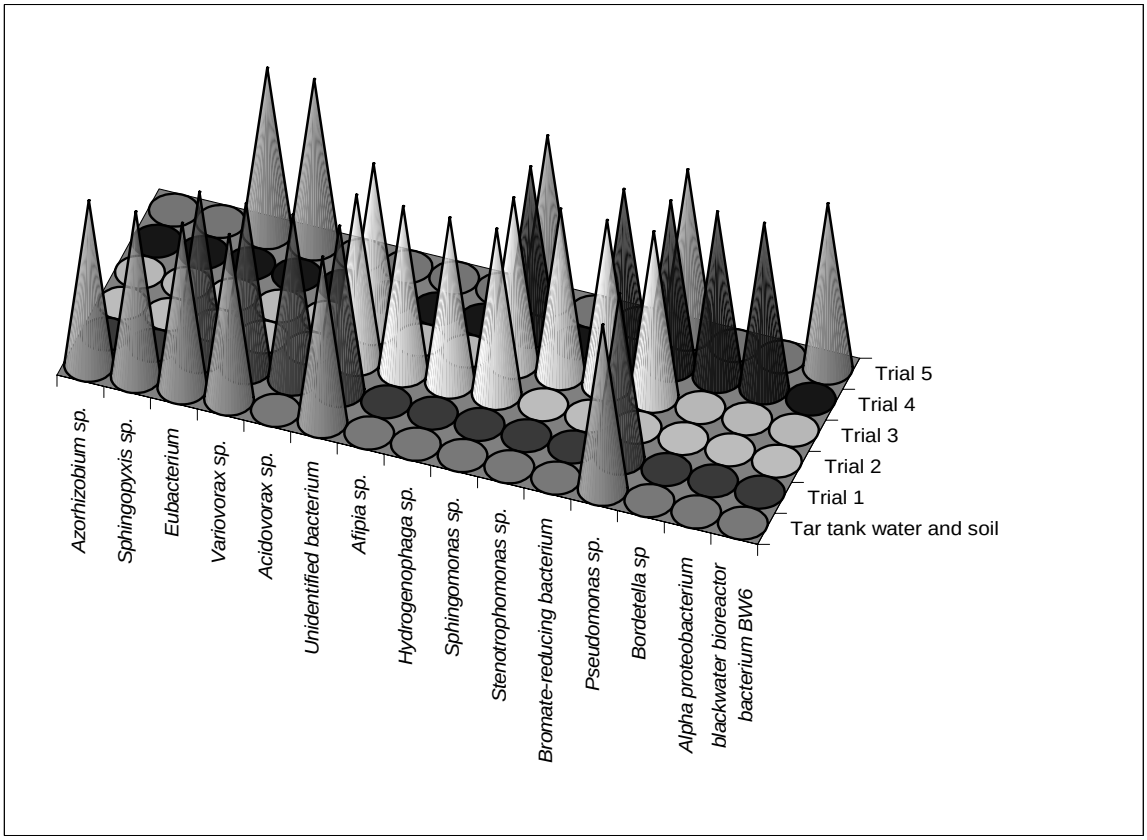


Figure 5.11: Diagrammatic representation of the changes in the microbial composition of the slurry throughout the five trials

Though some of the microorganisms identified in the biotreatability trials were unusual (e.g. bromate reducing bacteria) most of the genera identified would be expected. The reason for the unstable microbial composition through the trials is unclear, although it could to be related to the toxic nature of the material being remediated.

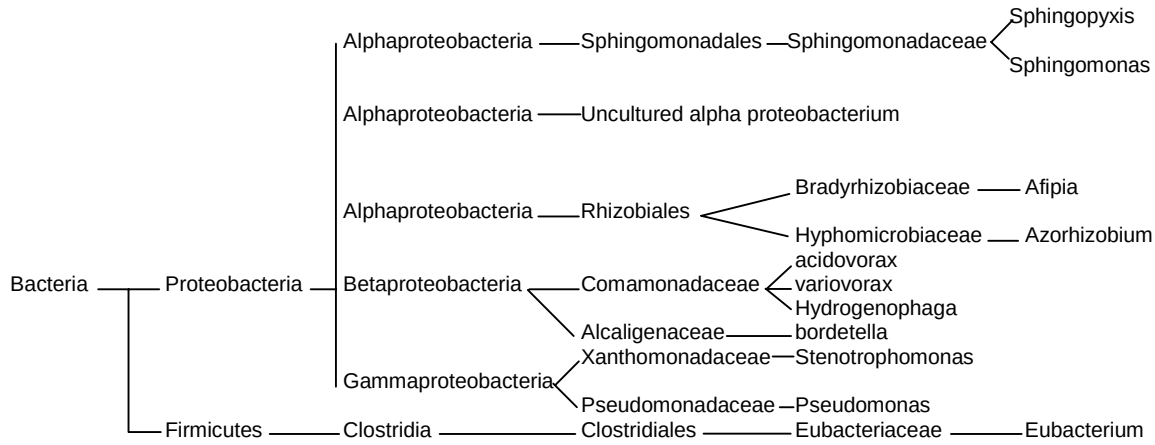


Figure 5.12: Phylogenetic tree of the most numerous organisms found during the biotreatability trials

From the samples taken, it can be assumed that the microbiology of the tar-tank material at the gasworks is predominantly proteobacteria (Figure 5.11 and Figure 5.12).

Although the composition of the tar used during the trials had a significant bias towards low molecular weight PAHs, there was a significant concentration of the 3- and 4-ring PAHs in material removed from TPs 1 and 2. The tar excavated from TP 2 was also found to contain significant quantities of 5-ring PAHs, such as benzo(a)pyrene. Historical information has shown that the tar tank contained a number of subdivided compartments, which were used for storing different tar products.

Catechol was the only phenolic compound present in the tar slurry in significant concentrations. Catechol is a breakdown product of phenol and other aromatic compounds.

The average data produced from the five trials showed a significant reduction in the concentration of total phenol (97.98 %), total PAH (60.53 %) and TPH (73.94 %). With the exception of naphthalene (which on average formed less than 1 % of the total PAH), all the other analytes were biodegraded. A similar level of degradation (around 65 %) was noted for both the 3 and 5-ring PAHs, while the biodegradation of the 4-ring PAHs was slightly less (at 53 %).

The results for PAH biodegradation are not as good as would normally be expected for biotreatability trials (expected biodegradation would be about 70 % to 75 %). It is possible that something in the material being treated was retarding the performance of the process. However, from the analytical data, there were no other analytes detected at sufficient concentration to inhibit the process (e.g. heavy metals or cyanide). Nonetheless the results of the laboratory trials still suggest that the material recovered from the tar tank at the gasworks would be potentially suitable for biodegradation using a field-scale slurry-phase bioreactor, particularly if the tar is mixed with a sandy soil.

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6. FIELD TRIAL PREPARATION

6.1 INTRODUCTION

The following sections detail the ancillary support measures that were put in place to ensure that the field trial complied with regulatory requirements, achieved the highest levels of environmental protection and presented the lowest risk to the health and safety of site workers.

6.2 SITE PREPARATION

Site preparatory works commenced on 5th August 2002, with clearing and proof-rolling of the proposed trial area. The trial area is delineated in Figure 6.1.

The trial compound is shown in Plates 6.1 and 6.2, and in Figure 6.1. It occupied an area of approximately 13.7 m by 16.7 m, within which an area of 5 m by 5 m was then excavated to 1.8 m depth. The excavation was filled with concrete of grade C20 (concrete which has a characteristic strength which can withstand 20 N/mm^2) from the base to 0.5 mbgl. The upper 0.5 m was filled with C40-grade concrete (concrete which has a characteristic strength which can withstand 40 N/mm^2) for additional strength. This area formed the base onto which the bioreactor was to stand. The remainder of the site compound was constructed using a polythene membrane over the proof-rolled ground, covered by a 150 mm thick layer of C40 concrete.

The concrete surface of the site compound drained to a central 300 mm square sump, from which accumulated water could be pumped. A dense concrete block wall 335 mm in height was formed around the area and lined with a bituminous sealant. This formed a bund capable of holding at least 1.2 times the entire contents of the bioreactor (up to 45 m^3). The general arrangement of this area is detailed on Figure 6.1.

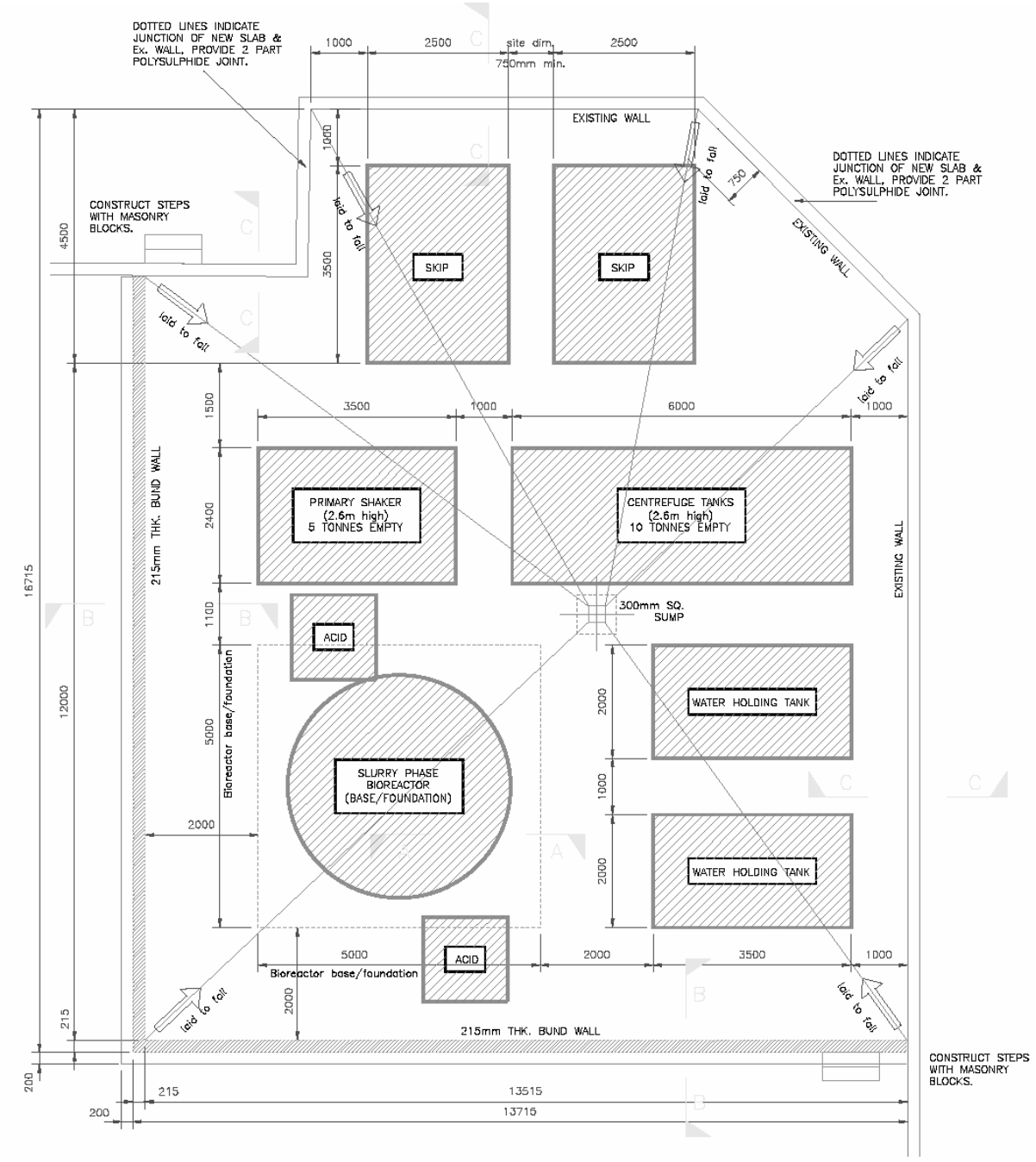
Plate 6.1: Bioreactor trial compound prior to waterproofing the concrete walls and breezeblock bund

A soil-holding pen (see Plate 6.3) was also constructed close to the trial compound, to accommodate the contaminated soil feedstock prior to treatment. The soil pen was approximately 10 m by 10 m, constructed of 150 mm C40 concrete and enclosed by a dense concrete block wall like that for the treatment compound. Heavy-gauge plastic sheeting was used to cover the soil feedstock to prevent ingress of water and consequently production of leachate.

The preparatory works took approximately one week to complete.

Plate 6.2: Bioreactor trial compound complete

Plate 6.3: Completed soil-holding pen with soil feedstock in place and security fencing



Source: Parsons Brinckerhoff (2001)

Figure 6.1: Layout and design of the slurry-phase bioreactor treatment area, showing the location of each component.

6.3 DESCRIPTION OF THE BIOREACTOR

The bioreactor vessel, constructed of mild steel plate had a maximum diameter of 3 m and a height of 7 m and was supported by a steel cradle with access platforms and ladders. It had a maximum capacity of 45 m^3 or 45,000 litres (water), but had been designed to operate with a maximum weight load of 40 tonnes. The load was assumed to be composed of approximately 10 tonnes to 15 tonnes of soil, with the remainder being water to form slurry. A maximum soil to water ratio of 2:3 was used, since above this ratio the mixing becomes too energy intensive. Soil was loaded into the reactor via a hatch on the top. This was designed to be accessed using either a conveyor system or, as for the case of these trials, a telehandler, which is a type of forklift truck with a telescopic long reach arm. Plates 6.4 and 6.5 show the bioreactor frame and the bioreactor being lifted into place.

Plate 6.4: Bioreactor frame in position in the bioreactor compound

Plate 6.5: Lifting the vessel of the bioreactor into the frame

The vessel was operated at atmospheric pressure and the contents were heated both by hot compressed air supplied via 12 air sparging nozzles, and by trace heating attached to the external surface of the reactor vessel cone and insulated with lagging (Plate 6.6). The hot air and trace heating were fitted on the cone shaped base of the reactor (Plates 6.6 - 6.10). The air compressor used was rated at 4 kW and supplied 120 cubic feet per minute (CFM). The air heater was rated at 6 kW. Water entering the vessel could also be heated by passing it through the heater (Plate 6.6) mounted on one of the support legs of the reactor.

Plate 6.6: Installation of lagging over the trace heating system

Recirculation of the vessel contents was achieved by piping slurry from the upper part of the vessel to the base of the cones, where it was pumped back by the slurry pump (Plate 6.7 and 6.8). The electric pump was set to circulate the entire volume once an hour.

Three peristaltic pumps were used to add hydrochloric acid (36 % concentration), sodium hydroxide (50 %), and silicone anti-foam solution. The operation of these pumps was controlled by the telemetry system, discussed in detail in Section 6.5.

To facilitate weighing of the reactor contents, the vessel had load cells attached to its four legs. These were linked to a control panel that displayed the reading.

Monitoring of the process was carried out via a series of probes inserted through the sides and top of the vessel. Three probes measuring temperature were inserted through the vessel sides and a single probe measuring dissolved oxygen was inserted through the top of the reactor. Two pH probes and a foam detection probe were also inserted through the top of the reactor. Each instrument was attached to the field point system linked to the remote telemetry. The vessel contents were sampled using a port located on the side of the reactor.

Any off-gases generated by the system passed out of the top of the vessel via a length of pipe into a drum of activated carbon, where the hydrocarbons were adsorbed. The activated carbon was sampled after each trial to deduce the amount of contamination that was removed in the off-gas so that it could be factored into the mass balance. The loading hatch at the top of the vessel was kept shut during the trials to prevent any fugitive emissions.

Plate 6.7: Base of bioreactor with recirculation pump and recirculation pipes in place

Plate 6.8: Base of bioreactor with recirculation pump and recirculation pipes in place

Emptying of the reactor was achieved by opening the valves at the base of the reactor with the pump on, and allowing the slurry to discharge. As the material was a slurry, it needed to be dewatered to enable the separation of solid and water phases. To achieve the separation a combined shaker (to remove coarse material) and a centrifuge (to remove fine material) were used.

6.4 PLANT MOBILISATION AND CONSTRUCTION

The main parts of the bioreactor arrived on site between the 14th and 16th August 2002. The supporting frame was bolted in place over the strengthened section of the slab. The reactor was then craned into place and secured. Access platforms and ladders were attached using a crane and a cherry picker and a secure fence was fitted around the top of the bioreactor to prevent falls.

Once the main structure had been erected, the cone section at the base of the reactor was lagged by subcontractors of VHE Shepley Engineering, and covered by an aluminium shield. Air hoses were fitted on the shield, attached to a sparge ring and fed via temperature-resistant hosing from a compressor and air heater. A large generator was used to provide the electrical supply.

The monitoring probes were then installed and wired to the field points and to an electrical supply. Security lighting was fitted. Two large water-holding tanks were positioned at the rear of the bioreactor to hold the treatment water between treatments. A combined centrifuge/shaker was positioned by crane close to the reactor, and connective hosing fitted between the discharge outlet of the reactor and the inlet of the centrifuge/shaker. The mechanical preparation of the reactor was complete at the end of August, having taken approximately 3 weeks.

Plate 6.9: Base of bioreactor, construction completed

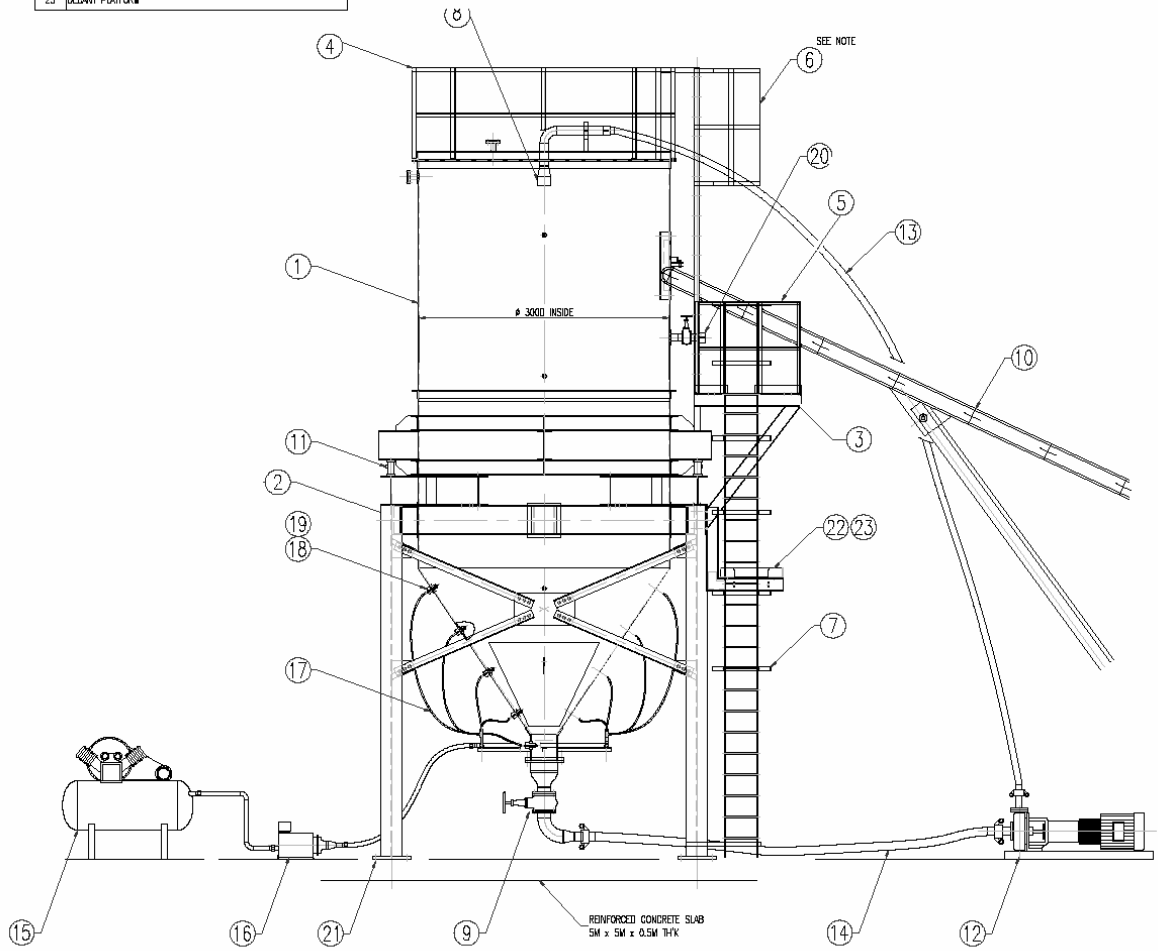
Plate 6.10: Air inlet hose attached to air inlet. Air inlets were positioned around the cone at the base of the bioreactor

6.5 TELEMETRY DESIGN AND INSTALLATION

During the previous trial in northern England, the bioreactor had to be supervised on a 24-hour basis, with all nutrients and chemicals being administered manually. After that trial, it was decided that a remote telemetry system would be a significant improvement, and would reduce labour requirements. VHE Shepley Engineering Ltd subcontracted Bytronics (a specialist programming company affiliated with National Instruments) to produce such a system (Plate 6.11). Bytronics attended a meeting with PB during which the specification and requirements of the system were defined.

Plate 6.11: Main control panel and electrical connections (including telemetry field bus)

ITEM	DESCRIPTION
1	45T SLUDGE VESSEL ARRGT & DETAILS
2	VESSEL FRAMEWORK ARRGT & DETAILS
3	SLUDGE VESSEL PLATFORM ARRGT & DETAILS
4	SLUDGE VESSEL HANDRAILS ARRGT & DETAILS
5	SLUDGE VESSEL HANDRAILS ARRGT & DETAILS
6	SLUDGE VESSEL LADDERS ARRGT & DETAILS - TOP
7	SLUDGE VESSEL LADDERS ARRGT & DETAILS - BOTTOM
8	DISCHARGE HEAD
9	RECIRCULATION LINE VALVE ASSY
10	CONVEYOR
11	LOAD CELL
12	"DISCFLO" PUMP
13	PUMP DISCHARGE HOSE ASSY - 3"
14	PUMP INLET HOSE ASSY - 4"
15	COMPRESSOR
16	IN LINE AIR HEATER
17	AIR DELIVERY HOSE ASSY
18	AIR INJECTION NOZZLE ASSY
19	AIR NOZZLE VALVE
20	DECANTING VALVE ASSY 2"
21	HILTI HSL M24 HEAVY DUTY ANCHOR
22	DECANT PLATFORM LADDER
23	DECANT PLATFORM



Source: VHE Shepley (2002)

Figure 6.2: Design of slurry-phase bioreactor.

The design, programming and installation of the system ran concurrently with the mechanical installation of the bioreactor. Programming commenced on 20th August 2002 and installation was complete by 4th September 2002. Some delays were encountered due to difficulties in having a telephone line installed at the site, which in turn delayed testing of the system.

The telemetry system monitored pH values by averaging data from the two pH probes inserted in the vessel top. If acid or alkali were required, their injection was automatic, via dosing pumps. If foam was created on the slurry surface, a sensor was activated which triggered injection of anti-foam solution. The system had wait timers, which allowed the vessel to circulate the added chemical for a set period before taking another reading to assess the need for further antifoaming agent. Foam forms as a result of extracellular polysaccharide (EPS) production by certain bacteria in the slurry. The telemetry also monitored dissolved oxygen. All of these factors were recorded in real time as a continuous data stream, and presented on a touch-screen monitor. A continuous graphical database of information was recorded, for access at any time. A historical record could also be interrogated, to check the performance of the system when staff were not in attendance.

A series of high-low limits were programmed into the system. If the system went outside those limits, an alarm system was triggered that sent a text message to a mobile phone or landline. The limits were selected to ensure that the system was kept at between pH 6 and pH 8.5, temperatures of between 20 °C and 32 °C, with negligible foam accumulation. If the system malfunctioned, the supervising engineer would then attend, day or night, seven days a week

The detailed instruction manual for the telemetry system has not been included in this report, but is available in the operations manual for the bioreactor. A selection of diagrams showing the touch screen interface, the limit settings and some examples of the graphical database are included in Appendix C, which also includes a transcript and analysis of the results database.

6.6 EXCAVATION AND PREPARATION OF FEEDSTOCK MATERIAL

The tar tank described in Section 4 was the first area of the site to be excavated. The contents of the tank were systematically removed, working in a direction from west to east. In the majority of the tank, the material was found to be demolition waste including a high proportion of bricks, concrete and gravel, together with tarry silt rather than concentrated tar (Plate 6.12). At the eastern end, the tar in the last compartment of the tank was more concentrated and viscous (Plate 6.13). Due to the high proportion of bricks and stones in the tank, the material required screening. However, it was not possible to use standard soil screening equipment (trommel).

Due to the high volume of tar, Nuttalls constructed an improvised screener using a series of grids of reinforcing bars placed over a dumper truck such that the tar passed through the screen and the coarser material was collected and removed. This method was relatively successful, although some coarser material did pass through. It was also slow and labour intensive, but there was no alternative plant specifically designed to easily screen tar or similar materials. The screened tar was placed in the soil-holding pen.

Contaminated sandy soil from excavations in other areas of the site was stockpiled and screened, using the large screener employed for the full remediation works. This material had been identified as contaminated from the previous ground investigation, but had no visible oily contamination (Plate 6.14). This material was then also transferred to the soil-holding pen.

As there was no weighbridge on site, the quantities of materials were estimated as closely as possible according to the capacity of the haulage plant. Checks were also made later using the load cells of the bioreactor.

Plate 6.12: View into one of the excavations

Plate 6.13: Coal tar recovered from the tar tanks for use in the bioreactor trial

Plate 6.14: The contaminated made ground to be mixed with coal tar

Plate 6.15: JCB mixing the coal tar recovered from the tar tanks with soil from the site. Tar to soil ratio was approximately 1:3

The tar and sandy soil were mixed evenly by a JCB™ 3CX Sitemaster in a ratio of approximately 1:3 to achieve a total of approximately 48 tonnes (Plate 6.15). Mixing the tar to achieve a homogeneous mix with the soil was difficult, as the tar tended to become surface-coated with sand, and did not blend easily.

The mixed material was covered with heavy-gauge plastic sheeting to prevent ingress of rainwater.

The chemical test results for these materials are summarised in Table 4.1 and are presented in full in Appendix B, and discussed in Sections 7 to 9.

6.7 PREPARATION OF INOCULUM AND TREATMENT WATER

Contaminated oily water (5 m^3) from the tar tank that was being excavated was pumped to a 15 m^3 water holding tank near the bioreactor. Samples of this oily water were used as the inoculum for the bioreactor trial. A 30 m^3 tank was filled with clean water from the mains and this water made up the remainder of the treatment water.

7. FIELD TRIALS OPERATION

7.1 INTRODUCTION

The field assessment was originally designed to consist of five separate trials. The intent of this was to demonstrate that the results achieved could be replicated. Due to technical difficulties that led to delays in the programme, it was decided to scale down the operation to four trials. However, equipment failure at the beginning of the fourth trial meant that it was not completed.

7.2 GENERAL PROCESS FLOW

The main stages in the operation of the bioreactor are shown in Table 7.1 and the individual trials are discussed in detail in Sections 7.3 to 7.5. A detailed analysis of the data from the telemetry system for the trials is included in Appendix C, which should be read in conjunction with this chapter.

Table 7.1: Process flow table for operating the slurry-phase bioreactor

Stage	Activity
Stage 1	The first step in the operation of the reactor was to pump the oily inoculum obtained from the tar tank, and clean water from holding tanks into the reactor. The water was pumped in via a water heater, in order to raise the temperature of the water to a level sufficient for the bacteria to reproduce effectively. The optimum water temperature is approximately 25 °C. The amount of clean water used could vary, and was calculated based on the amount and density of soil to be used. Approximately 5 m^3 of inoculum was required.
Stage 2	The telemetry system was turned on to monitor the pH, temperature and dissolved oxygen levels in the reactor.
Stage 3	When the volume of water in the vessel was sufficiently high, the recirculation pump and the compressed air supply were switched on. This begins the process of mixing and aeration and provides the optimum conditions for microbiological growth. Approximately 3 to 4 days were allowed for the fluid to incubate.
Stage 4	The soil feedstock was then loaded. The soil to water ratio must not exceed 2:3 in order for the material to be mixed effectively as a slurry. The weight of soil feedstock required to achieve capacity (40 tonnes) depended on the soil density. The soil was loaded through the loading hatch at the top of the reactor using a telehandler, which is a type of fork-lift truck with a telescopic reaching arm. A bucket was attached at the end of the arm.
Stage 5	The trial was then run for a pre-determined period, after which samples were taken. The first batch was run for longer than subsequent ones, for which the run times were reduced, based on the data obtained from the first trial.
Stage 6	At the end of the trial, the material was discharged in batches via flexible hosing to the centrifuge/shaker for dewatering. The pump was left on during this process (initially the constructors of the reactor had advised that the pump should be turned off, however the pump was left on for Trials 2 and 3 after difficulties encountered in Trial 1). Two discharge streams emanated from this plant, a coarse (>5 mm) stream and a fines stream. The treatment water was recirculated into the bioreactor for the next trial. At the end of the process, the water was discharged to sewer after pre-treatment. At this site, it was passed through the water treatment centre for the main remediation works.
Stage 7	If the chemical and geotechnical testing carried out indicated that the material was suitable for reuse, the coarse and fine discharge streams were mixed back together to reconstitute a well-graded soil.

7.3 TRIAL 1

Prior to the start of Trial 1, the inoculum was prepared over a four-day period (1st to 4th September 2002). Five tonnes of the oily inoculum from the tar tank and 22.9 tonnes of mains water were pumped into the reactor and heated (total weight approximately 28 tonnes). Approximately 13 kg of nutrients (10:10:40 NPK agricultural fertilizer) was added to assist biological growth. The inoculum was dosed with 100 mL of antifoam on all 4 days of the inoculum culturing period. The temperature of the liquid was approximately 27 °C during this period.

Trial 1 commenced on 5th September 2002. The trial ran for 10.5 days with unloading starting on the morning of Monday 16th September. This trial duration was chosen based on the results of the laboratory work.

The feedstock loading sequence took almost a day. A telehandler loaded 10.4 tonnes of soil feedstock into the bioreactor. This volume of feedstock required 24 loads, which equates to an average load size of 400 kg. The soil:water mix in the bioreactor was therefore approximately 36 %. The recirculation pump and the compressed air were both on during the loading sequence to keep the material circulating. When the loading was complete, four 25 kg bags of nutrients were added.

The temperature in the bioreactor remained fairly stable throughout Trial 1 with average water temperature ranging from 24 ºC to 27 ºC. Temperatures recorded by probe 1, located approximately 1.5 m from the top of the bioreactor, fluctuated the greatest. Temperatures recorded by probe 3, located in the cone at the base of the bioreactor, were the most stable, and were also the lowest of the three probes (probably due to being insulated by solid tarry material).

During day 1 of the trial average pH levels were above the maximum allowable pH of 8.5 whilst the dosing pumps were being commissioned. The reason for the high pH at this time is not clear, however, the fertilizer used would contain some alkaline components such as ammonia. With no pH control available then this would have increased the pH within the reactor. The pH recorded by probe 1 was above 8.5 throughout day 1 and reached a peak of 10.5. The pH levels recorded by probe 2 were in the acceptable range throughout day 1. Towards the end of day 1 the pH levels recorded by both probes suddenly dropped and after a short period of fluctuation stabilised. From day 2 to the end of Trial 1, pH levels remained stable, averaging from 7.1 to 7.8.

Dissolved oxygen (DO) levels dropped significantly over the first 2 days of the trial, to less than 10 %, indicating that biological activity was occurring. This first oxygen trough would have been related to the degradation of the more soluble PAH such as naphthalene and dissolved phase contamination; this has been observed previously in laboratory scale slurry-phase trials. The levels rose to just less than 80 % during days 3 to 7, before falling again to between 24 % and 27 % on day eight. This second trough may represent a further phase of intense microbial activity, relating to some of the less soluble PAH such as pyrene and fluoranthene. From day 9 to the end of the trial DO levels steadily increased again, reaching approximately 86 %.

Antifoam was not required during Trial 1 as there was no significant production of foam. No acid or alkali was required through the telemetry-controlled dosing system, as the pH levels remained stable and within acceptable limits.

The trace heating and hot compressed air was not required until nearly the end of the first trial (12th September 2002) as the vessel temperature remained in acceptable limits. The trace heating was controlled by the thermostat throughout the trial.

The weather conditions during the first trial were relatively good, so very little additional heat was required. The air temperature during the trial was a maximum of 28.1 °C, and a minimum of 12.3 °C. Atmospheric pressure dropped throughout the trial from 1023 mbars to 1002 mbars. No rain fell during the trial. The maximum wind speed was 8.0 m/sec.

Samples of feedstock, slurry and product were taken before, during and on completion of Trial 1. The slurry samples taken from the reactor were found to contain a lot of fine material, and the water had to be decanted off after centrifuging. This process was very time consuming. Table 7.2 summarises samples taken during Trial 1.

Table 7.2: Samples taken during Trial 1

Sample Description	Number of Samples Taken	Comments
Feedstock	6	Samples taken from the soil feedstock compound.
Feedstock	1	Composite of the 6 feedstock samples was prepared and sent for microbiological analysis.
Inoculum and water	1	Sample taken from the bioreactor prior to loading the soil feedstock.
Slurry (chemical testing)	7	Samples of slurry were taken from the bioreactor on days 1, 4, 5, 6, 7, 8, and 11. The samples were centrifuged to produce separate soil and water samples for chemical analysis.
Slurry (microbiological testing)	7	Samples of slurry were taken from the bioreactor on days 1, 4, 5, 6, 7, 8 and 11 for microbiological testing
Product	12	Of the 12 samples of product taken: Four were centrifuged fines; Eight were samples of 'mixed' product which had not passed through the centrifuge.
Geotechnical	8	Samples from the mixed product stockpile were taken by dividing the stockpile into eight areas and sampling each area.

Unloading of Trial 1 commenced on the morning of the 16th September 2002; the reactor was sampled for the last time and the telemetry system shut down. The compressed air and the pump were turned off, as this was the procedure that the constructors of the reactor had advised. The recirculation valves were closed and the bottom valves opened for the bioreactor to discharge to the centrifuge under gravity. A small volume of liquid initially discharged from the bioreactor, but that flow then stopped. The pump was restarted, but the recirculation pipes/system and flexible hosing had totally blocked. In order to empty the bioreactor the following steps had to be taken:

- An additional pump was brought to site. This allowed slurry to be pumped out of the top of the bioreactor and into the centrifuge, but the process was difficult as the hose had to be inserted into the vessel contents and constantly agitated; during this period it was noted that the centrifuge was only treating material in batches, as its dewatering rate was slower than the rate at which liquid could be pumped from the reactor. It was originally considered that the valves on the bioreactor could be opened/closed incrementally in order to get a balance between the bioreactor discharge rate and the centrifuge dewatering time. However, any reduction in valve aperture led to the material falling from suspension and blocking the pipes.

- If the centrifuge was filled and operated too quickly it could not dewater effectively and the material was too wet. The centrifuge tank also filled up very quickly and was likely to overflow. Operating in this manner meant that the solids remaining in the pipes settled out once a batch of material had been transferred to the centrifuge, so blocking the pipes. A significant amount of time was spent unblocking the pipes and progress was slow. In addition, the majority of the material pumped out of the bioreactor was water and fines and very little coarse material was seen.

- The majority of the water (and fine sediment) had been removed from the bioreactor by approximately 5 days after Trial 1 ended. On day 6 of this shutdown period the valve at the base of the bioreactor, and the small section above it, were removed. The base of the cone on the bioreactor was completely blocked with gravels and some cobbles and brick fragments.

- Seven days after Trial 1 had ended, the last of the product was removed from the bioreactor. This was achieved by washing the coarse solids in the bioreactor out into the loading skip, which was positioned directly under the bioreactor. Water was washed through the bioreactor until the skip was full of solids, and the wash-water was then pumped back into the bioreactor.

During unloading of the bioreactor, it was noted that there were some untreated/semi-treated lumps of coal tar in the product. Despite the efforts made to screen the tar from the tar tank, a number of cobbles and gravels were found in the soil feedstock. These materials were difficult to identify when the material was first mixed, due to the coating of tar on the feedstock. It is possible that this oversize material was too heavy for the pump to circulate, and it sank to the base of the bioreactor, partially blocking the inlet. This partial blockage may have slowed the flow leading to further deposition of solids. Thus it is possible that only the water and fine soil fractions were re-circulating throughout the majority of Trial 1.

Despite the difficulties in material handling during Trial 1, many lessons were learned, particularly with respect to the optimum operating conditions for the centrifuge. The telemetry system was given its first 'live' test and performed well.

The main disappointment of this trial was the fact that the slurry samples taken would not settle out as quickly as had been hoped, and had to be centrifuged on site before despatch to the laboratory. This resulted in an increased labour input. In addition, the delays caused by the difficulties in emptying the bioreactor had a significant impact on the forward programme for the works.

7.4 TRIAL 2

Trial 2 commenced on the 27th September 2002. The trial ran for 7 full days with unloading commencing on the 3rd October 2002.

Loading of the water took approximately half a day and the loading of the soil feedstock approximately a day. Loading commenced on the 26th September with 26.8 tonnes of water, 12.5 kg of nutrients and 2.6 tonnes of soil feedstock being placed in the bioreactor. In an attempt to speed up the loading process it was decided to load the water and soil feedstock simultaneously for this trial. This also meant that clean water could also be drawn from the mains at the same time to refill the water holding tanks.

The water was not heated during loading, as the trace heating was sufficient to warm the water to within the allowable temperature range. Due to the problems encountered during Trial 1 as a result of some oversize material being inadvertently loaded into the bioreactor, the feedstock was re-screened prior to loading. This re-screening was achieved by placing a metal grid/mesh over the top of the feedstock loading skip and physically raking and pushing the feedstock through. In addition to removing the oversize particles (>40 mm diameter) from the feedstock, this screening process also ensured that lumps of tar were broken down to a more treatable size. This process was quite time consuming, as it had to be done by hand.

The remaining soil feedstock was loaded into the bioreactor on 27th September 2002 and the trial started when a further 150 kg of nutrients were added. Soil feedstock (7.05 tonnes) was transferred to the bioreactor in a series of 24 loads using the telehandler, which equated to an average load size of approximately 295 kg. The ratio of soil to water in the bioreactor was approximately 1:4.

After eight loads of feedstock had been placed into the bioreactor, the pump stopped working. It was re-started, but it became apparent that the recirculation pipes were blocked as the pipes started heating up significantly. By breaking off and cleaning out the pipe attached to the outlet of the pump (which was half full of solids), opening and shutting the valves and turning off the air, the bioreactor began circulating material again.

Throughout Trial 2 only two of the three temperature probes in the bioreactor were working (probes 1 and 2). No definitive comments can therefore be made on the temperatures in the cone area (base) of the bioreactor, which would have been recorded by probe 3. Temperatures recorded by probes 1 and 2 were very stable throughout the trial. Probe 1 (located towards the top of the bioreactor), showed a slightly higher degree of fluctuation than probe 2. This may be because

probe 1 was nearer the surface of the slurry and therefore near the air space at the top of the reactor. Average temperatures recorded by probe 2 (located approximately half way up the bioreactor) were generally 4 ºC to 5 ºC higher than those recorded by probe 1. Temperatures recorded by probe 1 during Trial 2 ranged from 22 ºC to 28 ºC. Temperatures recorded by probe 2 during the trial ranged from 25 ºC to 33 ºC. The optimum temperature range for the process was between 25 ºC and 30 ºC, deviation from the optimum range to either 22 ºC or 33 ºC would have reduced the performance, though it would have not have significantly inhibited growth or caused the microorganisms to die.

The pH levels were generally stable throughout Trial 2, with the average pH ranging from 7.0 to 7.3 from day 1 to day 6. Approximately half way through day 6 a period of fluctuation occurred, resulting in an average increase in pH of 0.5. The pH levels gradually increased during the remainder of day 6 and throughout day 7, with an average pH level of 8.28 recorded just prior to ending the trial. The reason that the slurry became more alkaline was due to the addition of fertilizer. As the fertilizer was utilised as a nutrient source and the tar acid compounds were degraded (e.g. phenol) this would have led to a general reduction in the acid compounds in the slurry and a gradual increase in the pH.

Dissolved oxygen (DO) levels were variable, with some distinct peaks and troughs from day 1 to half way through day 2 of the trial. DO levels then started to steadily decrease, reaching a low of 5.5 % approximately half way through day 3 and remaining stable at 5.5 % until the last few hours of day 4. By the end of day 4, DO levels had risen to 21.5 % and levels continued to rise steadily throughout day 5 and the majority of day 6, peaking in the low 60 % range. From late in day 6 DO levels steadily decreased, reaching minimum levels in the low 20 % range. DO levels continued to fall until early on the final day of the trial when they started to increase steadily again. DO levels were in the range 40 % to 50 % when Trial 2 was ended.

The pattern of DO levels described above suggests that the most intense biological activity took place between days 2 and 4 of the trial, when pH levels were low and falling, with a second peak of activity during day 6 of the trial when DO levels dropped again. This first increase in biological activity would be related to the biodegradation of the soluble low molecular weight aromatic hydrocarbons, such a phenols, BTEX and 2- to 4-ring PAHs. The second period of biological activity would relate to the biodegradation of the high molecular weight PAHs, with more than five rings in their structure, e.g. benzo(a)pyrene.

During Trial 2 the pH of the reactor contents remained stable and in the allowable range, so no acid or alkali addition was required. On days 4/5 it was found that the acid pump was no longer working, so it was replaced. In addition, the acid barrel had started expanding due to a pressure build up from the HCl decomposition during storage. The cap was opened and the pressure released under controlled conditions.

Frequent doses of antifoam had to be administered to the bioreactor during Trial 2. A significant amount of foam was produced during the night of the 25th/26th September 2002 (prior to the bioreactor being fully loaded). During this period, the foam probe alarm was almost constantly triggered. Foam spilled out of the top of the bioreactor on this night and on a number of occasions on day 1 and day 2 of the trial. On the occasions when foam spilled over, antifoam was administered to the bioreactor via the computer system until foam production was controlled. The auto dose was increased on day 2 of the trial and this kept the foam production under control. However, a thickness of approximately 1 m of foam remained on top of the slurry in the bioreactor.

During this trial, the telemetry system occasionally sent error messages. It was discovered that the generator had stalled on these occasions, causing the telemetry computer to shut down and reboot itself. The generator was serviced and no specific problem was found. The computer was protected by a ‘surge protection’ braker, but occasional interruptions to electrical supply continued to occur.

The trace heating was required during Trial 2, according to its thermostatic control. The weather conditions during the trial were slightly colder than Trial 1, with maximum air temperature of 22.8 °C, and a minimum of 14.8 °C. Heavy rainfall occurred on one night only, where 7 mm was recorded. Atmospheric pressure ranged from 1015 mbars to 1023 mbars. The maximum wind speed was 7.6 m/sec.

Samples of feedstock, slurry and product were taken before, during and on completion of the trial. Table 7.3 summarises samples taken during Trial 2.

Table 7.3: Samples taken during Trial 2

Sample Description	Number of Samples Taken	Comments
Feedstock	6	Samples taken prior to re-screening.
Feedstock	1	A composite of the 6 feedstock samples prepared and sent for microbiological analysis.
Water	3	Samples taken from the bioreactor prior to loading the soil feedstock.
Feedstock (re-screened)	3	Samples taken from the feedstock loading skip once re-screening had taken place.
Feedstock (re-screened)	1	A composite of the 3 re-screened feedstock samples prepared and sent for microbiological analysis.
Slurry	4	Samples of slurry taken from the bioreactor on days 1, 4, 6 and 7 of Trial 2. The samples were centrifuged to produce separate soil and water samples. The water sample attained from the slurry sample taken on day 7 was used as the final water sample.
Slurry (microbiological testing)	4	Samples of slurry were taken from the bioreactor on days 1, 4, 6 and 7 for microbiological testing.
Product	14	Of the 14 samples of product taken:
		Four were centrifuged fines;
		Two were samples of the coarse material removed by the primary shaker;
		Eight were samples of 'mixed' product which had not passed through the centrifuge.
Geotechnical	8	Samples from the mixed product stockpile were taken by dividing the stockpile into eight areas and sampling each area.

Unloading of Trial 2 commenced on the 3rd October 2002. During the discharge process the recirculation pump was kept running, the recirculation valves kept open and the compressed air on.

On the 3rd October 2002, 3 batches of product were discharged to the centrifuge. Unloading was slow as it took the centrifuge approximately 1.5 hours to process each batch of product, although it was noted that the larger particles of soil feedstock were not being discharged. Attempts were made to slow the flow of material from the reactor by restricting the opening of the valve at the base of the bioreactor, in order to allow the centrifuge to cope with the material. When the valve was fully opened it sounded as if a significantly more coarse material was being discharged from the bioreactor, which suggested that coarse material might later start backing up in the bioreactor discharge and recirculation pipes. Approximately 19 tonnes to 20 tonnes of slurry were discharged from the bioreactor on that day.

Overnight the remaining approximately 14 tonnes of material were circulated in the bioreactor. On the 4th October approximately 6 tonnes to 7 tonnes of product were discharged into the centrifuge before the system started to block up. A description of the discharge process on the 4th October 2002 is as follows:

- Six tonnes to seven tonnes of material was discharged from the bioreactor into the centrifuge. The material was much coarser than that discharged on the previous day;

- The pipe connecting the bioreactor and the centrifuge and the pipe between the base of the reactor and the release valve became blocked;

- The pipes were unblocked;

- More material was discharged to the centrifuge. Pipes and the entry point into the centrifuge were blocked again almost immediately;

- The pipes were unblocked again;

- The remaining solid material in the bioreactor had to be discharged onto the floor of the bioreactor compound, as it could not be discharged from the reactor any other way. The sampling port located at the bottom of the bioreactor was used to remove the final material from the bioreactor. Some water from the holding tanks was added to the bioreactor during the emptying process to ensure that the material remained fluid;

- The product was removed from the floor of the bioreactor compound and the water, which had separated, was pumped back into the holding tanks.

Where material had been successfully passed through the centrifuge, it was still found to be relatively wet. Several alterations to the speed of the centrifuge did not reduce the water content any further.

During this trial it was noticed that the load cells that weigh the contents of the reactor were reading erratically. We were informed that an electrical surge from the generator was the probable cause of their failure and that they would need full factory recalibration. It was not possible to remove them from the frame with the reactor in place. Subsequent weights were calculated using the reactor design drawings and estimated slurry density.

In summary, the problems encountered during Trial 2 were again associated with material handling on loading and unloading. However, during the active period of the trial, the material circulated much more effectively than in Trial 1, with no blockages occurring until discharge commenced. The discharged materials appeared cleaner than in Trial 1.

7.5 TRIAL 3

Trial 3 commenced on the 11th October 2002. The trial ran for 5.75 days, with unloading commencing on the 17th October 2002.

On October 7th, 25 tonnes of water was loaded into the bioreactor. The water was not heated as it was loaded into the bioreactor, as the trace heating was sufficient to warm the water to the allowable temperature range. The water was circulated through the pump and the air was turned on.

Loading of the soil feedstock for Trial 3 did not take place until the 11th October 2002, due to a number of problems:

- The recirculation pump was leaking and had to be repaired;

- In order to try and improve the recirculation of heavier solids in the bioreactor a new pulley was fitted to the pump, as recommended by the manufacturer. The pulley should have allowed the pump to run faster. Unfortunately the new pulley drew too much electrical current from the pump and caused it to fail. The recommendation was that a bigger motor was required which was not feasible for the purposes of this trial. The original pulley had to be put back in place.

The soil feedstock (7.6 tonnes of soil) was re-screened as described in Trial 2 and placed into the bioreactor using a telehandler in 27 loads (average load size of approximately 280 kg) on

October 11th 2002, the trial started when 137 kg of nutrients were added. The soil:water ratio in the bioreactor was approximately 1:3.

Temperatures in the bioreactor were fairly stable throughout Trial 3, the average ranging from 27 ºC to 31 ºC during the trial. The temperature in the bioreactor appeared to increase from top to bottom, with probe 3 (located in the cone at the base of the bioreactor) recording the highest temperatures and probe 1 (located approximately 1.5m from the top of the bioreactor), recording the lowest temperatures. Temperatures recorded by probe 3 frequently exceeded the maximum allowable temperature of 32 ºC, reaching a maximum of 34 ºC (this would have retarded degradation slightly). Unlike the first trial, where mixing was poor and a low reading at probe 3 was recorded (suggesting that the probe was caked in the solids from the slurry and thus insulated), in Trial 3, probe 3 recorded the highest temperature, suggesting that the poor mixing had led to the probe being exposed directly to the heated sparge air.

Average pH levels in the bioreactor were greater than 8 at the start of Trial 3. pH levels steadily increased, reaching the maximum allowable pH of 8.5 approximately 2 hours after the trial started. A dose of acid was automatically administered to the bioreactor by the computer-controlled system when the pH exceeded 8.5. This dose of acid resulted in the average pH dropping to between 6.95 and 7.25. This gradual increase in pH would relate to microbial activity through the biodegradation of acidic hydrocarbons such as phenol, giving rise to a reduction in the acidity of the slurry. From day 2 of the trial, pH levels were generally stable but showed a steady slight increase. Average pH levels ranged from 7.1 to 7.7 during the remainder of the trial. No alkali was required at any time.

Dissolved oxygen (DO) levels were high throughout Trial 3. DO levels were constantly in the high 70 % and low 80 % range from 2 hours into the trial. Those levels suggested that biological activity during the trial was low.

Only a small amount of foam was produced during Trial 3 and the foam probe was not triggered during the trial. A 25 minute dose of antifoam had been administered to the bioreactor, via the computer system, prior to loading the feedstock. The small amount of foam production again suggested that biological activity during this trial was low.

During the trial, it was noted that one of the higher level circulation pipes appeared full of solids, as there was no sound of material passing through.

Samples of feedstock, slurry and product were taken before, during and on completion of Trial 3. Table 7.4 summarises the samples taken during Trial 3.

Weather conditions during Trial 3 were much cooler, with the maximum air temperature being 14.1 °C, and the minimum 5.9 °C. Rain fell almost continually during this trial, with 36 mm recorded over the period. Atmospheric pressure was low, ranging from 1001 mbar to 1011 mbar. The maximum wind speed was 5.5 m/sec.

Unloading of Trial 3 commenced on the 17th October 2002. During the discharge process the pump was running and the compressed air was on.

Approximately six batches of slurry were discharged to the centrifuge in the correct manner. The slurry discharge contained mainly the silt and fine sand fractions of the original feedstock. Very little of the coarser fractions of feedstock was discharged. The fines produced by the centrifuging process were very moist.

Table 7.4: Samples taken during Trial 3

Sample Description	Number of Samples Taken	Comments
Water (pre-trial)	3	Samples taken from the bioreactor prior to loading the soil feedstock
Feedstock (re-screened)	6	Samples taken from the feedstock loading skip once re-screening had taken place
Feedstock (re-screened)	1	A composite of the 6 feedstock samples was prepared and sent for microbiological analysis
Slurry (chemical testing)	3	Samples of slurry were taken from the bioreactor on days 2, 3 and 5. The samples were centrifuged to produce separate soil and water samples for chemical analysis
Slurry (microbiological testing)	3	Samples of slurry were taken from the bioreactor on days 2, 3 and 5 for microbiological testing
Product	6	Of the 6 samples of product taken:
		3 were centrifuged fines
		3 were samples of 'mixed' product which had not passed through the centrifuge
Product	1	A composite of the 6 samples of product was prepared and sent for microbiological analysis
Water (post trial)	3	3 samples of water were taken from the holding tanks once discharge of Trial 3 was complete

After a short period, the flow of water and silt stopped, a small amount of solids was discharged and then the system became blocked up. It is possible that as in Trial 1 the solid material had not been circulating correctly and had settled to the bottom of the bioreactor. A description of how the material was then discharged is as follows:

- The pump was turned off, as material was no longer circulating;
- The recirculation pipes were broken off. The pipes connected to the pump inlet and outlet were caked in silt/fine sand and the pipe through which the treated material is discharged was full of coarse gravel;
- The material remaining in the bioreactor (mainly solids) was discharged onto the floor of the bioreactor compound. Some water from the holding tanks was added to the bioreactor to aid the discharge process;
- The product was removed from the floor of the bioreactor compound and any water was pumped back into the holding tanks.

During unloading, it was noted that the product contained a small amount of untreated/partially treated lumps of coal tar. This information, together with the fact that dissolved oxygen levels and temperatures were high throughout the trial, and that one of the pipes became blocked, indicated that the material cannot have been circulating effectively enough to treat all the contaminated soil.

7.6 TRIAL 4

Loading of Trial 4 commenced on the 22nd October 2002 with 28 tonnes of water and 3.02 tonnes of soil feedstock being loaded into the bioreactor. This volume of feedstock required 10 loads, which equates to an average load size of approximately 300 kg. The soil to water ratio in the bioreactor was approximately 1:10. This smaller weight of soil was used due to the problems with mixing, circulation and discharge during the previous trials.

No problems were encountered during the loading process, but approximately 45 minutes after loading was completed the pump failed. The pump was restarted but the recirculation system was completely blocked up and the pump started to become very hot. The trial was aborted at this stage as the problems with recirculation of material could not be solved at that stage with the equipment available.

Six samples of feedstock were taken prior to starting Trial 4. The feedstock for Trial 4 had been taken from the last compartment of the tar tank and was slightly more viscous than the tar previously supplied. Chemical test results provided in Appendix B and discussed in Section 9 indicate that this tar was more concentrated than the material previously used. This should not necessarily have been a problem, particularly as the weight of contaminated material and the soil to water ratio was low. It is possible that this material was both slightly more dense than that previously used, and may have started settling out during the loading sequence.

8. TRIAL CONCLUSION

8.1 VALIDATION TESTING AND FATE OF MATERIAL

The soil remediation target concentrations for the remediation of this gasworks site were agreed between ENTEC UK Ltd, the Local Authority and Environment Agency, and are listed in Table 8.1 below. Although, these were not the main targets of this trial, it was hoped that the material treated by the bioreactor would be less than these specified levels and therefore suitable for reuse on site. Targets other than those in Table 8.1 were set to achieve the lowest possible result, especially for the high molecular weight PAH compounds such as benzo(a)pyrene.

Table 8.1: Remediation target concentrations

Contaminant	Remediation Target (mg/kg)
Ammonium	50
Naphthalene	100
Phenols	5
Benzene	2.5
Toluene	30
Ethylbenzene	40
Xylenes	50

On completion of each trial, samples of product were taken for chemical testing as discussed in Section 3.

Once sampled, the product from each bioreactor trial was placed on heavy-gauge plastic liner. The centrifuged fines, coarse material removed by the primary shaker and the un-centrifuged product were mixed using an excavator. The product was covered and stockpiled until the chemical testing was complete.

The chemical test results were issued to ENTEC UK Ltd to allow them to make a decision as to whether the material was suitable for reuse on site. The product from Trials 1, 2 and 3 could not be incorporated into the remedial works because:

- Samples of product from Trial 1 exceeded the site remedial target for soils for phenols, naphthalene, ammonium and benzene;
- Samples of product from Trial 2 exceeded the site remedial target for soils for naphthalene and ammonium;
- Samples of product from Trial 3 exceeded the site remediation targets on naphthalene, ammonium and phenols.

The material was not acceptable from Trial 2 for reuse on site as some of the contaminants concentrations in the fines exceeded the remediation targets. If the material were to have been successfully re-mixed, then the mean concentrations of contaminants from Trial 2 would have been below the remediation targets and therefore acceptable for reuse on site. Thus proving that the technology would have been able to meet the remedial targets set.

A summary of the proportion of samples of product that failed, for each bioreactor trial, is presented below. The majority of residual contamination was in the fines, which forms only a small proportion

of the total product, but artificially skews the results. If the validation results are corrected to allow for the proportion of fines to the whole mass, the residual contaminant levels meet the remediation targets in a number of instances. This is summarised below, and discussed in Section 9. The raw and corrected results are presented in Appendix B.

8.1.1 TRIAL 1

i) Ammonium: of the 12 samples of product, 3 exceeded the site remedial target of 50 mg/kg. All 3 exceedances were centrifuged fines. The corrected average for all the samples was 30.7 mg/kg, which was better than the site remedial target;

ii) Naphthalene: of the 12 samples of product tested, 5 exceeded the site remedial target of 100 mg/kg. Four of the exceedances were centrifuged fines and 1 was uncentrifuged product. The fines exceeded the remedial target by up to 9 times. The corrected average for all the samples was 128 mg/kg, which did not meet the site remedial target;

iii) Phenols: of the 12 samples of product tested all exceeded the site remedial target of 5 mg/kg. The corrected average for all the samples was 28.7 mg/kg, which was still almost six times over the remedial target;

iv) Benzene: of the 12 samples of product tested, 2 exceeded the site remedial target of 2.5 mg/kg. Both exceedances were uncentrifuged product. The corrected average for all the samples was 2.03 mg/kg, which was better than the site remedial target.

8.1.2 TRIAL 2

i) Ammonium: of the 14 samples of product tested, 4 exceeded the site remedial target. All four exceedances were centrifuged fines. The corrected average for all the samples was 17.6 mg/kg, which was less than half the site remedial target.

ii) Naphthalene: of the 14 samples of product tested, 2 exceeded the site remedial target. Both exceedances were centrifuged fines. The corrected average for all the samples was 43.7 mg/kg, which was less than half the site remedial target.

8.1.3 TRIAL 3

i) Ammonium: of the 6 samples of product tested, all samples exceeded the site remedial target. The corrected average for all the samples was 180 mg/kg, which was still over three times the site remedial target of 50 mg/kg.

ii) Naphthalene: of the 6 samples of product tested, 1 sample of centrifuged fines exceeded the site remedial target. The corrected average for all the samples was 61.27 mg/kg, which was 39 mg/kg below the site remedial target.

iii) Phenols: of the 6 samples of product tested all samples exceeded the site remedial target. The corrected average for all the samples was 10.57 mg/kg, which was over double the site remedial target of 5 mg/kg.

Trials 1 and 3 each met, or bettered, the remediation targets for compounds (benzene and phenol) that would be relatively simple to degrade by traditional bioremediation methods. However, due to the very poor mixing in the reactor during these trials, they were not degraded in a significant amount of the material. If the mixing had been as effective as in Trial 2 then these exceedances would likely not have been observed.

The products of the trials were sent to a nearby landfill, based on the raw chemical results. The material was also still very moist and would not have compacted well. The geotechnical results are discussed in Section 9.

The water used in the bioreactor was passed through the on-site water treatment centre and discharged to foul sewer after treatment.

8.2 DECONSTRUCTION, REMOVAL AND STORAGE OF THE BIOREACTOR

At the end of the trials the bioreactor pipework and pump was removed and cleaned out. VHE Shepley Engineering Ltd returned to site and dismantled the bioreactor frame and vessel. The electrics, telemetry and monitoring probes were disconnected, labelled, and wrapped. The bioreactor is currently being stored at the VHE Shafton premises.

9. RESULTS AND DISCUSSION

9.1 INTRODUCTION

The chemical and microbiological results of the field trials are presented in a series of tables and graphs contained in this section, with further data in Appendix B. The results of the soil feedstock testing for each trial are averaged (mean, median and mode) and compared with the averaged (mean, median and mode) results from the final product. Statistical analyses have been run on the data, and the percentage change in results between the feedstock and final product samples defined.

The US 95 (upper bound value) for each determinand has also been calculated in accordance with the guidance in the DEFRA/Environment Agency publication CLR7 and, where applicable, compared to the Soil Guideline Values recently issued.

The feedstock results for all three trials have been compared with one another and subjected to statistical analysis, in order to define the material variability. The same has been undertaken for the final products.

The results from testing of water prior to and after use in the bioreactor are also presented, together with the results for the slurry samples taken during the trial. The results of the slurry samples are deducted from the initial starting concentration, in order to demonstrate the percentage reduction on a day-to-day basis.

The graphs included show the difference in concentration between the product and feedstock for the following:

- TPH
- PAH
- Total phenols and BTEX compounds
- Number of benzene rings

A mass balance for both the soils and water was also calculated, based on the amounts of each organic determinand in the feedstock and product. The results of the analysis of the activated carbon used to filter out gaseous emissions from the bioreactor are also presented.

The results of the microbiological analysis from the fieldwork are included and, where possible, links between particular bacteriological species and the trends in temperature, pH and dissolved oxygen are made. Reference should also be made to the results from the telemetry database presented in Appendix C.

The results as detailed above are discussed separately for each trial in the following sections. For conciseness, the discussion is focused on the determinands of principal interest with the results presented in full in Appendix B.

9.2 TRIAL 1

9.2.1 FEEDSTOCK

The analysis of the feedstock in Trial 1 showed that material was highly heterogeneous, with a wide range of variability in the chemical analysis results (Table 9.1), especially with respect to PAHs. Such was the variance that when statistical analysis was carried out, it was not possible to determine a ‘mode’ value for all determinands. The heterogeneity occurred even after a considerable amount of mixing of the feedstock. This highlights the problem of gathering of representative data from both stockpiles and bioremediation processes in general. Coal tar, by its

nature, does not form a homogenous material when mixed with materials like made ground; it preferentially forms agglomerations in the soil rather than mixing with it in a uniform manner.

Table 9.1: The mean concentration of analytes within the feedstock (before treatment) and products (after treatment) for Trial 1 (values are in mg/kg except pH)

Analyte	**Mean feedstock conc. (mg/kg)**	**Mean product conc. (mg/kg)**	**Analyte**	**Mean feedstock conc. (mg/kg)**	**Mean product conc. (mg/kg)**
pH	7.6	7.6	Water Soluble SO_4	2,683.3	673.8
Cresols	1.3	2.0	Water Soluble Cl	57.3	30.7
Xylenols & Ethylphenols	14.4	14.1	Exchangeable Ammonium	131.5	22.9
Catechol	0.9	0.1	Nitrate	8.5	10.8
Phenol	0.6	1.0	Arsenic	65.2	48.4
Trimethylphenol	8.3	11.5	Cadmium	1.4	0.9
Total Phenols	**25.3**	**28.7**	Chromium	48.0	37.6
Naphthalene	538.3	127.8	Lead	495.0	355.1
Acenaphthylene	170.0	137.2	Mercury	2.7	1.2
Acenaphthene	36.0	30.9	Selenium	1.3	0.5
Fluorene	148.3	119.5	Copper	74.8	52.9
Phenanthrene	468.3	353.6	Nickel	38.3	33.3
Anthracene	141.7	112.8	Zinc	546.7	414.3
Fluoranthene	293.3	264.2	Boron	1.5	0.7
Pyrene	281.7	250.9	Benzene	2.9	2.0
Benzo(a)anthracene	88.3	109.5	Toluene	1.9	2.0
Chrysene	76.0	82.6	Ethylbenzene	0.3	0.2
Benzo(b)fluoranthene	51.8	61.9	Xylenes	1.7	2.4
Benzo(k)fluoranthene	45.7	58.7	**Petroleum Hydrocarbons**		
Benzo(a)pyrene	62.5	76.1	C6-C8 (Aliphatic)	5.0	6.0
Indeno(1,2,3-cd)pyrene	35.2	48.3	C8-C10 (Aliphatic)	5.0	6.4
Di-benzo(a,h)anthracene	8.2	7.7	C10-C12 (Aliphatic)	5.0	61.7
Benzo(g,h,i)perylene	37.5	45.8	C12-C16 (Aliphatic)	10.0	194.2
Anthanthrene	17.0	19.7	C16-C21 (Aliphatic)	304.3	178.8
Benzo(e)pyrene	42.0	55.5	C21-C40 (Aliphatic)	25.0	282.2
Cyclopenta(c,d)pyrene	4.6	11.7	C6-C7 (Aromatic)	5.0	5.0
Total PAH	**2,546.4**	**1,979.9**	C7-C8 (Aromatic)	5.0	5.0
Easily-liberable Cyanide	1.0	1.0	C8-C10 (Aromatic)	5.0	87.0
Complex Cyanide	23.3	17.1	C10-C12 (Aromatic)	1,046.7	523.9
Total Cyanide	**23.5**	**17.3**	C12-C16 (Aromatic)	1,038.3	1,356.5
Thiocyanate	-	-	C16-C21 (Aromatic)	1,385.0	2,135.5
Elemental Sulphur	100.0	155.1	C21-C40 (Aromatic)	1,091.7	3,661.3

The PAH results indicate that the highest PAH concentrations were recorded at the low to medium molecular weight PAH range (from 2-ring naphthalene which had an average of 538 mg/kg, to 4-ring pyrene at 281 mg/kg). However, significant concentrations of PAH were recorded across the whole US EPA 16 range (Table 9.1). The total PAH concentrations varied between 2,138 mg/kg and 2,966 mg/kg, with an average of 2,546 mg/kg. This was a lower concentration than expected based on the back-calculations of tar concentrations from the laboratory tests.

The tar tank contained a range of tar types and this variability was noted in the tar during the trials, in particular the tar used for Trial 4, which was significantly more viscous than the tars used in the first three trials. Ideally the same tar type would have been used for all trials.

The standard deviation (SD) of the results was found to be higher for the low molecular weight PAH, such as naphthalene (SD of 80). Standard deviation at the higher molecular weight PAH range was much lower (e.g. the SD of benzo(a)pyrene was 11).

The total cyanide concentration in the feedstock was an average of 23.5 mg/kg. Of the heavy metals recorded in the soil, lead and zinc were present in the highest concentrations, with averages of 495 mg/kg and 546 mg/kg respectively. The concentrations of BTEX compounds in the feedstock were relatively low, with average concentrations of 2.9 mg/kg and 1.7 mg/kg for benzene and xylene respectively.

The Total Petroleum Hydrocarbons (TPH) results indicated that the highest concentrations were recorded in the C10 - C40 aromatic range (Figure 9.1), which made up approximately 92 % of the total organic fraction. The TPH testing was carried out at a different laboratory to the rest of the organic testing. There is a difference between the sum of the analysis for the TPH and the sum of all the other organic testing (they should correlate). However, variations would exist due to (a) the different analytical methods used to quantify the total result and (b) the type of compounds which the methods could detect, which may be confirmed by the fact that the standard deviation on the TPH results was quite high.

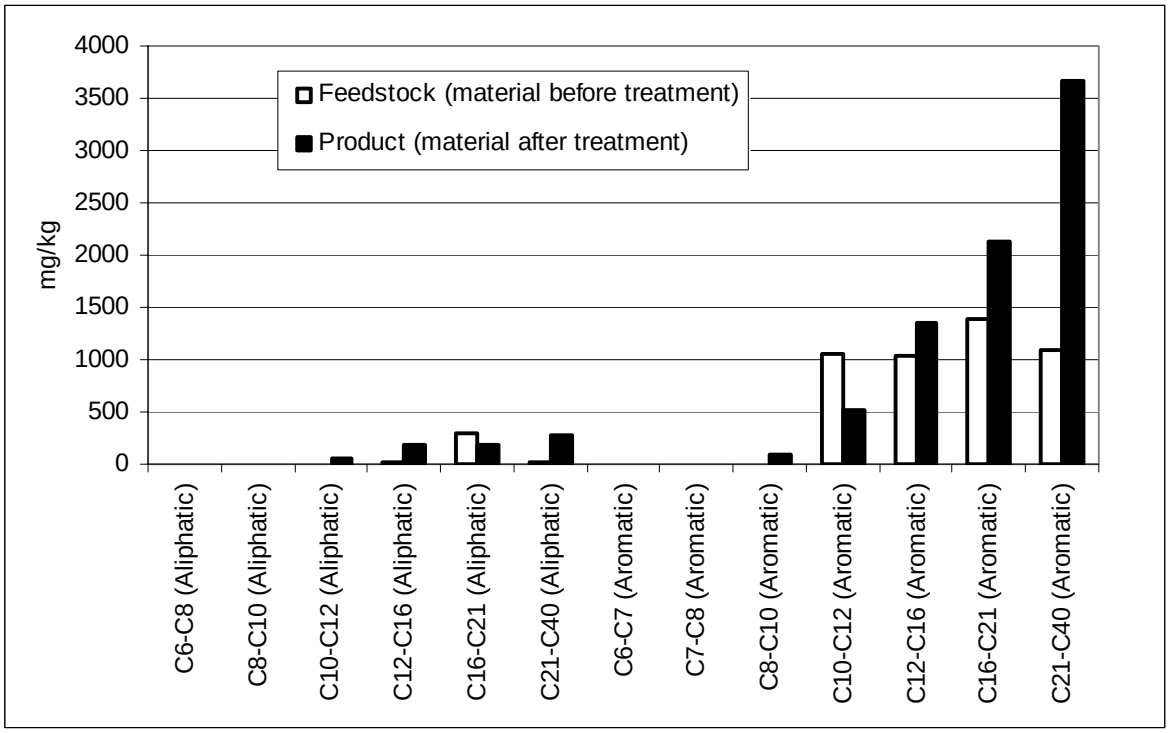


Figure 9.1: Comparison of total petroleum hydrocarbons profiles for the feedstock (material sampled before treatment) and final product (material sampled after treatment) from Trial 1

9.2.2 SLURRY SAMPLES

During Trial 1, slurry samples were taken on a daily basis apart from weekends. The slurry samples contained a high proportion of fines, and very little of the coarser material that was being treated. It was not known whether this was a factor of the design and location of the sampling port or attrition in the reactor, or was due to the coarser sediment settling out lower in the reactor due to poor recirculation. The results discussed in the following paragraphs relate to the soil samples produced on dewatering the slurry. Due to the high proportion of fines, it would not have been representative to compare the results against the feedstock, so the daily results have been compared to the first slurry sample taken (Figure 9.2).

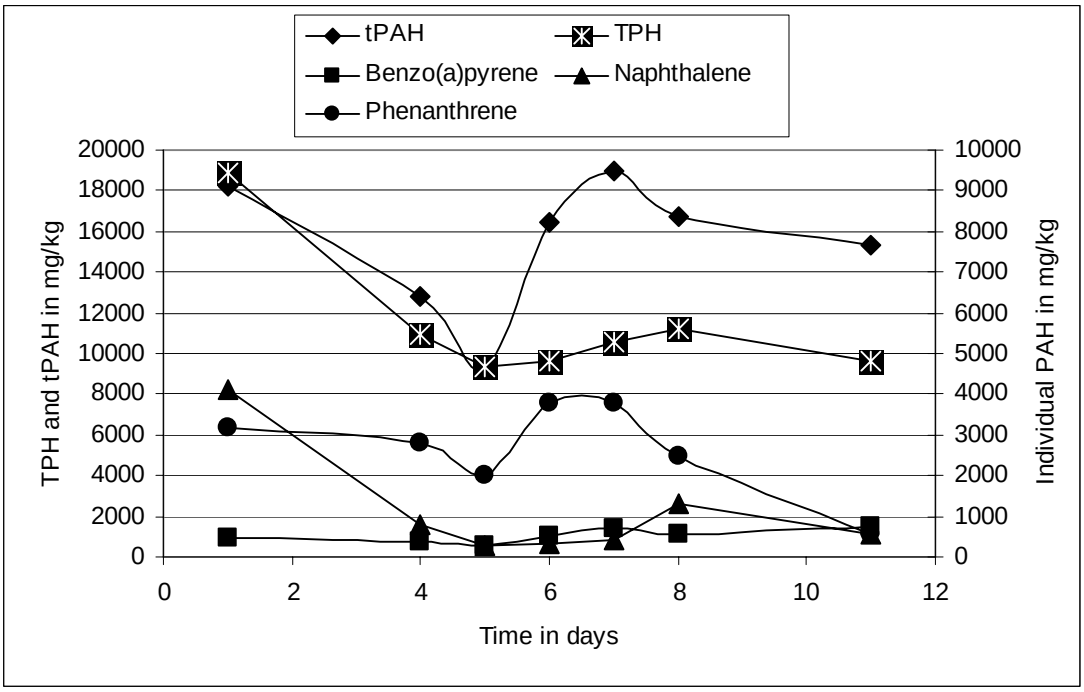


Figure 9.2: Results of the chemical analysis of selected analytes for the slurry samples taken during Trial 1

By day 4, the concentration of naphthalene had decreased by 81 % from 4,100 mg/kg to 780 mg/kg, with the majority of the other PAHs reducing by between 12 % and 24 %. This pattern was repeated on day 5, where naphthalene had reduced by 93 %, and the other PAHs by between 25 % and 45 %. However, on days 6 to 11, most of the PAHs appeared to increase in concentration. By the end of the slurry sampling, naphthalene was the only compound still showing a decrease.

It was probable that the increase in PAH contamination in the slurry samples was due to PAHs in coal dust and particles containing coal tar dispersing in the reactor (homogenising) as it was mixed. The mixing would have caused some attrition of the material in the reactor, so creating more contaminated fines. This would have led to more of the contaminated material being converted into fines. The preferential degradation of naphthalene was most likely due to its higher solubility and greater bioavailability.

The bias towards a poorer performance in the degradation of the high molecular weight PAH in the slurry was probably due to their lower solubility and lower bioavailability.

Variability in the slurry samples was also noted in the previous field trial. Alterations to the sampling port had been made after that trial in order to facilitate better and more representative sampling. However, it appears that during Trial 1 recirculation was not adequate to generate a representative slurry sample (it was noticed that there was little movement on the surface of the slurry) and difficulties with materials discharge were encountered.

Telemetry data showed that dissolved oxygen concentrations dropped to their lowest levels in the first few days of the trial, which was indicative of biological activity and was consistent with the decrease in contaminant concentrations recorded in the slurry samples over the same period.

9.2.3 PRODUCTS

At the end of Trial 1, difficulties were encountered with the bioreactor discharge process. Some fine material was separated out by the centrifuge, but a significant quantity had to be removed from the base of the reactor without centrifuging and was therefore of mixed size gradings. Geotechnical testing carried out on the mixed material indicated that it comprised approximately 6 % fines (size <63 microns), with the remaining 94 % being of coarser grain sizes.

The results of the chemical analyses indicated that the majority of residual contamination was concentrated in the fine product ('fines'), particularly with respect to the PAHs (Appendix B). These have a relatively even distribution across the US EPA 16 range, with an average of 667 mg/kg for naphthalene, 1,400 mg/kg for pyrene and 420 mg/kg for B(a)P.

The concentration of contaminants was significantly higher in the fines (average total PAH concentration of 10,975 mg/kg), than in the coarse product or feedstock material. That is what would be expected as the fines have a higher surface area to volume ratio than the coarse fractions and can therefore adsorb more tar relative to the coarse material, and this greater adsorptive capacity increases the concentration of tar in the fines fraction. In addition to this, attrition of the material in the reactor would mean that more coal dust and particles containing entrained tar (where biodegradation is limited due to low bioavailability of the contaminants within the particles) would become part of this fraction, so also giving rise to higher contaminant concentrations.

As the mixed material contained approximately 6 % fines, when the chemical results for the material were averaged, the higher contaminant concentrations in the fines skewed the average results. The raw results have, therefore, been subjected to a correction factor to account for the small proportion of fines present. Both the raw and corrected results are tabulated in Appendix B.

The results for the mixed product indicate a slight increase in the concentration of total phenols from the feedstock value of approximately 25 mg/kg to 28 mg/kg (approximately 3 %). The increase was considered insignificant and did not display any significant trend.

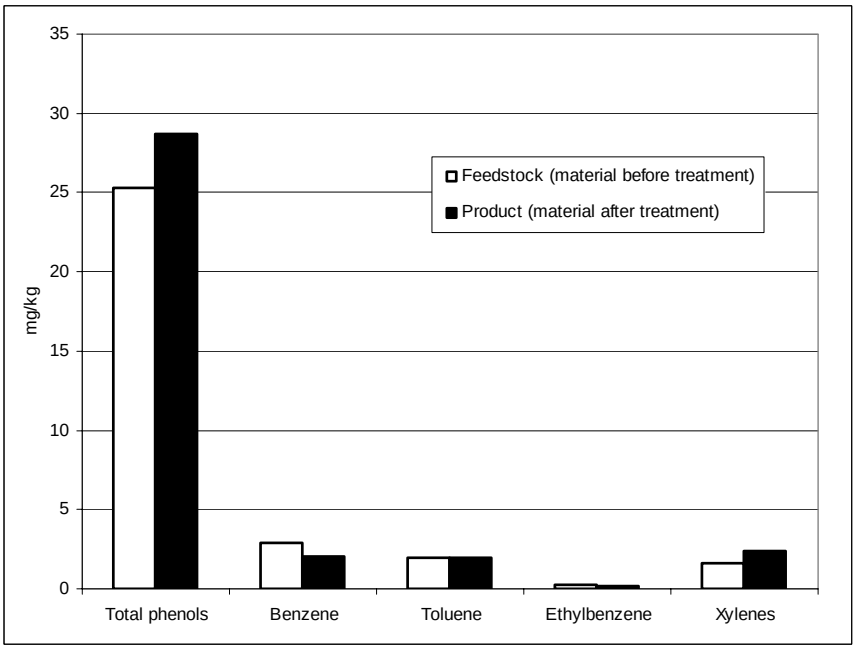
Of the US EPA 16 PAHs, the low molecular weight hydrocarbons showed the greatest reduction in concentration (Figure 9.3). Naphthalene, for example, was reduced on average from 538 mg/kg to 127 mg/kg, which was a reduction of 76 %. The 3-ring, acenaphthylene to anthracene range, compounds were reduced by between 14 % and 24 %, the residual concentration of acenaphthylene being 137 mg/kg and anthracene being 112 mg/kg. The remaining heavier PAHs indicated an average increase in contamination, with the concentration of 5-ring B(a)P at 76 mg/kg exceeding the Soil Guidance Value for this determinand (37 mg/kg), calculated by running the CLEA model. The reason for this could be that tarry contamination was identified in the product that was not encountered in the feedstock. This may be as a result of the blending (homogenising) and attrition of the material within the reactor.

Complex and total cyanide concentrations were reduced by approximately 26 % from approximately 23 mg/kg to 17 mg/kg. An increase in the nitrate concentration of the fines also occurred, from an average of 8.5 mg/kg to 10.7 mg/kg. This may be explained by the use of agricultural fertilizer as a nutrient source for the reaction.

Concentrations of heavy metals were moderately reduced during this trial, with the concentration of lead being reduced by 28 % from 495 mg/kg to 355 mg/kg and zinc reduced by 24 % from 546 mg/kg to 414 mg/kg. The reasons for the reduction in metal concentrations could have been due to aeration of the feed converting the metals from insoluble metal sulphides to soluble metal compounds. Some may also have been utilized as trace nutrients by the microorganisms.

Benzene concentrations decreased by approximately 29 % to approximately 2 mg/kg (Figure 9.3). The other BTEX compounds showed an increase, which may be due to homogenisation of the material its breakdown into finer particles. The finer particles are generally charged, and so contaminants can readily become complexed with them.

(a)



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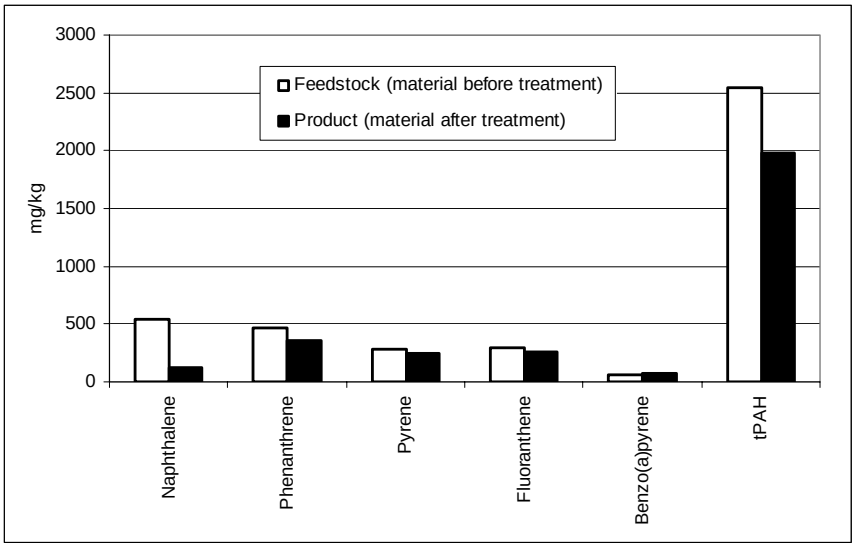

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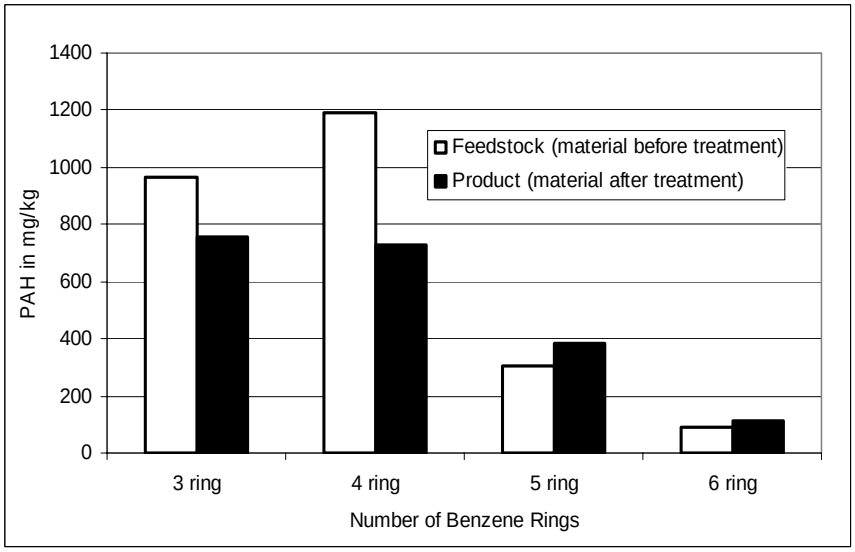


Figure 9.3: Concentration of (a) total phenols and BTEX compounds; (b) selected PAHs; and (c) PAHs grouped according to their number of benzene rings in the feedstock (material sampled before treatment) and final product (material sampled after treatment) from Trial 1

With respect to TPH, the carbon banding results (Figure 9.1) indicated higher concentrations of organics in the C16-C21 and C21-C40 aliphatic range (approximately 7 % of the organic total), and across the C10-C40 aromatic range (approximately 91 %). It is possible that these increases may have been related to the formation of breakdown products.

In summary, the results of Trial 1 are very variable, with a bias towards degradation of the lighter PAHs which is consistent with the published literature on bioremediation. However, the results were not as good as the potential indicated by the laboratory tests. Due to the problems with blockages encountered during discharge from the reactor after this trial, it was possible that recirculation was not effective during the treatment period. If blockages occurred as the treatment progressed, it is probable that optimum mixing conditions were not occurring in the reactor, and that temperature and dissolved oxygen concentrations were not evenly distributed.

9.2.4 WATER SAMPLES

The initial water placed into the bioreactor contained 5 m^3 of inoculum from the tar tank. The results from analysis of the water samples taken at the end of Trial 1 are shown in Table 9.2 and Figure 9.4. There was an increase in total phenols from 2.5 μg/l to 6.3 μg/l. The concentration of PAHs in the aqueous phase increased significantly. If the reactor had been working effectively then no residual organic contamination would remain in the aqueous phase. The PAHs that dissolved most readily into the aqueous phase were the 2- to 4-ring compounds naphthalene, acenaphthene, fluorene, phenanthrene and pyrene. Naphthalene increased from 0.29 μg/l to 2.6 μg/l, acenaphthene from 0.28 μg/l to 8.2 μg/l, phenanthrene from 0.03 μg/l to 10 μg/l and pyrene from 0.067 μg/l to 1.8 μg/l. Benzo (a) pyrene and benzo(e)pyrene also dissolved readily into the aqueous phase, increasing in concentration from 0.02 μg/l to 0.065 μg/l and 0.02 μg/l to 0.062 μg/l respectively. The total PAH increase was approximately 96 %.

With respect to total petroleum hydrocarbons, the greatest increases were recorded in the C12-C40 aromatic range, particularly C21-C40 where the concentration increased from 264 μg/l to 2,476 μg/l.

Table: 9.2: The mean concentration of the analytes detected in the water used in the slurry-phase bioreactor, at the start and end of Trial 1 (all concentrations are in μg/l)

Analyte	**Start Trial 1**	**End Trial 1**	**Analyte**	**Start Trial 1**	**End Trial 1**
Cresol	0.50	0.50	Anthanthrene	0.02	0.02
Xylenol & Ethylphenols	0.50	3.37	Benzo(e)pyrene	0.02	0.06
Catechol	0.50	0.50	Cyclopenta(c,d)pyrene	0.00	0.00
Phenol	0.50	0.50	**Total PAH**	**0.96**	**30.33**
Trimethylphenol	0.50	2.77	Benzene		10.00
Total Phenols	**2.50**	**6.30**	Toluene		10.00
Naphthalene	0.29	2.6	Ethylbenzene		10.00
Acenaphthylene	0.00	0.00	Xylenes		48.33
Acenaphthene	0.28	8.23	**Total Petroleum hydrocarbons**	**464.00**	**3,960.00**
Fluorene	0.10	5.63	C6-C8 (Aliphatic)	10.00	10.00
Phenanthrene	0.03	10.00	C8-C10 (Aliphatic)	10.00	193.33
Anthracene	0.12	0.75	C10-C12 (Aliphatic)	10.00	10.00
Fluoranthene	0.07	0.99	C12-C16 (Aliphatic)	20.00	20.00
Pyrene	0.07	1.80	C16-C21 (Aliphatic)	20.00	20.00
Benzo(a)anthracene	0.02	0.04	C21-C40 (Aliphatic)	50.00	50.00
Chrysene	0.02	0.12	C6-C7 (Aromatic)	10.00	10.00
Benzo(b)fluoranthene	0.02	0.04	C7-C8 (Aromatic)	10.00	10.00
Benzo(k)fluoranthene	0.02	0.02	C8-C10 (Aromatic)	10.00	10.00
Benzo(a)pyrene	0.02	0.07	C10-C12 (Aromatic)	10.00	10.00
Indeno(1,2,3-cd)pyrene	0.02	0.02	C12-C16 (Aromatic)	20.00	700.00
Di-benzo(a,h)anthracene	0.02	0.02	C16-C21 (Aromatic)	20.00	440.00
Benzo(g,h,i)perylene	0.02	0.03	C21-C40 (Aromatic)	264.00	2,476.67

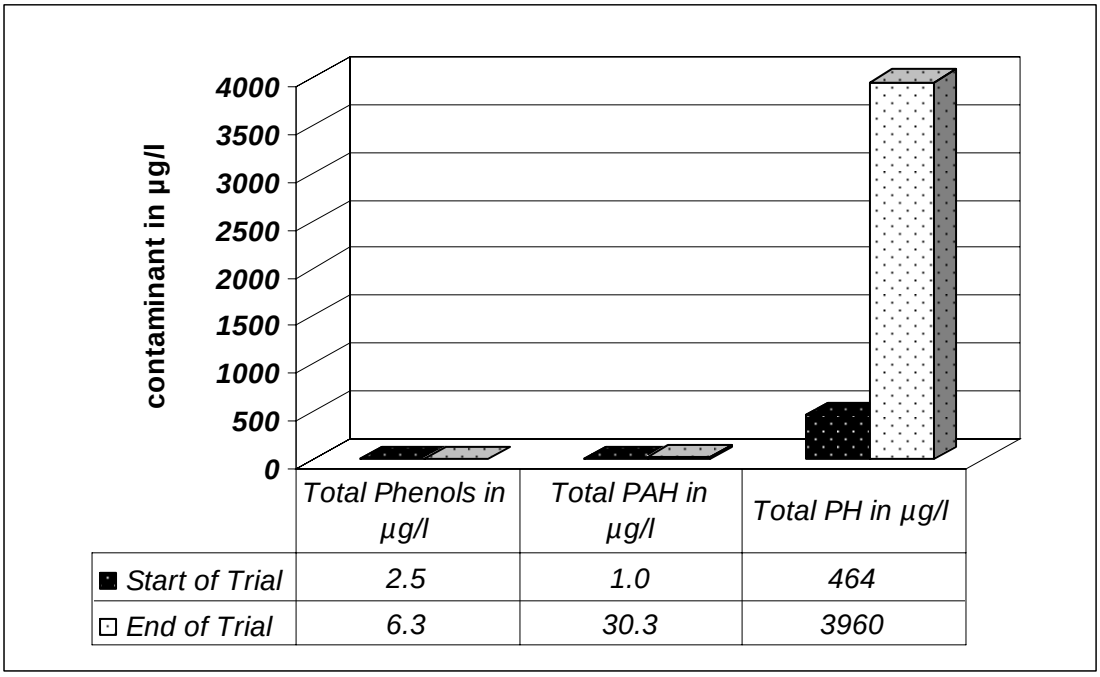


Figure 9.4: The mean concentration of the major groups of compounds in the water used in the slurry-phase bioreactor, at the start and end of Trial 1.

9.2.5 OFF-GASES

Analysis of the gases exiting the bioreactor (off-gases) was undertaken by passing them through an activated carbon filter. Samples of the activated carbon were taken from the input port of the filter and no contamination was detected in the activated carbon after the trials, indicating that no hydrocarbon was lost to the atmosphere as off-gas.

9.2.6 MASS BALANCE

The mass balance for Trial 1 is shown in the Table 9.3. Overall, the reduction in the organic contaminant load for the trial was 9.16 %. These results showed that the process was working very poorly, probably as a result of the poor mixing which limited the amount of biodegradation that occurred.

Table 9.3: Mass balance of organic analytes in the bioreactor

	Pre Trial 1	**Post Trial 1**	**% change**
Waters (g)	0.10	1.58	-1,489.13
Soils (g)	27,239	24,769	9.17
Total (g)	27,239	24,771	**9.16**

NOTES:
1) Mass balance columns show the concentrations recorded for each determinand multiplied by either the volume of water used or the weight of soil used.
2) Mean concentrations of organics in soil have been taken from this bioreactor trial - Soil Samples: Appendix B, Table B7.
3) Mean concentrations of organics in water have been taken from this bioreactor trial - Water Samples: Appendix B, Table B4
4) In Table 9.3 a negative figure indicates an INCREASE in contamination.
5) No contamination was detected in the activated carbon after the trials, indicating that no hydrocarbon was lost to the atmosphere as off-gas.

9.3 TRIAL 2

9.3.1 FEEDSTOCK

As in Trial 1, the results for Trial 2 also indicate a degree of variability in the feedstock, particularly with respect to PAHs and TPH (Table 9.4). Again, it was not possible to determine a statistical 'mode' value for most organic determinands, as the same value did not appear more than once in the results.

Table 9.4: The mean concentration of analytes in the feedstock (before treatment) and products (after treatment) for Trial 2 (values are in mg/kg except pH)

Analyte	Mean feedstock conc. (mg/kg)	Mean product conc. (mg/kg)	Analyte	Mean feedstock conc. (mg/kg)	Mean product conc. (mg/kg)
pH	7.6	7.9	Water Soluble SO_4	1,220.0	740.8
Cresols	23.2	0.2	Water Soluble Cl	46.0	26.0
Xylenols & Ethylphenols	42.9	1.6	Exchangeable Ammonium	77.2	46.9
Catechol	0.1	0.1	Nitrate	5.2	17.6
Phenol	8.6	0.1	Arsenic	55.8	39.1
Trimethylphenol	23.2	1.7	Cadmium	0.9	0.5
Total Phenols	**98.9**	**3.4**	Chromium	33.3	31.4
Naphthalene	851.7	43.7	Lead	403.3	295.0
Acenaphthylene	285.0	71.9	Mercury	1.8	0.7
Acenaphthene	61.8	15.9	Selenium	1.0	0.5
Fluorene	246.7	63.3	Copper	58.0	41.7
Phenanthrene	740.0	178.9	Nickel	32.8	27.6
Anthracene	218.3	63.8	Zinc	463.3	320.5
Fluoranthene	508.3	133.4	Boron	1.2	0.7
Pyrene	461.7	139.3	Benzene	3.9	0.6
Benzo(a)anthracene	178.0	55.3	Toluene	3.5	0.7
Chrysene	162.0	50.1	Ethylbenzene	0.4	0.1
Benzo(b)fluoranthene	113.5	34.2	Xylenes	3.9	0.9
Benzo(k)fluoranthene	118.3	35.0	**Petroleum Hydrocarbons**		
Benzo(a)pyrene	141.2	45.4	C6-C8 (Aliphatic)	25.0	5.0
Indeno(1,2,3-cd)pyrene	69.5	25.4	C8-C10 (Aliphatic)	25.0	5.0
Di-benz(a,h)anthracene	22.4	8.3	C10-C12 (Aliphatic)	25.0	52.8
Benzo(g,h,i)perylene	81.7	26.1	C12-C16 (Aliphatic)	50.0	144.0
Anthanthrene	29.6	12.9	C16-C21 (Aliphatic)	50.0	109.1
Benzo(e)pyrene	96.8	31.0	C21-C40 (Aliphatic)	125.0	26.7
Cyclopenta(c,d)pyrene	12.5	6.5	C6-C7 (Aromatic)	25.0	5.0
Total PAH	**4,400.0**	**1,027.3**	C7-C8 (Aromatic)	25.0	5.0
			C8-C10 (Aromatic)	25.0	223.1
Easily-liberable Cyanide	1.0	1.8	C10-C12 (Aromatic)	1,417.2	871.6
Complex Cyanide	8.9	13.5	C12-C16 (Aromatic)	1,258.2	1,724.6
Total Cyanide	**8.9**	**15.6**	C16-C21 (Aromatic)	1,856.5	1,228.4
Elemental Sulphur	87.2	93.4	C21-C40 (Aromatic)	2,861.3	1,107.3

The average concentration of total phenols was 98 mg/kg in the feedstock; however, this was affected by one very high result. The median concentration is 44.5 mg/kg.

The PAH results indicate that the highest PAH concentrations were recorded at the low to medium molecular weight PAH range (for example, 2-ring naphthalene, average of 851 mg/kg, and 4-ring phenanthrene, average 740 mg/kg). However, significant concentrations of PAH were recorded across the whole US EPA 16 range. The total PAH concentration varied between 2,100 mg/kg and 9,000 mg/kg, with an average of 4,000 mg/kg. This was higher than in the material used in Trial 1, despite being from a similar area of the tar tank. This further confirmed the significant variability of the gasworks waste found on the site.

The standard deviation of the results was found to be higher for the lighter PAHs, decreasing with increasing molecular weight. The average concentration of the 5-ring PAH B(a)P (141 mg/kg) was also higher than Trial 1.

The total cyanide concentration in the feedstock had an average of 8.9 mg/kg, which was lower than in Trial 1. Of the heavy metals recorded in the soil, lead and zinc were again present in the highest concentrations, with averages of 403 mg/kg and 463 mg/kg respectively. The concentrations of BTEX compounds in the feedstock were higher than in Trial 1, with average concentrations of 3.9 mg/kg for both benzene and xylene.

The TPH results indicated that the highest concentrations were recorded in the C10-C40 aromatic range, which comprises approximately 95 % of the total organic fraction (see Figure 9.5). The highest concentration proportion was the C21-C40 band, which made up 37 % of the total.

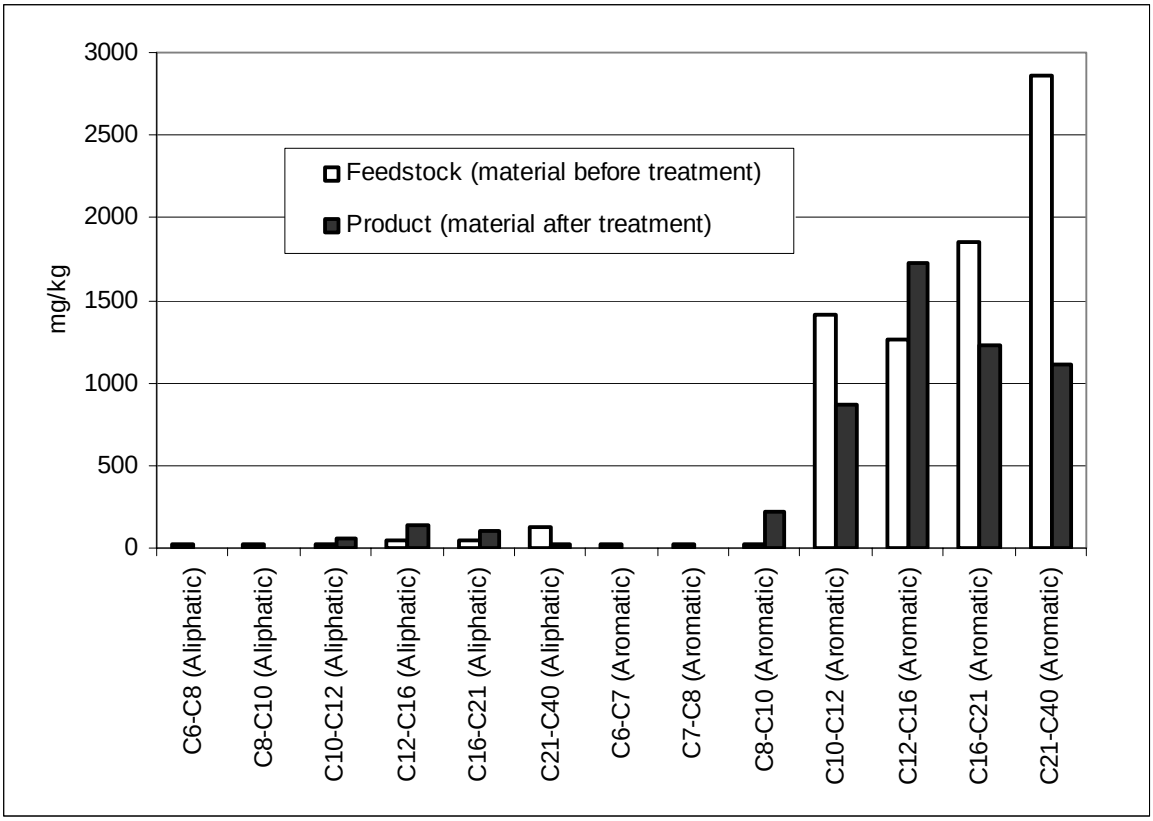


Figure 9.5: Comparison of total petroleum hydrocarbons profiles for the feedstock (material sampled before treatment) and final product (material sampled after treatment) from Trial 2

9.3.2 SLURRY SAMPLES

Slurry samples were taken on days 1, 4, 6 and 7 during Trial 2. As detailed in Section 7, slurry recirculation was better in Trial 2 (the slurry could be heard moving around the reactor) than in Trial 1. Problems with blockages only occurred during discharge to the centrifuge/shaker.

The results from the slurry samples reflect this improved performance. Decreases in contamination were recorded across the PAH range (Figure 9.6). By day 4, the results were variable and species-specific. The lowest reduction was for 4-ring pyrene at 8.6 %. However, phenanthrene decreased by 90 % (from 500 mg/kg to 50 mg/kg), and 3-ring anthracene by 50 % (from 160 mg/kg to 80 mg/kg). From benzo(b)fluoranthene to indeno(1,2,3-cd)pyrene the reduction was over 40 %, including B(a)P which was reduced by 42.5 % from 120 mg/kg to 69 mg/kg. At this early stage, degradation did not appear to favour the lighter PAHs, as naphthalene was reduced by only 35 %.

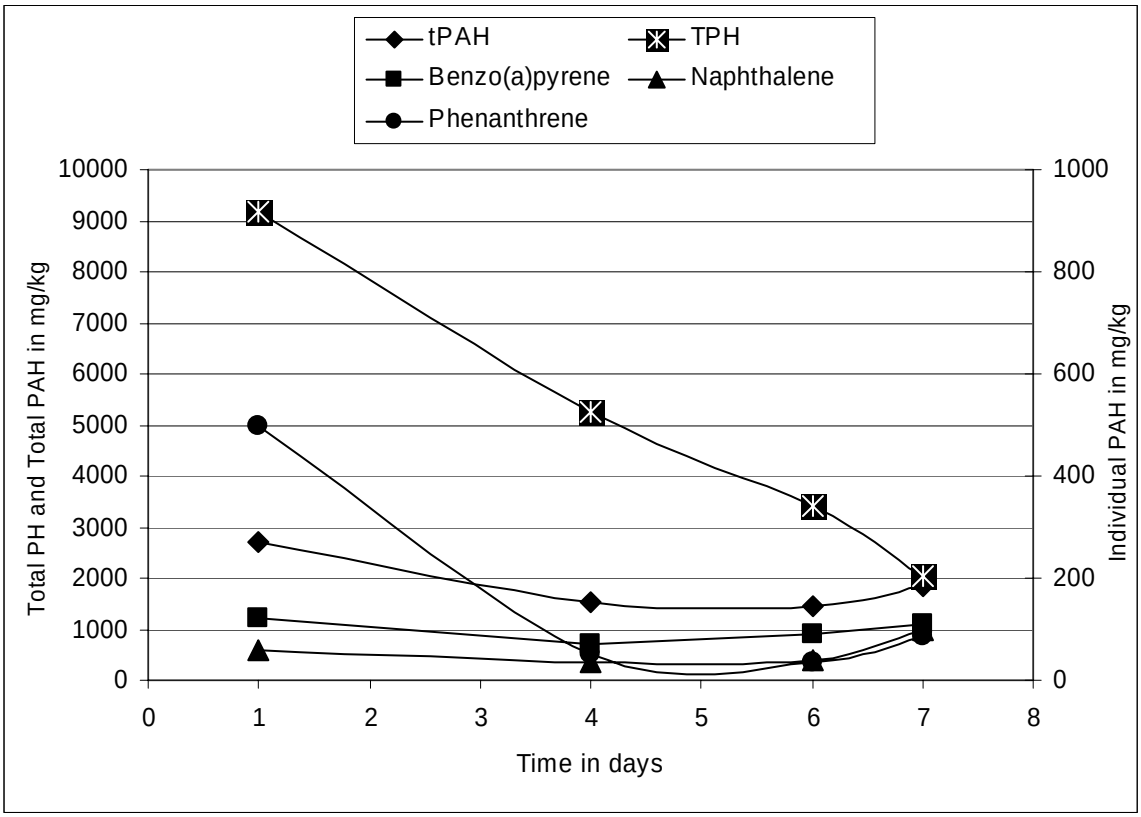


Figure 9.6: Results of the chemical analysis of selected analytes for the slurry samples taken during Trial 2

However, by day 6, 3-ring fluorene and 4-ring phenanthrene had been degraded by 98 % and 93 % respectively (170 mg/kg to 2.9 mg/kg and 500 mg/kg to 43 mg/kg). Five-ringed cyclopenta(c,d)pyrene was reduced by 14.5 %, and 6-ring anthanthrene by 86.6 % from 29 mg/kg to 3.9 mg/kg.

By day 7, a number of compounds were indicating an increase in contamination relative to day 1. Naphthalene, pyrene, indeno (1,2,3-cd) pyrene and anthanthrene increased the most significantly. This was similar to the trend of Trial 1. The remainder of the lighter PAHs decreased by between 33 % and 83 %. Cyclopenta(c,d)pyrene showed an 85 % reduction at the heavier end of the PAH range.

It is probable that the increases in contamination in the slurry samples were due to both the coal dust and tar fraction of the material dispersing in the reactor as it was mixed. The mixing would also have caused attrition of the material in the reactor, so releasing more fines. Overall, this would have led to more of the contaminated material being transferred into the slurry phase. The bias towards a poorer performance in the degradation of the high molecular weight PAH in the slurry

would probably have been due to their lower solubility and bioavailability, therefore, they did not degrade as effectively as the low molecular weight PAHs.

TPH results were variable throughout the trial; however the TPH decreased from 9,181 mg/kg (total aliphatic hydrocarbons 1,505 mg/kg, total aromatic hydrocarbons 7,676 mg/kg) to 2,023 mg/kg (total aliphatic hydrocarbons 477 mg/kg, total aromatic hydrocarbons 1,546 mg/kg), giving a 78 % decrease by the final day of the trial. The greatest decrease in contamination was 99 %, seen in the C21-C40 aromatic range.

9.3.3 PRODUCTS

As in Trial 1, difficulties were encountered on dewatering and discharging the slurry, and a variety of products resulted, specifically, separate fine and coarse streams (produced when slurry was free running and could be pumped into the centrifuge), and a mixed sample (produced when the bioreactor became blocked).

The results of the chemical analyses indicate that the majority of residual contamination was concentrated in the fine product, particularly with respect to PAHs. However, unlike Trial 1, these results were not higher than the feedstock, indicating that degradation of contaminants in the fine fraction had occurred. The highest concentrations were recorded at the lighter end of the PAH range, such as naphthalene and benzo(a)pyrene, which had average concentrations of 187.5 mg/kg and 117 mg/kg respectively. The total PAH concentration in the fines was 1,925 mg/kg.

In the fines, the concentration of total cyanide increased from 8.9 mg/kg to 34 mg/kg. This was probably due to the attrition of lumps of spent oxide (cyanide bearing waste) into finer particles, which would result in a higher concentration in the finer fraction of the final product, as was seen in Trial 1. This means that the final product would have been more homogenous than the starting product, which would have been expected if the material had been mixed intensively for a long period. Similar increases in nitrate and ammonium were likely to be due to the use of fertilizer as a nutrient supply. The residual concentrations of nitrate and ammonium were not as high in this trial as in Trial 1, perhaps because of the more effective recirculation in this trial enabling these nutrients to fully dissolve and be more readily utilised by the microorganisms.

Of the heavy metals, lead and zinc were present in the highest concentrations at 353 mg/kg and 360 mg/kg respectively.

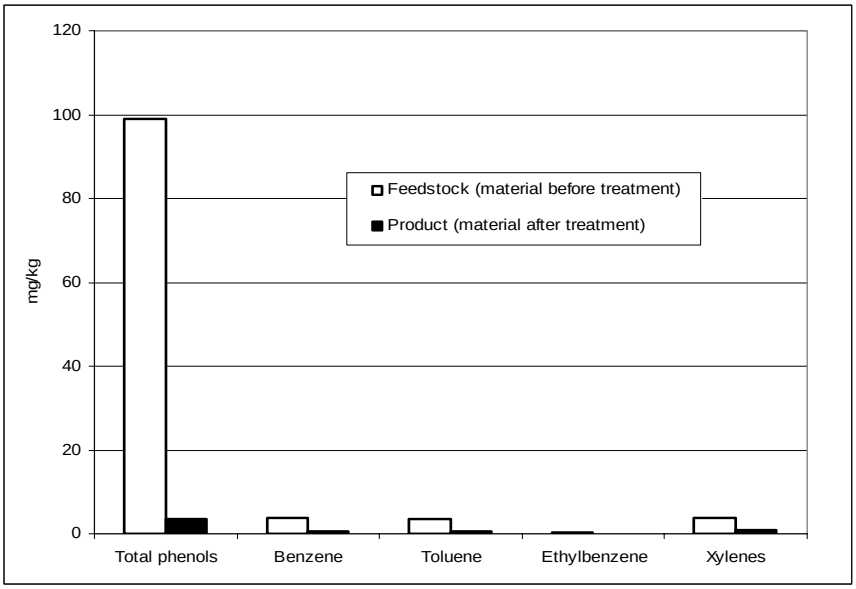
With respect to the coarse stream that was separated off in the shaker, the contaminant levels were much lower than observed in the fines, the PAH concentrations being approximately a quarter of the concentration in the fines, with a total PAH of 535 mg/kg. Significant reductions in contamination were recorded across the whole range of PAHs.

For the uncentrifuged mixed sample, average results were higher than in the coarse stream, but not as high as those recorded in the fines, which is to be expected. The total PAH concentration was just over 1,000 mg/kg but, ideally, remediation techniques should aim to meet, or better this value, although it is promising that this treatment has shown such a reduction in PAH contamination. The average concentration of benzo(a)pyrene was 45.3 mg/kg, slightly above the soil guidance value derived from running the CLEA model using similar site and material characteristics. The most significant reductions were recorded at the lighter end of the PAH range.

It was estimated that 74 % of the product from Trial 2 was recovered as the ‘mixed’ sample, 20 % as ‘coarse’ fraction, and 6 % as ‘fines’. As discussed for the results of Trial 1, it is essential to correct the raw results to account for the presence of a small proportion of highly contaminated fines.

The corrected results indicate reductions in cresols, xylenols, ethylphenols, phenols and trimethylphenols of between 92 % and 99 %. Total phenols decreased by 96.5 % from 98.9 mg/kg to 3.4mg/kg (see Figure 9.7).

(a)



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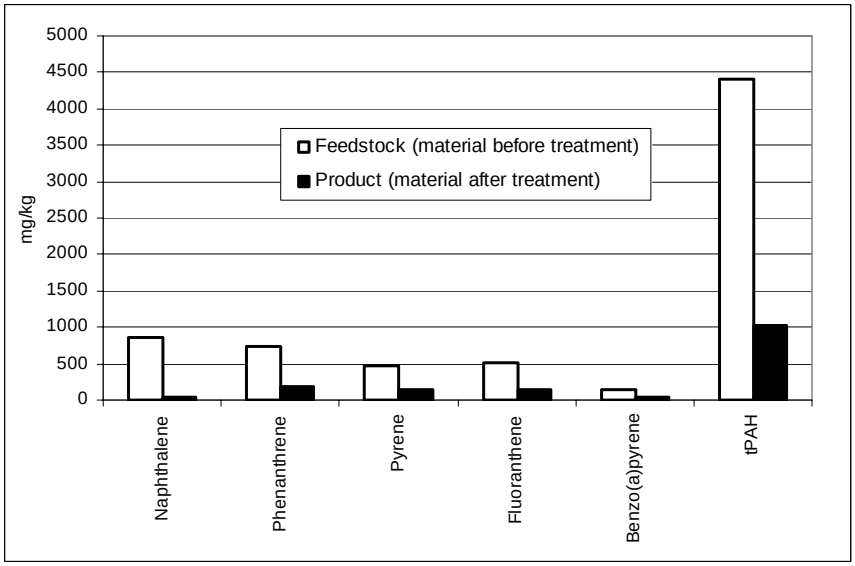


(c)

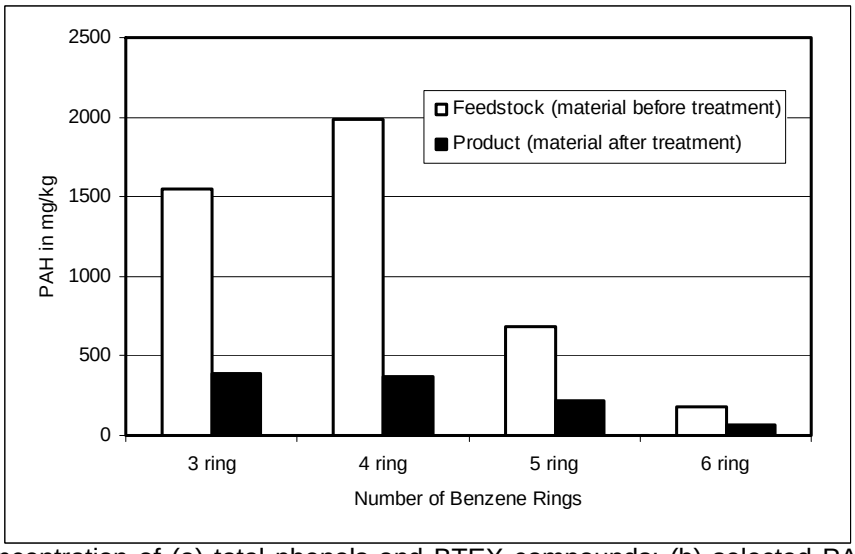


Figure 9.7: Concentration of (a) total phenols and BTEX compounds; (b) selected PAHs; and (c) PAHs grouped according to their number of benzene rings in the feedstock (material sampled before treatment) and final product (material sampled after treatment) from Trial 2

In addition, the best results were achieved for lighter end PAHs, but with significant reductions across the whole range. Naphthalene was reduced by 95 %, from 851 mg/kg to 43.7 mg/kg. All the other PAHs were reduced by between 56 % (6-ring anthranthene) and 76 % (4-ring phenanthrene), with the exception of 6-ring cyclopenta(c,d)pyrene that was reduced by 48 %,from 12.5 mg/kg to 6.5 mg/kg. Benzo(a)pyrene was reduced by nearly 68 %, from 141 mg/kg to 45 mg/kg. Total PAHs were reduced from an average of 4400 mg/kg to 1027 mg/kg (see Figure 9.7).

These results are particularly significant as they demonstrate very high reductions in the higher molecular weight PAHs. Conventional landfarming has, to date, achieved significant reductions with only up to 4-ring compounds, even for treatments lasting many weeks.

The concentrations of heavy metals were also significantly reduced, (for example by 5.7 % for chromium and 62 % for mercury). This may be for the same reasons described earlier in Section 7.2.18. Significant mercury removal may be due to microbial mercury detoxification processes, in which absorbed mercury is methylated to form volatile methyl mercury, which can be released to atmosphere. In this case, the activated carbon used for this trial will have prevented any fugitive emissions.

Of the BTEX compounds, benzene was reduced by 84 %, from 3.9 mg/kg to 0.6 mg/kg. Toluene, ethylbenzene and xylene were reduced by 80 %, 63 % and 77 %, respectively (see Figure 9.7).

The concentration of complex and total cyanides increased during the course of the trial from 8.9 mg/kg to approximately 13.5 mg/kg, possibly due to spent oxide particles breaking down into fines, as explained previously.

Analysis of the telemetry results indicates that the most intense biological activity may have taken place between days 2 and 4, with a further period of activity on day 7, as these were the times when the dissolved oxygen levels were at their lowest. This is further verified by the significant amounts of foam produced during the trial.

In summary, the biotic processes in Trial 2 were significantly more effective at degrading the target contaminants than in Trial 1, consistent with the improved performance (especially mixing) achieved by the reactor. The Trial 2 results therefore probably represent the reductions in contamination that may be achieved when the plant is operating under optimum conditions.

The product was not accepted for reuse on site by ENTEC UK Ltd as the results for naphthalene and ammonium exceeded the site remedial targets. These results related to the fines fraction of the material, which was more contaminated and not representative of the treated material in general. However, at the time, no geotechnical information was available on the material, so the proportion of fines in the overall product was not known. ENTEC therefore had to average the entire set of results, with the results for the fines being given equal weight to these for the coarser material, resulting in the material failing to meet the target.

As the centrifuging process ran into difficulties, only a relatively small amount of fines was segregated, with the majority of the fines remaining in the mixed sample. If the difficulties can be addressed, it may in future be pertinent to keep the fines fraction separate from the rest of the product, for further treatment or special disposal. This would likely result in the majority of the other product material being suitable for reuse.

9.3.4 WATER SAMPLES

The results from analysis of the water samples taken at the end of Trial 2 are shown in Table 9.5 and Figure 9.8. The water used in Trial 2 was recycled from Trial 1. By the end of Trial 2, the majority of contaminants had decreased relative to the samples at the start, including all PAHs except pyrene. This was consistent with contaminants in the aqueous phase being degraded biologically; it may also suggest that the remaining contamination in the solid phase was not readily bioavailable or is unable to partition into the dissolved phase. The most dramatic reductions in concentration occurred in the low molecular weight PAHs such as naphthalene, which reduced from 10.4 μg/l to 0.33 μg/l. Pyrene increased only slightly from 0.193 μg/l to 0.22 μg/l.

Table 9.5: The mean concentration of the analytes detected in the water used in the slurry-phase bioreactor, at the start and end of Trial 2 (all concentrations are in μg/l).

Analyte	Start Trial 2	End Trial 2	Analyte	Start Trial 2	End Trial 2
Cresol	0.50	140.00	Anthanthrene	0.02	0.02
Xylenol & Ethylphenols	4,900.00	150.00	Benzo(e)pyrene	0.03	0.02
Catechol	87.00	0.50	Cyclopenta(c,d)pyrene	0.00	0.00
Phenol	56.00	76.00	**Total PAH**	**29.67**	**3.50**
Trimethylphenol	3,333.33	0.50	Benzene	10.67	
Total Phenols	**8,400.00**	**360.00**	Toluene	21.00	
Naphthalene	10.77	1.7	Ethylbenzene	14.67	
Acenaphthylene	0.04	0.00	Xylenes	183.33	
Acenaphthene	0.03	0.33	**Total Petroleum hydrocarbons**	**5,946.67**	**1,990.00**
Flourene	0.03	0.22	C6-C8 (Aliphatic)	50.00	20.00
Phenanthrene	0.02	0.36	C8-C10 (Aliphatic)	50.00	20.00
Anthracene	0.08	0.63	C10-C12 (Aliphatic)	50.00	20.00
Fluoranthene	0.04	0.04	C12-C16 (Aliphatic)	100.00	40.00
Pyrene	0.02	0.22	C16-C21 (Aliphatic)	100.00	40.00
Benzo(a)anthracene	0.02	0.02	C21-C40 (Aliphatic)	250.00	100.00
Chrysene	0.03	0.02	C6-C7 (Aromatic)	50.00	20.00
Benzo(b)fluoranthene	0.03	0.02	C7-C8 (Aromatic)	50.00	20.00
Benzo(k)fluoranthene	0.02	0.02	C8-C10 (Aromatic)	50.00	20.00
Benzo(a)pyrene	0.08	0.02	C10-C12 (Aromatic)	2,290.00	20.00
Indeno(1,2,3-cd)pyrene	0.04	0.02	C12-C16 (Aromatic)	1746.76	40.00
Di-Benzo(a,h)anthracene	0.02	0.02	C16-C21 (Aromatic)	910.00	40.00
Benzo(g,h,i)perylene	0.02	0.02	C21-C40 (Aromatic)	250.00	1,590.00

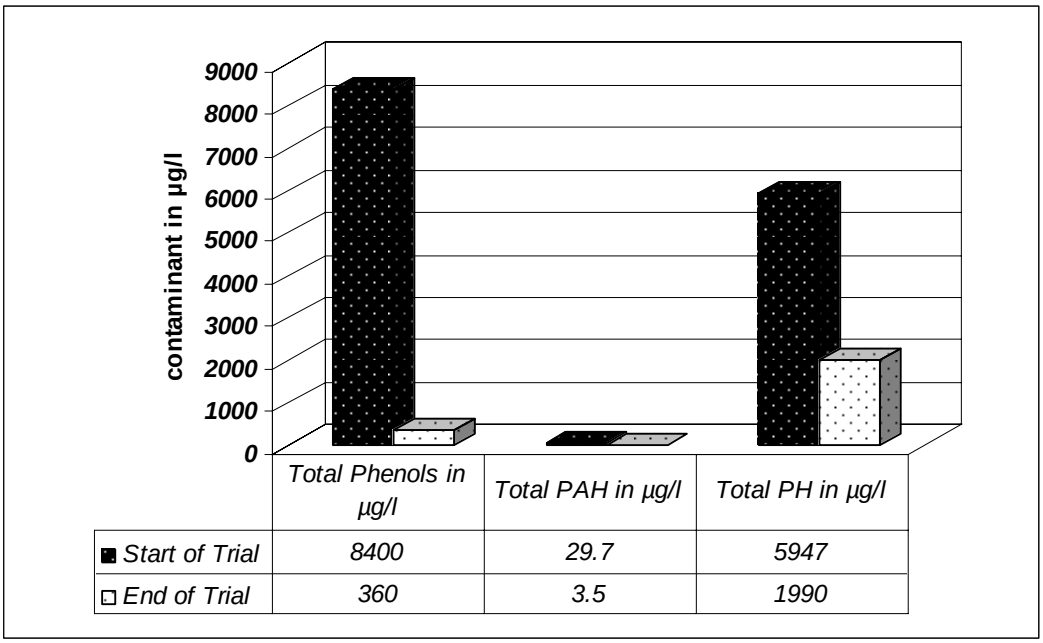


Figure 9.8: The mean concentration of the major groups of compounds in the water used in the slurry-phase bioreactor, at the start and end of Trial 2

9.3.5 OFF-GASES

Analysis of the off-gases was undertaken by passing them through an activated carbon filter. Samples of the activated carbon were taken from the input port of the filter and no contamination was detected in the activated carbon after the trials, indicating that no hydrocarbon was lost to the atmosphere as off-gas.

9.3.6 MASS BALANCE

The mass balance for Trial 2 is shown in the table below. Overall the reduction in the organic contaminant load for the trial was 77.34 %. These results showed that the process was working very effectively, in line with expectations from the laboratory-scale trials. The improved performance coincided with significantly more effective mixing in the bioreactor, indicating that the poor mixing which had occurred in Trial 1 may have been the cause of the poor performance.

Table 9.6: Mass balance of organic analytes in the bioreactor.

	Pre Trial 2	Post Trial 2	% change
Waters (g)	227.66	10.00	95.61
Soils (g)	32,483	7,401	77.22
Total (g)	32,711	7,421	**77.34**

NOTES:

1) Mass balance columns show the concentrations recorded for each determinand multiplied by either the volume of water used or the weight of soil used.
2) Average concentrations of organics in soil have been taken from the bioreactor trial - Soil Samples: Appendix B, Table B9.
3) Average concentrations of organics in water have been taken from the bioreactor trial - Water Samples: Appendix B, Table B17.
4) No contamination was detected in the activated carbon after the trials, indicating that no hydrocarbon was lost to the atmosphere as off-gas.

9.4 TRIAL 3

9.4.1 FEEDSTOCK

Table 9.7 shows the mean concentration of analytes in the feedstock and products. As in both Trials 1 and 2, significant variation in the results for the feedstock was noted. A statistical 'mode' value could not be calculated for a number of organic results, as the same value did not occur more than once.

The average concentration of total phenols in the feedstock was 58.2 mg/kg. The highest concentrations of PAHs were recorded at the lighter end of the PAH range, with naphthalene having the highest average concentration at 505 mg/kg. The concentration of B(a)P was 54.8 mg/kg. The average total PAH concentration was 2,000 mg/kg, but the samples varied from 1,400 mg/kg to 3,200 mg/kg. The standard deviation for the results at the lighter end of the range was very high, but the standard deviation of the heavier 6-ring compounds was almost negligible.

The total cyanide concentration was 18.9 mg/kg. Consistent with the previous trials, of the heavy metals, lead and zinc recorded the highest concentrations, 488 mg/kg and 561 mg/kg respectively (Table 9.7).

Of the BTEX compounds, benzene was recorded in the highest concentration (4.2 mg/kg). For TPH, the highest concentration was within the C10 - C12 aromatic range, accounting for 25 % of the TPH, and the ranges C12-C16, C16-C21 and C21-C40 accounting for 20 %, 24 % and 24 % of the TPH respectively (see Figure 9.9).

Table 9.7: The mean concentration of analytes within the feedstock (before treatment) and products (after treatment) for Trial 3 (values are in mg/kg except pH)

Analyte	Mean feedstock conc. (mg/kg)	Mean product conc. (mg/kg)	Analyte	Mean feedstock conc. (mg/kg)	Mean product conc. (mg/kg)
pH	7.9	7.5	Water Soluble SO_4	2,176.7	2,586.7
Cresols	18.4	0.3	Water Soluble Cl	52.3	70.6
Xylenols & Ethylphenols	21.6	5.5	Exchangeable Ammonium	46.5	179.8
Catechol	0.1	0.1	Nitrate	9.5	40.4
Phenol	9.5	0.1	Arsenic	67.3	77.2
Trimethylphenol	9.8	4.9	Cadmium	0.8	0.9
Total Phenols	**58.2**	**10.6**	Chromium	40.0	53.9
Naphthalene	505.0	61.3	Lead	488.3	543.3
Acenaphthylene	126.2	114.1	Mercury	2.1	1.7
Acenaphthene	28.5	26.2	Selenium	1.3	0.9
Fluorene	110.0	106.2	Copper	70.5	85.2
Phenanthrene	311.7	298.0	Nickel	37.3	50.7
Anthracene	104.5	102.2	Zinc	561.7	597.0
Fluoranthene	200.0	206.7	Boron	1.7	1.8
Pyrene	188.3	190.7	Benzene	4.2	0.4
Benzo(a)anthracene	77.8	89.7	Toluene	2.3	0.5
Chrysene	64.0	84.5	Ethylbenzene	0.2	0.1
Benzo(b)fluoranthene	44.5	54.1	Xylenes	2.1	0.9
Benzo(k)fluoranthene	40.8	57.3	**Petroleum Hydrocarbons**		
Benzo(a)pyrene	54.8	54.9	C6-C8 (Aliphatic)	5.0	5.0
Indeno(1,2,3-cd)pyrene	31.7	24.9	C8-C10 (Aliphatic)	5.0	5.0
Di-benz(a,h,)anthracene	8.1	8.5	C10-C12 (Aliphatic)	42.5	26.4
Benzo(g,h,l)perylene	33.2	33.5	C12-C16 (Aliphatic)	162.7	125.8
Anthanthrene	15.9	10.8	C16-C21 (Aliphatic)	86.8	88.8
Benzo(e)pyrene	33.0	40.5	C21-C40 (Aliphatic)	113.3	59.7
Cyclopenta(c,d)pyrene	2.4	1.0	C6-C7 (Aromatic)	69.5	5.0
Total PAH	**2,000.0**	**1,566.7**	C7-C8 (Aromatic)	114.3	5.0
			C8-C10 (Aromatic)	609.7	34.4
Easily-liberable Cyanide	0.9	1.1	C10-C12 (Aromatic)	4,367.0	205.9
Complex Cyanide	18.5	33.8	C12-C16 (Aromatic)	3,575.0	1,118.4
Total Cyanide	**18.9**	**34.0**	C16-C21 (Aromatic)	4,276.7	2,287.0
Elemental Sulphur	84.2	128.8	C21-C40 (Aromatic)	4,258.3	2,750.3

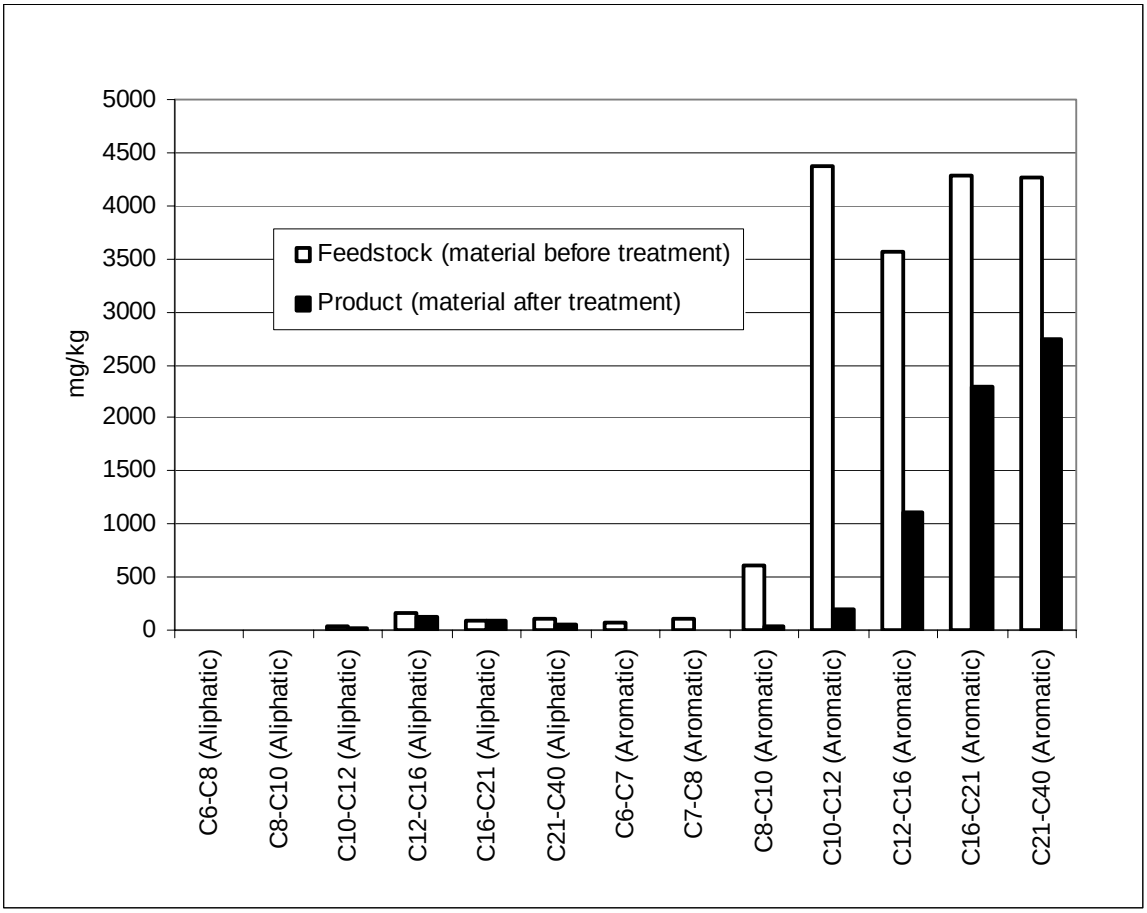


Figure 9.9: Comparison of total petroleum hydrocarbons profiles for the feedstock (material sampled before treatment) and final product (material sampled after treatment) from Trial 3

9.4.2 SLURRY SAMPLES

During this trial, slurry samples were taken on days 2, 3 and 5 (Figure 9.10). Between days 2 and 3 all of the PAHs tested had decreased by between 10 % and 72 %, with no particular bias towards the low molecular weight PAHs. However, between days 3 and 5, all of those compounds except naphthalene recorded an increase in concentration compared to day 2.

Between day 2 and 3 the BTEX compounds decreased by between 67 % and 77 %, and by 92 % to 99 % by day 5.

It was probable that the increase in the PAH contamination (except naphthalene) in the slurry samples was due to both the coal dust and particles containing entrained tar dispersing in the reactor as it was mixed. The mixing would also have caused attrition of the material in the reactor, so releasing more coal dust and particles with entrained tar, leading to more of the contaminated material being transferred into the slurry phase, which was then detected in the sampling. The bias towards a poorer performance in the degradation of most of the PAHs in the slurry would probably have been due to their lower solubility and bioavailability, with the result that they did not degrade as effectively as naphthalene and the BTEX compounds.

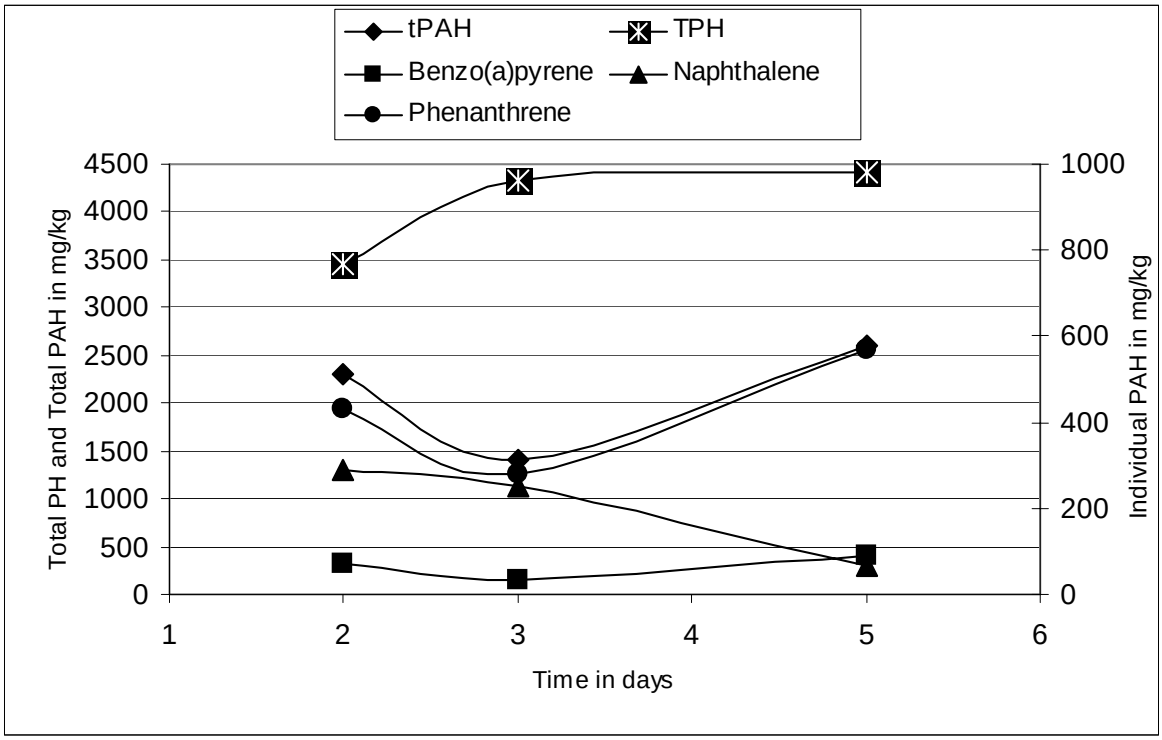


Figure 9.10: Results of the chemical analysis of selected analytes for the slurry samples taken during Trial 3

9.4.3 PRODUCTS

Due to the difficulties in discharging during Trial 3, the products formed were a fines fraction and a mixed, uncentrifuged product formed when the pipework to the reactor had to be dismantled.

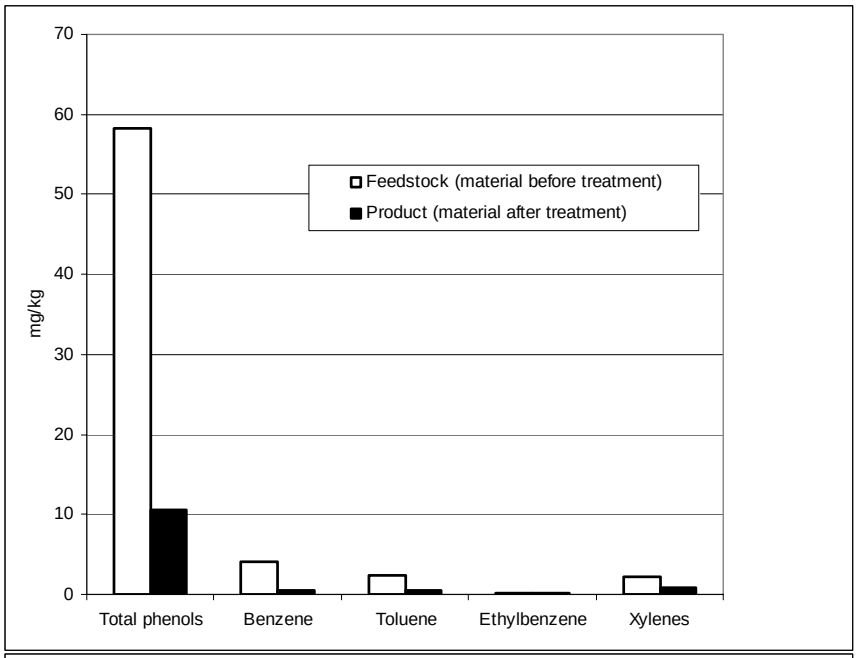
As in the previous trials, the fines fraction was consistently more contaminated after treatment than the mixed product. The concentration of total phenols had, however, decreased significantly from 58.2 mg/kg in the feedstock to 11.4 mg/kg in the fines (Figure 9.11).

Of the PAHs, naphthalene and cyclopenta(c,d)pyrene were the only compounds to reduce in concentration. The naphthalene decrease was not unexpected, as it is quite soluble and is a low molecular weight hydrocarbon; however, it is unclear why 6-ring cyclopenta(c,d)pyrene appears to have degraded in preference to lighter PAHs. All other PAHs became slightly more concentrated, particularly the lower molecular weight compounds. The average total PAH load increased from 2,000 mg/kg in the feedstock to 2,266 mg/kg in the fines.

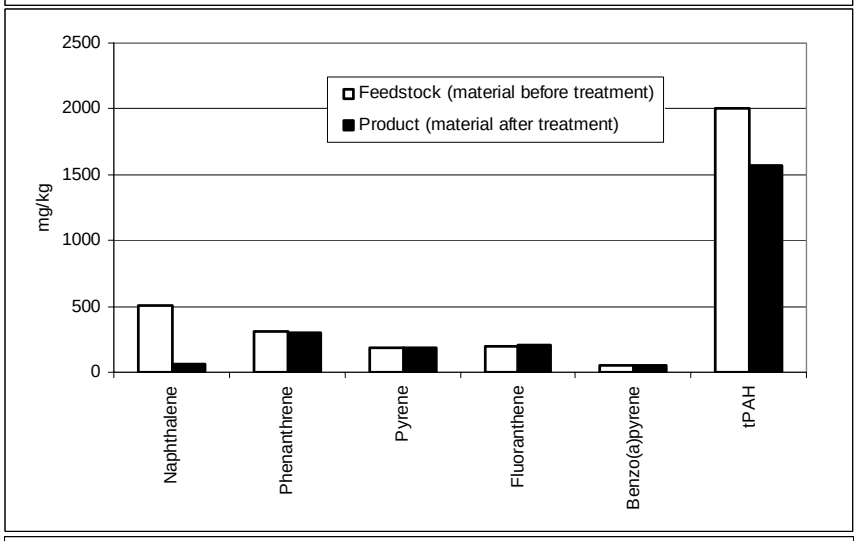
The concentration of total cyanide increased from 18.9 mg/kg to 55.7 mg/kg, possibly due to mixing of entrained spent oxide, which is consistent with the results from the previous two trials. Ammonium and nitrate in the fines also increased significantly from 46.5 mg/kg to 390 mg/kg and from 9.5 mg/kg to 98 mg/kg respectively, which is likely to be due to the use of fertilizer as a nutrient source. Recirculation during this trial was not very effective, so it is possible that not all of the fertilizer was consumed in the biological reactions, so leading to these high residual concentrations.

The concentrations of heavy metals in the fines also increased, particularly lead and zinc, which increased from 488 mg/kg to 776 mg/kg and from 561 mg/kg to 800 mg/kg respectively.

(a)



(b)



(c)

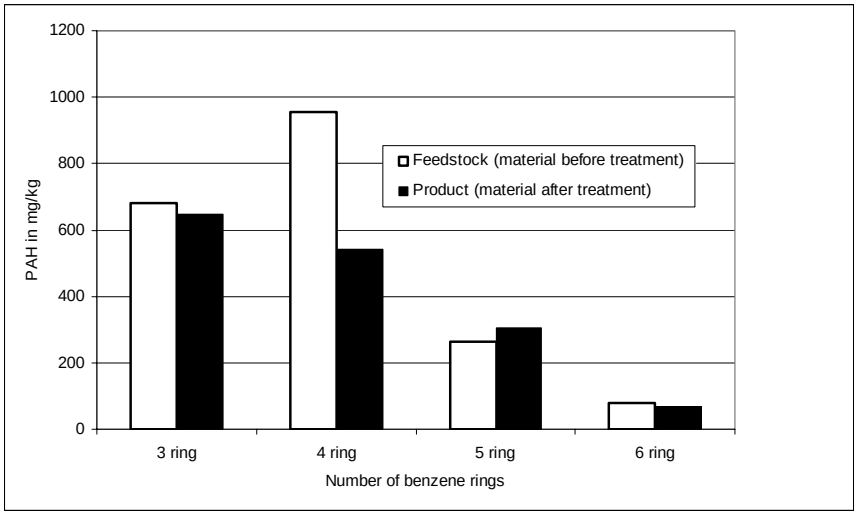


Figure 9.11: Concentration of (a) total phenols and BTEX compounds; (b) selected PAHs; and (c) PAHs grouped according to their number of benzene rings in the feedstock (material sampled before treatment) and final product (material sampled after treatment) from Trial 3

The concentration of BTEX compounds in the fines reduced significantly, with benzene being reduced from 4.2 mg/kg to 0.6 mg/kg (Figure 9.11).

For the mixed product, as in the previous trials, the contaminant concentrations were not as high as those in the fines, the total PAH concentration of 1,266 mg/kg being only approximately half the concentration in the fines.

No geotechnical testing was carried out on the material from Trial 3, as it was anticipated that the results would be consistent with the previous two trials, and testing time was limited. It is estimated that approximately 70 % of the product was recovered mixed and uncentrifuged, with the finer grading making up the remaining 30 %.

When the raw results are corrected to account for this proportion of fines, the concentration of total phenol has reduced by 82 %, from 58.2 mg/kg to 10.5 mg/kg. The PAH results are very variable, with a number of compounds increasing in concentration. Circulation during Trial 3 was not very effective, so increases in concentration may have resulted from partially treated/untreated tar being detected in the product sampling. The lighter PAHs, from naphthalene to anthracene, were degraded to some extent. For naphthalene, this was of the order of 88 % but, generally, degradation was less than 10 %.

The concentration of total cyanide, ammonium and nitrate increased significantly, possibly for the same reasons as in the previous two trials. The whole range of heavy metals also increased in concentration.

In this trial, the BTEX compounds were treated the most successfully, with benzene and toluene reduced by 89 % and 79 % respectively and ethylbenzene and xylene being reduced by 50 % and 59 %, respectively.

In summary, the results of Trial 3 indicate that recirculation was not effective during the trial, and that biological activity was low. This is confirmed by the fact that the concentration of dissolved oxygen remained high throughout the trial.

9.4.4 WATER SAMPLES

The results of water testing before and after Trial 3 (Table 9.8) indicated that the total phenol concentration increased during the trial, from 403 μg/l to 3800 μg/l. This was partly due to the addition of mains water to the reactor at the start of the trial, which would not have had time to become saturated with contaminants and therefore created a dilution effect. The increase in phenolic compounds in the water would have occurred from the dissolution of the phenols from the neat tar into the aqueous phase; since the material was not being mixed effectively then biodegradation would have been limited, with the rate of biodegradation being lower than the rate of dissolution.

In the case of PAHs, the low molecular weight compounds had all increased in concentration by several orders of magnitude, whereas the high molecular weight PAHs had decreased significantly (Figure 9.12). In addition the bias towards the low molecular weight PAHs would be a reflection of the greater solubility of the low molecular weight PAHs, and the poor performance of the bioreactor at degrading the target compounds when mixing was ineffective. This had resulted in the total PAH concentration in the water increasing from 7.99 μg/l to 26.66 μg/l.

The concentration of BTEX compounds in the water had also increased slightly during the trial, with xylene having the greatest increase from 10 μg/l to 42 μg/l.

Table 9.8: The mean concentration of the analytes detected in the water used in the slurry-phase bioreactor, at the start and end of Trial 3 (all concentrations are in µg/l)

Analyte	**Start Trial 3**	**End Trial 3**	**Analyte**	**Start Trial 3**	**End Trial 3**
Cresol	85.7	0.5	Anthanthrene	0.14	0.02
Xylenol & Ethylphenols	120.0	3,800.0	Benzo(e)pyrene	0.52	0.02
Catechol	0.5	0.5	Cyclopenta(c,d)pyrene	0.00	0.00
Phenol	0.5	0.5	**Total PAH**	**8.00**	**26.67**
Trimethylphenol	128.0	0.5	Benzene	10.00	29.33
Total Phenols	**403.3**	**3,800.0**	Toluene	10.00	30.00
Naphthalene	0.60	10.63	Ethylbenzene	10.00	10.00
Acenaphthylene	0.00	0.00	Xylenes	10.00	42.33
Acenaphthene	0.15	2.20	**Total Petroleum hydrocarbons**	**1,914**	**60,046**
Flourene	0.08	5.57	C6-C8 (Aliphatic)	20.0	25.0
Phenanthrene	0.09	6.70	C8-C10 (Aliphatic)	20.0	25.0
Anthracene	0.33	0.71	C10-C12 (Aliphatic)	20.0	25.0
Fluoranthene	0.56	0.45	C12-C16 (Aliphatic)	40.0	732.7
Pyrene	2.94	0.24	C16-C21 (Aliphatic)	40.0	4,266.7
Benzo(a)anthracene	0.08	0.03	C21-C40 (Aliphatic)	100.0	34,136.7
Chrysene	0.12	0.02	C6-C7 (Aromatic)	20.0	25.0
Benzo(b)fluoranthene	0.35	0.02	C7-C8 (Aromatic)	20.0	25.0
Benzo(k)fluoranthene	0.28	0.02	C8-C10 (Aromatic)	20.0	276.3
Benzo(a)pyrene	0.89	0.02	C10-C12 (Aromatic)	399.0	625.3
Indeno(1,2,3-cd)pyrene	0.45	0.03	C12-C16 (Aromatic)	40.0	2,036.7
Di-Benzo(a,h)anthracene	0.05	0.02	C16-C21 (Aromatic)	198.0	4,056.7
Benzo(g,h,i)perylene	0.45	0.02	C21-C40 (Aromatic)	977.3	13,790.0

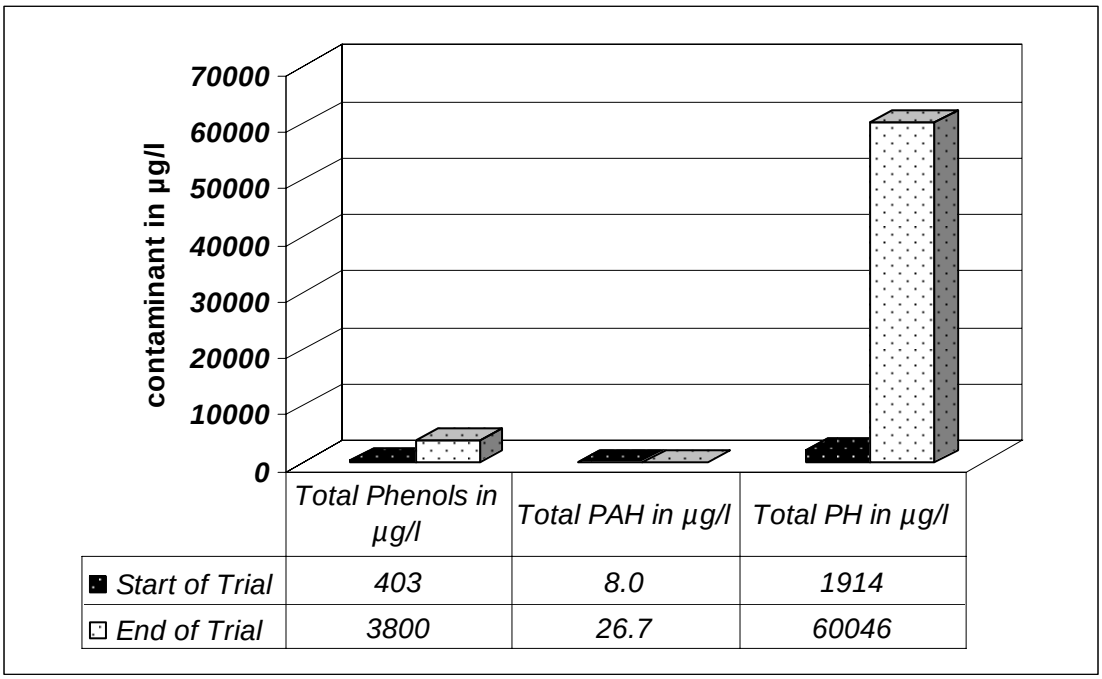


Figure 9.12: The mean concentration of the major groups of compounds in the water used in the slurry-phase bioreactor, at the start and end of Trial 3

9.4.5 OFF-GASES

The off-gases were passed through an activated carbon filter, to remove any contaminants. Samples of the activated carbon were taken from the input port of the filter and no contamination was detected in the activated carbon after the trials, indicating that no hydrocarbon was lost to the atmosphere as off-gas.

9.4.6 MASS BALANCE

The mass balance for Trial 3 is shown in Table 9.9 below. Overall, the reduction in the organic contaminant load for the trial was 24.16 %. These results showed that the process was working to some extent, although, the poor mixing limited the amount of biodegradation that occurred.

Table 9.9: Mass balance of organic analytes in the bioreactor.

	Pre Trial 3	Post Trial 3	% change
Waters (g)	20.53	81.39	-296.35
Soils (g)	14,874	11,214	24.61
Total (g)	14,894	11,295	**24.16**

NOTES:

1) Mass balance columns denote the concentrations recorded for each determinand multiplied by either the volume of water used or the weight of soil used.
2) Average concentrations of organics in soil have been taken from the bioreactor trial - Soil Samples: Appendix B, Table B11.
3) Average concentrations of organics in water have been taken from the bioreactor trial - Water Samples: Appendix B, Table B20.
4) In Table 9.9 a negative figure denotes an INCREASE in contamination.
5) No contamination was detected in the activated carbon after the trials, indicating that no hydrocarbon was lost to the atmosphere as off-gas.

9.5 TRIAL 4

9.5.1 FEEDSTOCK

As discussed in Section 5, tar for the feedstock for Trial 4 was taken from a different compartment of the tar tank than the samples taken for the other trials, and then mixed with other contaminated soil. The material appeared more viscous than the samples for Trials 1, 2 and 3.

The results of chemical testing indicate that the feedstock had a total phenol concentration of 25.5 mg/kg. In the case of PAHs, the feedstock contained a very high concentration of naphthalene (9,650 mg/kg). Other light PAHs were also present generally above 2,000 mg/kg. The concentration of B(a)P was 613 mg/kg.

Total cyanide was present at an average concentration of 3.7 mg/kg. The concentration of BTEX compounds in this feedstock was very low, each compound being present at less than 1 mg/kg.

The results indicate that the feedstock for this trial was considerably more highly contaminated than the previous three trials. However, even though slightly more viscous, there was no obvious reason for expecting the tar to have a higher concentration of contaminants. The bioreactor should have been able to treat this concentration of contamination, providing the mixing in the reactor was efficient. A number of reasons may have contributed to the failure of Trial 4, but likely significant reasons included the increased propensity of the material to stick together forming large particles less likely to stay in suspension, an increase in the occurrence of blocked pipework and the problems with the pump.

9.6 COMPARISON OF ALL FEEDSTOCK AND PRODUCT SAMPLES

As discussed previously in this section, the results of chemical testing of the material excavated on site were variable. In order to assess the degree of variability in the contaminated material, a series of tables has been produced, comparing all the results obtained for the feedstock and the

treated products. These tables are included in Appendix B for reference and are summarised in Table 9.10 and discussed in the following paragraphs.

For the feedstock, 18 samples of contaminated soil mixed with tar have been compared. For total phenols, the concentration varied from 7.4 mg/kg to 130 mg/kg, with an outlying result of 410 mg/kg. The median concentration was 28 mg/kg.

For the PAHs, the highest concentrations were biased towards the lighter compounds, with the highest average value being 631 mg/kg for naphthalene. The average concentration of benzo(a)pyrene was 86.2 mg/kg, but a few samples had concentrations in the hundreds of mg/kg, up to a maximum of 260 mg/kg. The average total PAH concentration was just under 3,000 mg/kg, which was not as high as had been expected on blending tar to soil in a 1:3 ratio.

With respect to the BTEX compounds, the average concentrations were 3.6 mg/kg for benzene, 2.6 mg/kg for toluene and xylene, and 0.3 mg/kg for ethylbenzene. Analysis of the TPH results indicated that the highest concentrations were found in the aromatic carbons bandings between C10 and C40.

For the products, 32 samples have been compared with each other, including both the fines and the coarse fractions, on an equal weighting. The effect of the highly contaminated fines on the overall values for the product is significant. If the fines are included, the average total PAH content is 2,671 mg/kg; if the fines are excluded, the concentration is only 1,184 mg/kg.

Table 9.10: The mean concentration of analytes within the feedstock (before treatment) and products (after treatment) for all the trials (values are in mg/kg except pH)

Analyte	**Mean feedstock conc. (mg/kg)**	**Mean feedstock conc. (mg/kg)**	**Analyte**	**Mean feedstock conc. (mg/kg)**	**Mean feedstock conc. (mg/kg)**
pH	7.7	8.5	Elemental Sulphur	90.4	161.6
% Loss on Ignition	10.0	9.2	Water Soluble SO_4	2,026.7	1,375.9
% Moisture	14.4	19.2	Water Soluble Cl	51.9	50.1
% Stones	29.7	28.2	Exchangeable Ammonium	85.1	93.8
Cresols	14.3	1.0	Nitrate	7.7	27.5
Xylenols & Ethylphenols	26.3	7.1	Arsenic	62.8	59.4
Catechol	0.4	0.1	Cadmium	1.1	0.9
Phenol	6.2	0.5	Chromium	40.4	42.6
Trimethylphenol	13.8	6.2	Lead	462.2	446.6
Total Phenols	60.8	14.7	Mercury	2.2	1.5
Naphthalene	631.7	170.1	Selenium	1.1	0.8
Acenaphthylene	193.7	204.6	Copper	67.8	64.2
Acenaphthene	42.1	44.4	Nickel	36.2	39.0
Fluorene	168.3	170.0	Zinc	523.9	493.8
Phenanthrene	506.7	476.9	Boron	1.5	1.3
Anthracene	154.8	165.8	Benzene	3.6	1.0
Fluoranthene	333.9	378.3	Toluene	2.6	1.0
Pyrene	310.6	372.9	Ethylbenzene	0.3	0.2
Benzo(a)anthracene	114.7	155.9	Xylenes	2.6	1.6
Chrysene	100.7	128.1	**Petroleum Hydrocarbons**		
Benzo(b)fluoranthene	69.9	93.7	C6-C8 (Aliphatic)	11.7	7.9
Benzo(k)fluoranthene	68.3	96.2	C8-C10 (Aliphatic)	11.7	8.8
Benzo(a)pyrene	86.2	116.1	C10-C12 (Aliphatic)	24.2	66.0
Indeno(1,2,3-cd)pyrene	45.4	65.3	C12-C16 (Aliphatic)	74.2	214.6
Di-benz(a,h,)anthracene	12.9	17.5	C16-C21 (Aliphatic)	147.1	175.6
Benzo(g,h,i)perylene	50.8	69.2	C21-C40 (Aliphatic)	87.8	177.6
Anthanthrene	20.8	29.9	C6-C7 (Aromatic)	33.2	5.5
Benzo(e)pyrene	57.3	85.6	C7-C8 (Aromatic)	48.1	5.5
Cyclopenta(c,d)pyrene	6.5	11.0	C8-C10 (Aromatic)	213.2	154.4
Total PAH	**2,988.9**	**2,871.4**	C10-C12 (Aromatic)	2,276.9	710.1
Easily-liberable Cyanide	0.9	1.5	C12-C16 (Aromatic)	1,957.2	1,740.4
Complex Cyanide	16.9	26.7	C16-C21 (Aromatic)	2,506.1	2,293.8
Total Cyanide	17.1	27.9	C21-C40 (Aromatic)	2,737.1	3,107.0

9.7 RESULTS OF AIR MONITORING

The results of air monitoring (see Appendix B) indicated that for the contaminants tested, no concentrations were recorded at or above the detection limit for any contaminant during the trials.

In addition, the results of testing the activated carbon used to filter the off-gases from the reactor also indicated that no compounds were present at concentrations higher than the method detection limit.

9.8 MASS BALANCE

The mass balances for organic analytes in each of the trials has been calculated and are summarised in Table 9.11 and presented in more detail in Appendix B. The raw results for both soil and water have been multiplied by the weight of soil or volume of water used to achieve the mass balance. No air monitoring results have been included, as the results were all below detection limits.

Table 9.11: Summary of the mass balance results for Trials 1 to 3

	Mass balance of organic analytes in the bioreactor		
	Pre Trial 1	**Post Trial 1**	**% Change**
Water (g)	0.10	1.6	-1489.1
Soil (g)	27,239	24,742	9.2
Total (g)	27,239	24,744	9.2
	Pre Trial 2	**Post Trial 2**	**% Change**
Water (g)	227.7	10.00	95.6
Soil (g)	32,483	7,401	77.2
Total (g)	32,711	7,411	77.3
	Pre Trial 3	**Post Trial 3**	**% Change**
Water (g)	20.5	81.4	-296.4
Soil (g)	14,874	11,214.4	24.6
Total (g)	14,894.5	11,295.4	24.2

NOTES:

1) Mass balance columns denote the concentrations recorded for each determinand multiplied by either the volume of water used or the weight of soil used.
2) Average concentrations of organics in soil have been taken from the bioreactor trial - Soil Samples: Appendix B, Tables B7, B9 and B11.
3) Average concentrations of organics in water have been taken from the bioreactor trial - Water Samples: Appendix B, Tables B14, B17 and B20.
4) In Table 9.11 a negative figure denotes an INCREASE in contamination.
5) No contamination was detected in the activated carbon after the trials, indicating that no hydrocarbon was lost to the atmosphere as off-gas.

For Trial 1, the hydrocarbon mass balance showed a loss of 9.2 % overall. This reduction was accounted for as a 9.2 % loss from the solid phase (contamination associated with the soil). The mass of hydrocarbon contamination increased in the water phase. This would have been due to dissolution of the contamination from the solid phase into the liquid phase, and the low rate of degradation would have meant that this was not degraded from the water phase.

The results for Trial 2 are significantly better; the hydrocarbon mass balance showed a loss of 77.3 % overall, with a 95.6 % reduction in the hydrocarbon mass from the water phase (from 227.7 g to 10.00 g), and a 77.2 % reduction from the solid phase (from 32,483 g to 7,401 g).

The performance of Trial 3 was poor, with the hydrocarbon mass balance showing a loss of 24.2 % overall. This was due to a 24.6 % reduction in hydrocarbon mass from the solid phase, and an increase in the mass of hydrocarbon contamination increased in the water phase. Again this would have been due to dissolution of the contamination from the solid phase into the liquid phase, and the low rate of degradation would have meant that this was not degraded.

9.9 MICROBIAL ANALYSIS

The results of the microbial analysis are discussed in the following paragraphs, in the order that the samples were taken. In all cases, sequence matches of 91 % or greater were achieved when compared to the National Center for Biotechnology Information (NCBI) database in the USA. In most cases, the match was 94 % or more. References in brackets refer to publications listed in the references section.

9.9.1 TRIAL 1

During Trial 1 there was a slight increase in the number of bacteria from around 1 x 10^7 colony forming units (cfu)/g to about 1 x 10^8 cfu/g soil after day 5. However, the increase was not as significant as expected. The microorganisms detected in Trial 1 are shown in Figure 9.13.

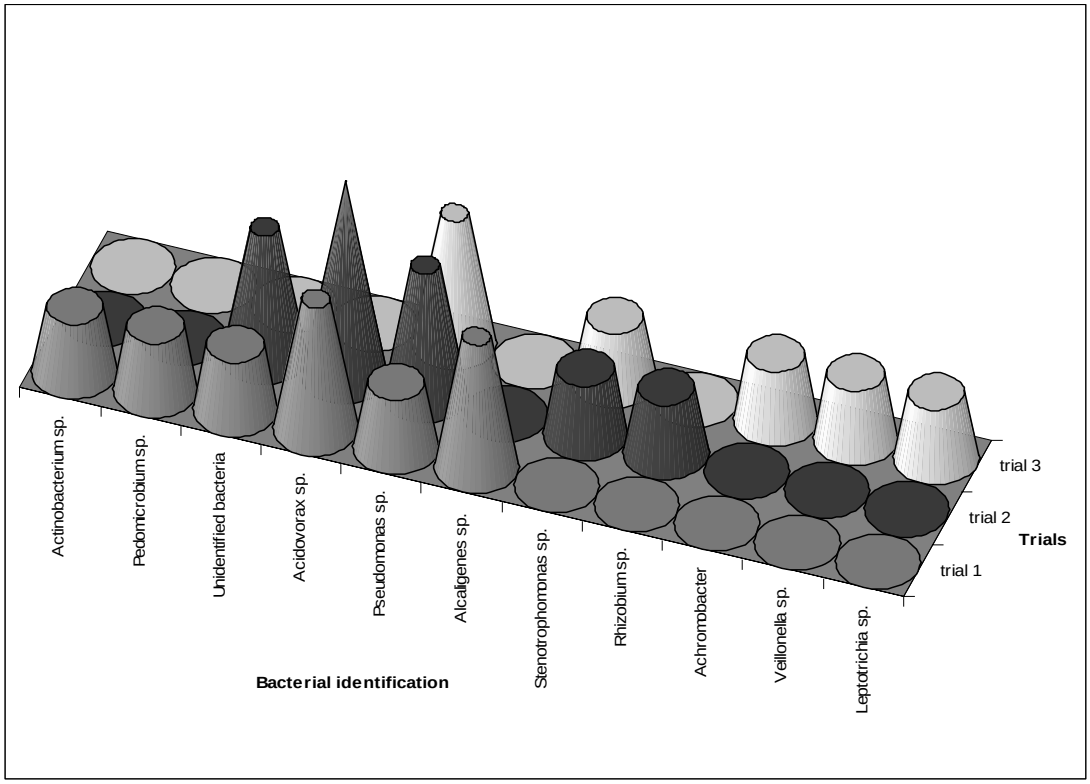


Figure 9.13: Microorganisms detected during the three field trials of the slurry-phase bioreactor

9.9.1.1 Feedstock

Total microbial counts varied from 9.2 x 10^6 cfu/g to 1.1 x 10^8 cfu/g soil, with highest counts on nutrient agar (NA) at 25 °C (this is to be expected as the bioreactor was being operated at 25 °C), and lowest on NA at 37 °C. The more-minimal Burks medium produced an intermediate level of 2.3 x 10^7 cfu/g soil. Microbial identifications from the sludge were diverse, ranging from the actinomycete, *Actinobacterium sp.* to *Pedomicrobium manganicum* and an uncultured cloned bacterium. *Pedomicrobium manganicum and Actinobacterium sp*. have not previously been identified as microorganisms capable of biodegradation, and are therefore unexpected for a soil undergoing bioremediation.

9.9.1.2 Days 2 to 6

Microbial counting indicated that colony concentrations in the slurry were between 10^4 cfu/g and 10^8 cfu/g. The higher counts were again seen on either NA at 25 °C, or Burks at 25 °C, with all of the lowest counts observed on NA at 37 °C.

9.9.1.3 Day 7

Culture-based recovery from this sample was poor, with results obtained from only NA at 25 °C. Recovered sequences were again diverse for this sample, with *Pseudomonas stutzeri*, a bromate reducer closely matched to *Acidovorax sp*. and an *Alcaligenese sp*. all being identified. *Pseudomonas stutzeri* is a common soil bacterium, and it is well documented for the biodegradation of various organic compounds, including halogenated hydrocarbons such as carbon tetrachloride and 2-bromobenzoate and the PAH fluoranthene (Kozlovsky *et al.,* 1993). The bromate-reducing *Acidovorax sp.* was an unusual isolation, as bromate-reduction occurs only in anaerobic conditions, which should not prevail in the aerated bioreactor. However, *Acidovorax sp.* is known to degrade hydrocarbons (Diegor *et al.,* 2000; Alverez, *et al.,* 1998; Song *et al.,* 2000). *Alcaligenese sp*. are well documented for their ability to degrade a range of organic compounds, including polychlorinated biphenyls (PCBs), (Williams *et al.*, 1997), and benzoate and its halogenated derivatives (Schlomann *et al.*, 1990; Layton *et al.*, 1992). These microbial populations are what could be reasonably expected for a soil undergoing bioremediation.

9.9.1.4 Days 8 and 11

Microbial concentration for days 8 and 11 were in the range of 10^7 cfu/g to 10^8 cfu/g, with highest levels again at 25 °C on both NA and Burks agar. A bromate reducer was again identified from this sample, and this was closely matched to *Acidovorax delafieldii.* A non-culturable bacterium matched to one from the phenol-digestion of activated-sludge was also identified, and this was closely related to *Alcaligenes,* though distinct from culture-based sequences listed on the NCBI database. It is likely that these *Alcaligenes sp.* and *Acidovorax sp*. are the same or very similar to those isolated on day 7 and, as mentioned above, they are well documented in degrading hydrocarbons and organic contaminants.

9.9.2 TRIAL 2

9.9.2.1 Feedstock

Microbial levels in the Trial 2 feedstock were again all in the order of 10^7 cfu/g sludge. Although PCR-cloned sequences were recovered from this sample, only one of three generated a sequence of suitable quality to allow microbial identification. The reason for the failure of the other two sequences was unclear. The successfully identified sequence was that of *Stenotrophomonas maltophilia,* a Gram-negative bacterium previously classified as both a *Pseudomonas* sp. and a *Xanthamonas* sp., but now enjoying its own, distinct genus classification. *Stenotrophomonas maltophilia* was previously identified in the laboratory-scale trials and is well documented to degrade PAH, pentachlorophenol, dioxins and dibenzofurans (Oakley *et al.,* 2002; Lantz *et al.,* 1995; Lantz *et al.,* 1997 and Boonchan *et al.,* 1998). *Stenotrophomonas maltophilia* is characteristic of a contaminated soil undergoing aerobic bioremediation.

9.9.2.2 Days 1 to 4

On day one of Trial 2 microbial levels were slightly lower, at 10^8 cfu/g to 10^7 cfu/g slurry, although some overgrowth did occur on the M11 Burks medium, which prevented accurate counting of that sample. The microbial levels attained some of their highest levels on day 4 of Trial 2, where cfu numbers in the order of 10^9/g were noted. No sequence data were requested for these samples.

9.9.2.3 Day 7

The very high levels of microorganisms continued to day 7 (the final day of the trial) – levels of the order of 10^9 were noted on NA and Burks at 25 °C. Two distinct *Acidovorax sp*., as well as the previously unidentified bromate-reducing bacterium similar to *Acidovorax sp.,* were identified. Again the bromate-reducing *Acidovorax sp.* was an unusual isolation as bromate reduction occurs only in anaerobic conditions. As previously noted, *Acidovorax sp.* are known to degrade a wide range of hydrocarbons (Diegor *et al.,* 2000; Alverez, *et al.,* 1998; Song *et al.,* 2000). In addition to the *Acidovorax sp., Pseudomonas gingeri,* a *Rhizobium sp.* and *Pseudomonas stutzeri* were all identified by PCR-cloning. The identification of *Pseudomonas sp.* on contaminated sites is very common; they are probably the most regularly identified microorganisms involved in the

biodegradation of organic compounds (Kastner *et al.,* 1998; Mahaffey *et al.,* 1988*;* Stringfellow *et al.,* 1988; Grimberg *et al.,* 1996; Stringfellow *et al.,* 1994; and Eaton *et al.,* 1994).

9.9.3 TRIAL 3

9.9.3.1 Feedstock

All cfu counts were in the order of 10^7 cfu/g sludge. An *Achromobacter sp.,* previously associated with PAH-contaminated sludge, was identified, as were *Stenmaltophilia sp.* and *Pseudomonas stutzeri.*

9.9.3.2 Days 2, 4 and 5

Microbial counts were seen in the range 10^7 cfu/g to 10^8 cfu/g sludge, with overgrowth of plates on NA at 25 °C and 37 °C for day 5. Burks medium indicated levels of 7.8 x 10^8 cfu/g (25 °C). These levels were slightly elevated above that of the feedstock, though not as significantly as might have been expected. There was greater growth of microorganisms on plates incubated at 37 °C than at 25 °C, indicating that the bioreactor was warmer than 25 °C at the time.

9.9.3.3 Day 7

Microbial counts were again in the order of 10^7 cfu/g to 10^8 cfu/g, with a diverse range of bacteria now identified. *Pseudomonas stutzeri*, a previously uncultured *Veillonella sp*. and a *Leptotrichia* sp. were identified from cloned sequences. The *Pseudomonas stutzeri* is a common soil bacterium associated with bioremediation. *Veillonella sp*. and *Leptotrichia sp*. are quite unusual organisms to find associated with bioremediation processes. *Veillonella sp*. has been associated with the anaerobic biodegradation of dinitrophenols and *Leptotrichia sp.* has been associated with the disease bacteremia, but not in biodegradation processes.

9.10 DISCUSSION

Very little variation in cfu counts was observed across Trials 1 and 3. However, Trial 2 did show an increase of two orders of magnitude during the trial, in particular on days 4 and 7. The increase in cfu counts was due to the better mixing and aeration of the slurry, providing a more effective environment for microbial growth and biodegradation of the contaminants. This seems to have been accompanied by some considerable variation in the composition of the microorganisms present at the various stages of sampling.

As with the laboratory trials undertaken earlier, many of the closest matches to sequenced DNA were determined from previously cloned sequences found on the NCBI database, i.e. not from sequence data derived from cultured bacteria. This in turn suggests that many of the organisms identified in the samples taken during this demonstration project are novel, and have not previously been studied from cultured sources. (The ability to identify a particular microorganism is dependent on whether other workers have interrogated similar environments using PCR-cloning approaches, and it may be that some of the bacteria described here would only be culturable with difficulty).

Despite this, some workers have recovered isolates from the same genera as those described here and have done so from similar environments. Meyer *et al.*, (1999) studied PAH-degrading isolates from wastewater and soil samples, and recovered a number of *Acidovorax* and *Pseudomonas* species. Most of these isolates exhibited the 2,3-dioxygenase activity that allowed the bacteria to use PAHs as their sole carbon source. This activity was assessed by the Meyer group using PCR, and following an initial isolation of colonies. The ability of Proteobacteria such as *Acidovorax* and *Pseudomonas* to utilise halobenzoates was demonstrated by the work of Song *et al.*, (2000). These and other related genera within the Gram-negative Proteobacteria are known to exhibit this physiological ability under denitrifying conditions, and such microorganisms are widely distributed in soils and sediments.

It was interesting to note that another Gram-negative bacterium, *Rhizobium*, was detected during work performed on sample M14. This bacterium is associated with nitrogen fixation - as opposed to denitrification – and this typically occurs in the root micro-environment of higher plants, where suitable carbon sources (sugars) are abundant. In view of its fastidious nature it is unlikely that we

would have recovered *Rhizobium* by the culture-based approach. The presence of this and other microbial genera here gives a good indication of the physiological complexity of the bacterial populations within such samples.

Stenotrophomonas maltophilia, like many other Gram-negative microorganisms, is known to harbour plasmid-based genetic determinants, but its presence here is surprising. This bacterium is unusual in that it has also been identified as a significant cause of hospital acquired infection (HAI), where it has been cultured from drains, showerheads and other high-moisture environments inside hospitals. In the HAI context, it is readily culturable and is known to carry plasmid-based resistance to a number of antibiotics (Denton and Kerr, 1998). Previously classified as a Pseudomonas species, it is now recognised as genetically distinct and resides within its own genus.

Figure 9.14 shows the changes which have occurred in the diversity of the microorganisms detected during the laboratory and field-scale trials. As is common for bioremediation projects *Pseudomonas sp.* was the most consistently identified microorganism appearing in all but one of the trials (Mueller *et al.,* 1989, 1990, 1991; Eweis *et al.,* 1998; Cerniglia 1992; Pothuluri and Cerniglia, 1995).

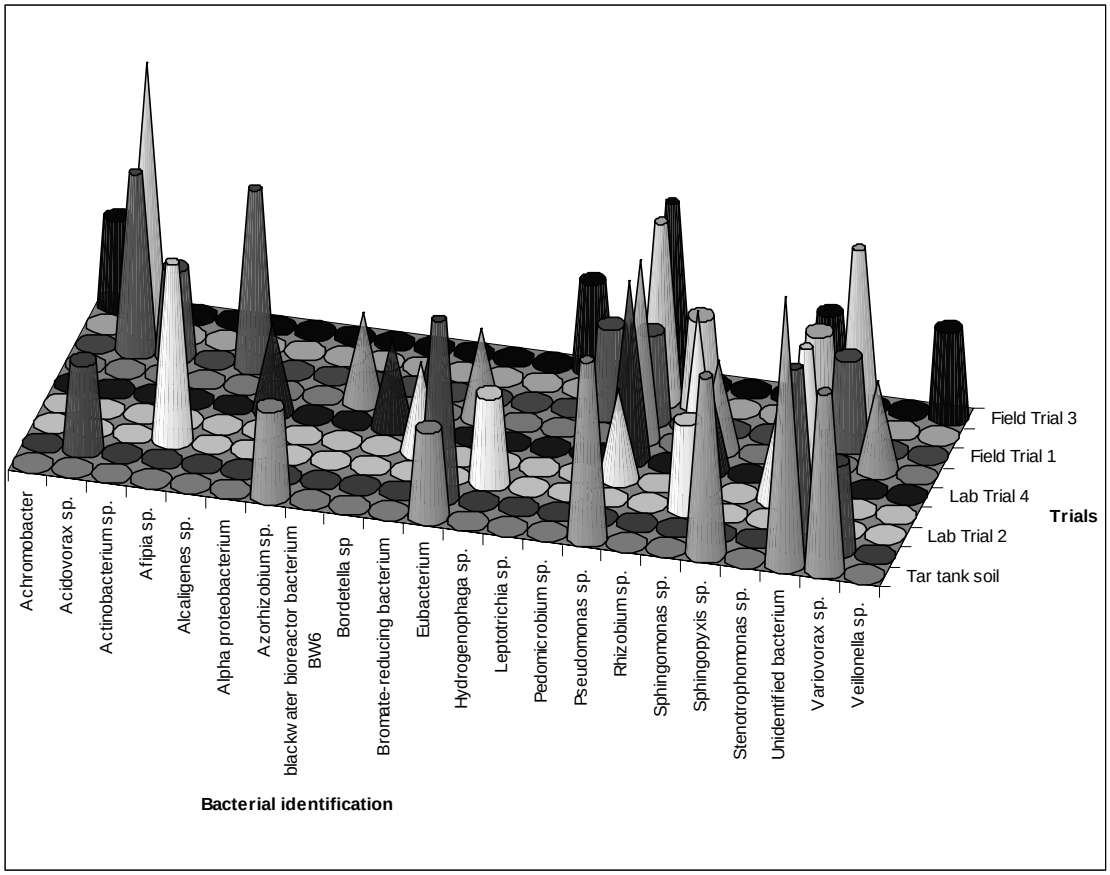


Figure 9.14: Microorganisms detected during the laboratory and field trials of the slurry-phase bioreactor

The microbial descriptions provided here are not exhaustive, but have been undertaken to illustrate that many of the bacteria identified from this demonstration project are well adapted to the chemically contaminated sludges and soils from which they were detected. Not only do they tolerate these conditions, but also these same bacteria can actively utilise the 'toxic' substances in their environment to survive and grow, during which process recalcitrant chemicals may be usefully degraded.

9.11 CONCLUSION

The conclusions from the microbial investigation of the field-scale trial are thus:

- There was only a limited increase in the number of microorganisms in Trials 1 and 3, where mixing was poor.
- A significant increase in the number of microorganisms was noted during Trial 2 where the mixing was the most effective and was also suggested by the degree of foaming that occurred.
- The composition of the microorganisms through the trials was highly variable.
- Many of the species were similar to clones previously detected in environmental samples. Some were little-studied strains.
- During the most successful trial (Trial 2), the slurry became predominated by species of *Pseudomonas* and *Acidovorax*.

9.12 GEOTECHNICAL TESTING

Sixteen bulk samples of product from the bioreactor trials were sent to Exploration Associates for geotechnical testing, including eight samples taken of the recombined product from both Trials 1 and 2.

The samples from each trial were scheduled for the following tests:

- Moisture contents (x8);
- Atterberg limits (x4);
- Particle size distributions (PSDs, x8);
- 4.5 kg Compaction (x1);
- Water soluble sulphates (x6);
- Acid soluble sulphates (x2).

The aim of the geotechnical testing was to determine whether the product from the bioreactor trials could be reused as an engineering fill using the Core Remediation Specification, Land Remediation Programme 2002 produced by SPH for use on their remediation projects. The results indicated that:

- The products from the trials were unsuitable for use as an engineering fill (class 1A/1B) due to high moisture content. However, it is possible that with further improvements to the dewatering system, or by draining on site, the material could be dried to within acceptable limits
- The design sulphate class of the product is DS-1(less than 0.24 % total sulphate and below 1.2 g/l sulphate in a 2:1 water:soil extract (BRE Special Digest 1)
- The Aggressive Chemical Environment for Concrete (ACEC) classification of the product is AC-1

In summary, except for the fact that it remained initially too wet for immediate reuse, the treatment process had no detrimental impact on the quality of the material.

9.13 PERFORMANCE SUMMARY

The performance of Trial 2 was significantly better than both Trials 1 and 3, which is consistent with the more effective recirculation noted in Trial 2 and it is considered that the results from Trial 2

represent the reductions in contamination that can be achieved by this treatment when it is working successfully.

It is possible that, in future work, the amount of nutrients (fertilizer) added could be reduced slightly to avoid the residual concentrations of ammonium and nitrate recorded in these trials.

10. ECONOMIC EVALUATION

10.1 COST OF TRIAL

The total cost of the trial was approximately £231,000. Approximately £103,000 was spent in making improvements to the reactor after the previous trial, and in design and installation of the new telemetry system. A further £120,000 was attributed to the site preparation, running costs, maintenance and laboratory testing; of this figure, the laboratory testing (chemical, geotechnical and microbiological) amounted to approximately £18,000. Removal of the reactor, packaging and storage to date is approximately £8,000.

10.2 COST OF TREATMENT

Twenty-five tonnes of material were treated over the 3 trials. It is unrealistic to determine a treatment cost per tonne based on the total cost of this work, as a significant amount relates to development costs of the reactor. However, in order to define the costs of using the reactor, a series of possible scenarios has been developed, as detailed below. These scenarios are based on the assumption that further design changes and modifications required on the bioreactor would have been undertaken.

10.2.1 SCENARIO 1 – SINGLE BIOREACTOR PERMANENTLY LOCATED ON SITE

It is envisaged that the bioreactor could be permanently located on a site such as a landfill or gasworks, and have material brought to it for treatment. The costs defined in Table 10.1 have been estimated based mainly on the running costs of the trials. However, broader estimates have had to be made relating to such aspects as water disposal and provision of a permanent electricity supply.

Table 10.1: Single bioreactor costs

Description	Unit	Quantity	Rate (£)	Amount (£)
a) Running Costs				
Electricity running costs (permanent supply)	day	9	35	315
Plant for loading bioreactor/mixing feedstock/moving product	hr	10	12	120
Maintenance	Per batch	1	100	100
Disposal of contaminated water [Note 1]	Per batch	1	75	75
Water (25,000 litres per 10 batches)	Per batch	1	50	50
b) Labour				
Sampling/Maintenance Operative	hr	30	12	360
Extra labour for loading & discharging	hr	10	12	120
Engineer (part time)	hr	10	25	250
On call costs	Per batch	1	100	100
c) Testing				
Samples of feedstock	Per batch	5	106	530
Samples of product	Per batch	10	106	1060
Microbiological plate counts (to assess bacterial count in water at end of batch)	Per batch	1	50	50
Transportation of samples	Per batch	1	50	50
Total				**3,180**

Note 1 Figure for disposal of contaminated water based on water being disposed of after 10 treatment batches. Cost of disposal up to approximately £1500 for 25,000 litres, dependent on quality. An on-site water treatment centre may be more economical.

The scenario is based on a maximum of 10 tonnes of contaminated feedstock undergoing 7 days of treatment in the bioreactor. The average contaminant concentration of the feedstock would ideally be similar to that of Trial 2. Preparation of feedstock, loading and unloading of the reactor is estimated at 2 days; however, with further improvements to the reactor, this could be reduced.

It should be noted that the sampling regime quoted in Table 10.1 is based on the operation during these trials and is more onerous than what would be required when operated commercially, and when greater experience has been gained from using the equipment. This cost could possibly be reduced to half of the current cost.

The cost per tonne for a single bioreactor would therefore be of the order of £320. Although this cost is high, it is comparable with incineration of similarly contaminated materials. However, it is likely that cost savings could be achieved by using a number of reactors in a treatment chain, as defined in Scenario 2. Another possible area for cost saving could be to reduce the density of samples taken.

10.2.2 SCENARIO 2 – MULTIPLE BIOREACTORS

This scenario is based on 10 tonnes of soil being treated for 7 days in each of six separate bioreactors. The reactors would run from one power supply, and would share such items as plant, labour and telemetry. The reactors would be run in tandem, so that there would always be loading, treatment or unloading activities being undertaken. However, it should be noted that there would be a very significant capital cost for building six of these units.

Table 10.2: Multiple bioreactor costs.

Description	Unit	Quantity	Rate (£)	Amount (£)
a) Running Costs				
Electricity running costs (permanent supply)	6 batches	1	1,350	1,350
Plant for loading bioreactor/mixing feedstock/moving product	hr	46	12	552
Maintenance	6 batches	1	600	600
Disposal of contaminated water Note 1	6 batches	1	450	450
Water (25 ,000 litres required after 10 batches of contaminated soil treated)	6 batches	1	300	300
b) Labour				
Sampling/Maintenance Operatives (*2)-assuming turnaround of batches is maximum 12 days	hr	192	12	2,304
Engineer (part time)	hr	25	25	625
On call costs	6 batches	1	200	200
c) Testing-assuming reduced costs due to higher sample numbers				
Samples of feedstock	6 batches	24	95	2,280
Samples of product	6 batches	48	95	4,560
Microbiological plate counts	6 batches	6	50	300
Transportation of samples	6 batches	3	25	75
Total				**13,596**

Note 1 Figure for disposal of contaminated water based on water being disposed of after 10 treatment batches. Cost of disposal up to approximately £1500 for 25,000 litres, dependent on quality. An on-site water treatment centre may be more economical.

If the cost of treating 60 tonnes of contaminated feedstock is approximately £13,600, the cost per tonne would be approximately £227. This is a saving of £91 per tonne compared to operating in single-batch mode.

It should be noted that the sampling regime quoted in Table 10.2 is based on the operation during these trials and is more onerous than what would be required when operated commercially, and when greater experience has been gained from using the equipment. This cost could possibly be reduced to half of the current cost.

The bioslurry reactor was designed to handle up to 16 tonnes of soil and was also designed so that it could be extended to handle 60 m^3 of slurry and a maximum of 24 tonnes of contaminated feedstock per trial. However, it may be optimistic to assume that the process would work effectively on material similar to that treated during these trials. Extrapolating costs from the data above gives a minimum cost of £94 per tonne, which should be competitive within a specialist market after the introduction of further regulations requiring pre-treatment and banning certain wastes (corrosive, liquid and flammable) from landfills. The design of slurry-phase bioreactor technology used during this project - and in deriving these costs - would not be the most cost-effective method of employing the technology, as the volume treated is limited to the size of the reactor vessel. If a significantly larger vessel could be constructed then a greater quantity of soil could be treated, thus reducing the unit costs of the process.

The reactor design use in these trials is not the most practical for materials-handling or from the civil engineering aspect. The current design is suitable for fine silts and clays, which are easily fluidized, the most obvious applications being for the treatment of soil washing fines and screened dredgings. However, for use with soils, further design modifications would be required to optimise the process and make it more robust and cost-effective, so that more practical operation could be achieved. Likely design changes are discussed in Section 11.2.

10.3 TREATMENT TIMESCALE

If a series of 6 bioreactors were employed to treat a site with 10,000 tonnes of tar-contaminated material, approximately 166 six-batch runs would be required. As each batch may take 7 days, the treatment time would be approximately 3 years.

Using the extended design with a capacity of 60 m^3 of slurry/24 tonnes of feedstock per trial, the timescale for treatment would be reduced to 69 weeks.

Ideally the system needs to be designed to treat the contaminated material within a period of 10 to 20 weeks, in line with other aspects of the site remediation, which would require a reactor with a volume of between 1,250 m^3 to 2,500 m^3. Such a volume would be unfeasible for one unit (20 m x 20 m x 6.25 m for a 2,500 m^3 batch), so a number of smaller units would be more feasible (for example 5 to 10 units, each 13 m x 5 m x 4 m).

10.4 ESTIMATED LANDFILL COSTS

In comparison to the treatment costs detailed above, the cost of disposal of hazardous waste of this nature to landfill is currently approximately £90/tonne. This is made up from landfill tax at £13/tonne, disposal charge at £72/tonne, haulage at £4-5/tonne, and the cost of consignment notes. However, in the case of contaminated land originating from historical uses, this material is usually exempt from landfill tax.

The Pre-Budget speech of December 2002 by the Chancellor of the Exchequer detailed the Government's plans to consult on an increasing landfill tax escalator. The current £13/tonne is likely to rise by £3 a tonne from financial year 2005/2006. In addition to these increasing costs, the largest effect on the cost of landfill disposal of coal tar contaminated waste will be the European Union (EU) Landfill Directive which will restrict the waste disposal to hazardous waste landfill sites only. As of the 1st July 2004 there are only three merchant landfill sites able to accept the type of contaminated material treated during the project reported here. This will significantly increase the cost of landfill disposal for such material. It is probable that costs will increase significantly in excess of the £72 figure quoted above, and with significantly increased haulage distances required to transport the material to a suitable landfill. As yet no-one is sure of the future of hazardous waste disposal to landfill, but it will certainly be much less favourable than current conditions.

It should also be noted that as a result of the Landfill Directive it is possible that coal tar material may be excluded from disposal to landfill in July 2005. The impacts of this legislation are discussed in Section 11. Landfill would then not be an available disposal route and alternative remediation methods would be required, such as slurry-phase remediation.

The main alternatives to landfill for this material which exist currently are on-site thermal desorption and incineration. Current market costs for these techniques are approximately £100/tonne and £300/tonne to £750/tonne respectively, dependent on the level of contamination and moisture content of the material. For on-site thermal desorption to be cost-effective then a very significant quantity of contaminated material is usually required (tens of thousand of tonnes). Licensing of thermal-based treatment systems can also be a complex, long and costly issue if they come under Integrated Pollution Prevention and Control (IPPC) rather than under a Mobile Plant Licence. Some companies in continental Europe are willing to import waste for thermal treatment at specialist waste treatment centres, at generally lower cost than on-site treatment, provided that clearance can be gained for transboundary shipment of the waste.

The development of any new remediation technology (such as the slurry reactor) to tackle complex wastes such as coal tars depends heavily on the attitude of the Government and regulatory bodies to reduce the UK's dependence on landfill, especially in the disposal of hazardous wastes. Only by

making the economics of landfill disposal significantly more unfavourable, will the UK make greater strides towards sustainable remediation. The Landfill Directive would appear to be the first step in tipping the economic balance towards such more sustainable remediation techniques.

11. CONCLUSIONS AND RECOMMENDATIONS

11.1 BIOREACTOR PERFORMANCE

Despite the physical difficulties encountered in operating the bioreactor, the results of these trials demonstrate the two key points of the technology: the process can bioremediate coal tar contaminated made ground effectively and the process is capable of effectively biodegrading the more recalcitrant and toxic 5- and 6-ring PAHs.

The results for Trial 2 in particular indicate significant levels of contaminant degradation, especially with respect to PAH. Low molecular weight PAHs were degraded by up to 95 %. However, the most promising results were associated with the high molecular weight PAHs such as benzo(a)pyrene (B(a)P), which decreased by 68 %. These results indicate how successful slurry-phase bioremediation can be in treating such contaminants within a short time-frame.

The results from Trial 2 were in line with expectations from the extensive laboratory and pilot-scale trials undertaken previously at Advantica where on average 70 % to 80 % of both the total PAH content and B(a)P was degraded. It had been found previously that for materials which were composed of made ground contaminated with coal tar, the maximum decrease in both total PAH and B(a)P content was about 80 %. The reason for this being that the majority of the PAH content of large agglomerated particles, coal dust or solid tar particles within the made ground would not be bioavailable. Only very soluble fractions such as naphthalene would be degraded significantly as they could diffuse from the particles more rapidly. For certain natural strata such as clay, sand and chalk, the performance of the slurry-phase bioreactor could be significantly increased to achieve near to 100 % biodegradation of the organic compounds.

Trials 1 and 3 recorded similar patterns of degradation, but not to the same degree as Trial 2. It is thought that the problems with recirculation of the slurry during these trials may have contributed to the lower rates of degradation.

The trials were also successful in that they demonstrated the use and applicability of remote telemetry in remediation projects; the system enabled the trials to be run on a 24-hr basis without continual supervision, therefore reducing the labour costs. It also resulted in a unique detailed database of information on the treatment process. This system can be developed further, if required, with very little additional cost input.

The trials were carried out with a best practice approach to environmental management, reflected from the beginning of the work in the construction of the purpose-built treatment and soil containment pens, with the best practice being continued through to completion, including the on-site treatment of contaminated water.

The concept of fitting this remediation trial into the main remediation of the gasworks was also successful, in that it allowed plant and labour to be shared between the work areas, thus keeping the costs down. The relationship amongst the various parties involved was generally good, with all parties contributing ideas to improve processes and develop solutions where problems occurred.

The main problems encountered in the trials related to difficulties in achieving adequate slurry recirculation, particularly on discharge of the slurry to the centrifuge/shaker. In the first instance, the pump capacity was not sufficient to maintain the material in suspension and circulate it sufficiently. The pump was upgraded prior to being brought to site, but it appears that this upgrade was not enough to cope with the demands of the variability in material size encountered.

In addition, where recirculation was a problem, some of the silt fraction settled out in the pipes, gradually blocking them. This led to further reduction in flow, adding to the circulation difficulties. During discharge, once the material started to move downwards towards the exit pipework, the pump again struggled to keep the material in suspension, and material settled out, blocking the pipework.

It is possible that some of these recirculation problems could be addressed by increasing the size of the motor on the pump. However, the pump would then have to be tested on a variety of material types and gradings to ensure that the problems had been solved. On this occasion, due to time constraints, the pump had not been tested with any materials specific to this project prior to installation, though it is used extensively on mineral processing sites worldwide for pumping gravels and sands.

Material size, suitability and handling proved to be some of the most difficult issues to be addressed in this project. Screening of the tarry material from the tar tank, to remove bricks and concrete, was one of the most challenging tasks, as the viscosity of the tar caused it to stick to any plant used. Screening was also very time-consuming.

In spite of the difficulties faced by screening the material, if the screening had been more effective initially, then the first trial would probably have been more successful. However, if the pump had been operated to its full capacity, or a more powerful pump had been used, then material grading may not have been such a critical issue.

It is possible that the size and layout of the pipework at the base of the reactor may also have contributed to the inefficiency of the pump. The internal diameter of the pipework reduced from 6 inch (152 mm) to 4 inch (101 mm) on exiting the pump, returning to the larger diameter of 6 inch (152 mm) shortly afterward, causing a velocity reduction which resulted in some of the slurry falling from suspension and coating the walls of the pipes. It is possible that the size reduction may also have caused a bottleneck, so leading to the failure of the pump.

The trials were conducted using a temporary electricity supply from a generator. This cut out very briefly on a number of occasions, which is a problem common to temporary supplies. The losses of the electricity supply caused problems with the electrical system, resetting the load cells, and the telemetry system (however, this did automatically restart). In future, it is recommended that a permanent supply be installed to minimise such problems. The relative cost of installing a fixed supply would reduce the longer the rig was operated and the greater the number of rigs operated at once.

As discussed above, the main problems encountered during this work have been associated with the lack of robustness of the bioreactor. The reactor needs to be able to handle changes in material size and density, loading weights and water volume, without loss of performance. At the moment, labour input at the front end is too intensive for a commercial-scale process. The turnaround time between trials also needs to be reduced.

The project has, nonetheless, demonstrated that heterogeneous, severely-contaminated material can be remediated using a sustainable biological process. It demonstrates that the limitations observed in scientifically robust trials of solid phase bioremediation can be overcome by undertaking remediation in the slurry phase. It has demonstrated that with further development, slurry-phase remediation could be used on a commercial scale, allowing compliance with the EU Landfill Directive and minimising the use of landfills.

11.2 APPLICABILITY AND POTENTIAL FUTURE DEVELOPMENTS

In order to move on from the problems encountered, and capitalise on the results of Trial 2 and previous work undertaken at Advantica, there are two main options for future development:

- Undertake a full re-evaluation of the system, leading to the construction of a new design based on minerals processing technology that is able to handle this type of material; or

- Further improve and upgrade the existing bioreactor system.

From the time and cost assessment detailed in Section 10, it is apparent that even with multiple reactors operated in parallel, the throughput is still not high enough to be commercially viable and due to the low batch volume, the treatment time for the average site is still too long. However, this form of treatment is still much quicker than conventional, solid-phase bioremediation in terms of treatment times, and treats a greater range of organic contamination more effectively.

Operating more than 6 reactors at a site is considered to be unfeasible, both on the grounds of space availability, number of vehicle movements for loading and unloading and the labour input involved. One full-time operative could operate a maximum of 3 bioreactors, with support on the loading and unloading tasks.

The only scenario where this process would be effective would be to use it on the end of a soil washing process, where the relatively small amount of fines (e.g. in these trials, 6 %) could be treated in a timely fashion within the remediation programme. Other scenarios where the technology might be effective in its current form would be the bioremediation of hydrocarbon-contaminated dredgings or drill cuttings from oil rigs (where space is limited).

On the other hand, it may be better to significantly change the design of the reactor before further use. Now that it is known that the bioengineering principles behind the process work, it may be better to adopt a very simple approach and build a type of treatment tank where material would be poured in, rather than pumped. Circulation could be achieved by a method such as the use of a continuous paddle with continuous air injection. This is a system similar to that used in the treatment tanks in sewage treatment works. If the system is kept as simple as possible, many of the problems that have been encountered could possibly be eliminated. A more effective method of dewatering would have to be designed in conjunction with the new system. It is recommended that design ideas be sought from suitable process engineers based on the information provided in this report, in order to develop a more robust treatment. This system could be either mobile, or installed at a fixed facility and could potentially be much larger in capacity than the current reactor

For the specific purpose for the slurry-phase bioreactor used during these trials, developing a new system may be a more practicable option than attempting large-scale changes to the current vessel.

The key factors to be considered in the redesign are:

- The loading and screening systems should be incorporated into one process to reduce pre-processing and handling time.

- Dependence on the use of pumps to recirculate the slurry should be reduced or removed and replaced with an alternative or hybrid (using pumps in combination with other methods) system.

- Unloading needs to be undertaken in one continuous process. Material that easily falls from suspension should be gravity separated and dewatering systems such as centrifuging should only be targeted at the slurry fines.

- Though there were issues with the soil mixing on the current design, the bioreactor was a very effective system for the growth of microorganisms and biodegradation in the aqueous phase. The current design would provide a highly efficient process for the treatment of contaminated water. The reason for this is due to the effectiveness of the pH, foam, temperature, dissolved oxygen supply and control systems, and this effectiveness needs to be designed into any future system.

- The system designed for this project was a mobile plant, but when units are intended to be mobile this significantly limits the design parameters, as the system needs to be easily transported between sites. The design and material choices for a permanent fixed facility would be significantly different, as a number of constraints would be removed.

Each of the above points is now discussed with potential solutions highlighted.

11.2.1 LOADING

Loading of the bioreactor during this trial was carried out using a telehandler with a bucket of a 0.5 m^3 capacity. The loading process used during these trials was time-consuming and required the use of labourers to load the telehandler, which would be ineffective on any large-scale project. In the previous trial a conveyor had been used, but this spilt a significant amount of material, and dust was also a problem.

The constraints on the loading system depend on the design of reactor. With the current format, material would need to be supplied on a more even basis rather than dropping 0.5 tonne batches of soil into the vessel. This may have been a contributory factor in the pump failing as the batches of soil may have blocked the pipework.

Ideally, if the plant were redesigned to form a horizontal vessel, then loading could be more easily achieved using direct loading by an excavator or by using a covered conveyor. To make the process more straightforward a powerscreen could be used to remove oversize material and to gradually feed soil to the vessel or conveyor.

Another option could be the use of a screw filler/auger that would load at an even rate into the vessel, without spillages, although this system could be prone to blockages if oversized material got into the auger.

11.2.2 MIXING SYSTEM

For contaminated water and easily suspended slurries (e.g. from a soil washing process) the current design would be a very effective solution. However, the current design is not optimal for the treatment of soils forming slurries where the particles easily fall out of suspension. For such slurries a variety of alternative mixing configurations could be used, these include:

A horizontal tank, with paddle stirrers suspended over the top of the tank with continuous air injection to the base of the tank, similar to the treatment tanks used in sewage treatment works. This design could be easily built and tested on a current sewage treatment works.

A rotating vessel, based on the design of cement batching plants. Figure 11.1 represents the conceptual design for such a horizontal reactor.

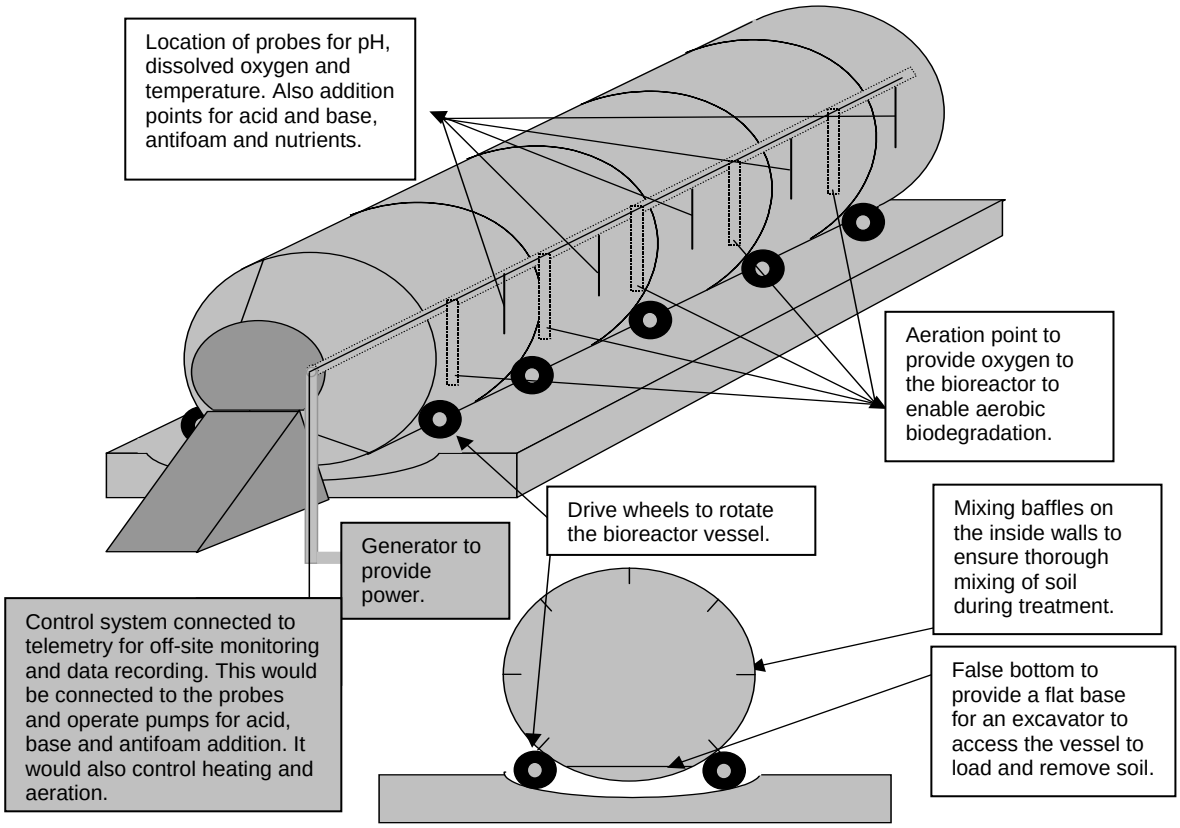


Figure 11.1: Diagram of a potential slurry-phase bioreactor system using a rotating horizontal mixing vessel

For the trials in this report it had been considered that the reactor should be turned on its side, rather like a cement mixer with internal paddle mixers inside the vessel to improve the agitation of the material. Both these previous ideas were rejected on the grounds of cost, which was estimated by the designers at 2 to 3 times the cost of the current design. Such a design change would reduce the useable volume of the reactor vessel by at least 50 %, but a larger unit may be more easily fabricated using this design. It was anticipated also that monitoring slurry in a horizontal rotating drum would be difficult, although it might be possible to install a long probe down the centre of the vessel.

In addition, a horizontal tank could be used, with ports along each side for slurry removal and re-injection using pumps. This would be expensive as more pumps would be required, but blockage of the pumps should be less likely as the material would not be resting over the ports.

11.2.3 UNLOADING AND DEWATERING

Unloading the current bioreactor design was seriously constrained by the low capacity of the centrifuge used. After further investigation it was concluded that it would not be cost-effective to hire or purchase a centrifuge of a larger capacity. Instead a more efficient unloading process would have been to directly discharge into another holding tank that could be used to settle heavier fractions from suspension. The remaining supernatant could then be drawn off and gradually fed to a centrifuge without the worry of the pipework blocking due to sedimentation of heavier particles. In the horizontal design, once drained of supernatant, an excavator could be used to remove the remaining solid material. Such a configuration would give a more costly system compared to the current format as another holding area would be required, but it would reduce downtime between treatment batches.

Alternatively a redesigned system could allow the bioreactor vessel to act also as a settling tank. After treatment the heavier suspended solids would fall from suspension rapidly, the remaining supernatant could then be drawn off and gradually fed to a centrifuge. Once drained of liquid, an excavator could be used to remove the remaining solid material. This process would be the most efficient format and would also require the least amount of space.

It is recommended that design ideas, based on the information provided in this report, be sought from suitable process engineers, in order to develop a more robust treatment. This system could either be mobile, or installed at a fixed facility.

11.2.4 ENGINEERING POSITIVE ASPECTS OF THE CURRENT SYSTEM INTO A NEW SYSTEM

As has been indicated above, the bioreactor system in its current design is very effective for the biotreatment of liquid wastes, but not slurry-phase wastes. This is because the design was adapted from stirred tank bioreactors used at smaller scales (from 1 litre to 1000 litres capacity). Such stirred tank reactors are used in the biotechnology industry for the growth of bioproducts such as fungi for penicillin production. In these processes cultures are grown in liquid media, where control of environmental conditions (temperature, pH and dissolved oxygen) is fundamental to process efficiency and product recovery.

The slurry-phase bioreactor adequately resolved all of the issues associated with the growth of microbial cultures, and so it is important that the positive aspects of the current system are engineered into any new system. Similar pH, temperature and antifoam control and telemetry processes could be transferred directly onto any new system, provided that mixing was sufficiently thorough, so that dose response times for acid, base and antifoam addition were effective for the system to maintain optimal conditions.

With regard to this process it would probably have been more effective if it had been designed around minerals processing equipment designed to handle this type of material.

11.2.5 DESIGN CONSTRAINTS OF FIXED/MOBILE SYSTEMS

With a fixed facility, the slurry-phase bioreactor could more easily be built larger in capacity than the current mobile reactor design. This is because the constraints of having to transport the rig are removed. Though a larger mobile unit could be fabricated and transported in sections, its reconstruction on-site would be more complex and take longer.

A fixed facility would require that contaminated material is brought to the site from surrounding sites undergoing remediation, incurring transport costs and increasing the process cost. However, such a hub site would have to operate under a waste management licence rather than a mobile plant licence, so ideally it would be best located on a current licensed-waste management site, such as a landfill, in tandem with other pre-treatment methods that will be required under the EU Landfill Directive.

A fixed facility would also allow a greater choice of construction materials and fabrication methods (e.g. reinforced concrete), leading to potentially cheaper cost. It may allow use of existing facilities such an unused sewage treatment works. Whichever option is used there are benefits and constraints either way, a fixed unit would be the cheapest to construct and a mobile facility would allow the most flexibility. Also, the type of company which would be using the bioreactor would affect the design; a landfill operator would probably prefer a fixed facility, whereas a remediation company would probably prefer a mobile unit which could be taken from site to site.

11.2.6 POTENTIAL MODIFICATIONS TO THE CURRENT DESIGN

Further modifications could be made to the slurry-phase bioreactor used in these trials. As discussed previously, upgrading the pump motor is an option. Alternatively, the entire pump system could be significantly increased in size. Increasing the size of the pump to 6 inch (152 mm) would cost between £10,000 and £25,000, excluding the cost of testing/commissioning using appropriate materials, which is considered critical. Increasing the pump size could increase flow in the pipes through better pressure. In conjunction with this, all of the pipes could be made 6 inch (152 mm) in order to prevent reductions in flow at 'pinch points'.

The loading system must also be improved, as discussed in section 11.2.1 and the design should be based on minerals processing equipment as discussed in section 11.2.4.

The sampling system could also be improved in order that samples taken during the trial are more representative of the slurry mix. It is considered that using a high volume probe through the slurry would be more effective.

The effect of particle size on the process suggests that this process, in its current form, would be best employed to treat easily suspended fines from processes such as soil washing or dredging. These are notoriously difficult to treat and are often the size fractions where the contamination is concentrated. These fines fractions are often dewatered and disposed of to landfill; this may not be an option in the future.

The capacity of the reactor could also be increased in order to treat a higher volume. However, it must be understood that the greater the increase in capacity, the bigger the pumping capacity required, and hence the greater the associated cost. The size of the reactor is also limited to a certain extent by logistics considerations. For example, if the reactor were any wider it would need a police escort for transportation. As mentioned above if the unit were static then these constraints could be removed.

11.3 IMPLEMENTATION OF THE LANDFILL DIRECTIVE

The implementation of the Landfill Directive will have a significant impact on the decisions that are made about the future of the bioreactor. The Landfill (England and Wales) Regulations 2002 ("the Landfill Regulations") came into force on 15 July 2002. These new regulations implement the Landfill Directive (Council Directive 1999/31/EC, "the Directive"), which aims to prevent, or to reduce as far as possible, the negative environmental impacts of landfill. The aim of the Directive is to increase the cost of landfill (Recital 10 of the Directive), reduce practices which involve long distance shipments of wastes for cheap disposal and ensure that the price charged includes: set-up

costs; financial security and site closure and long-term management costs (Recital 29 and Paragraph 11 of the Directive).

The Landfill Regulations will be subject to further amendments as further aspects of the Directive are implemented, this includes amendments to incorporate the European Waste Acceptance Criteria in 2004. The Directive and Landfill Regulations will have a major impact on waste regulation and industry in the UK.

On the 16th July 2004, major new requirements deriving from the Landfill Directive are:

- Ban on the co-disposal of hazardous and non-hazardous waste together in landfills;
- A requirement for pre-treatment of wastes prior to landfilling;
- Prohibition of certain wastes from landfills.

11.3.1 BAN ON THE CO-DISPOSAL OF HAZARDOUS AND NON-HAZARDOUS WASTES.

After July 16th 2004 landfill sites will operate as hazardous, non-hazardous or inert landfill sites. These are based on conditioning plans for the sites submitted to the Environment Agency (EA). It is believed that no more than 11 sites are likely to be operating as hazardous waste landfills after July 16th 2004; however, as of the 1st July 2004 only 3 landfill sites were licensed to accept the type of waste treated in this project. This is a significant reduction from the current number of about 200. This is expected to significantly increase the cost of hazardous waste disposal in the UK, by at least 3 times the approximate cost before the effect of the Landfill Directive. As of the 1st July, prices quoted for hazardous waste disposal are approximately £90/tonne. This is made up of landfill tax at £13/tonne (although most contaminated land projects are exempt), disposal charge at £72/tonne, haulage at £4-5/tonne, and the cost of consignment notes. As yet no one is sure of the future of hazardous waste disposal to landfill, but it will be much less favourable than current conditions.

The designation of wastes as hazardous, non-hazardous and inert is given as a minimum standard in the Council of Europe Decision on the European Waste Acceptance Criteria (EWC). This has been undertaken in England and Wales through Regulation 10 and Schedule 1 of the Landfill Regulations and the Interim Waste Acceptance Criteria (WAC) published by the EA in November 2002.

The WAC specify that the producer of the waste must provide the following information:

- Origin of the waste;
- Information on the processes applied;
- Description of the waste treatment(s) applied;
- Composition of the waste and leaching behaviour;
- Appearance of the waste (e.g. smell and colour);
- Relevant EWC Code;
- Hazard properties according to annex III of the Hazardous Waste Directive (91/689/EEC);
- The landfill class to be used;
- Check whether it can be recycled;
- Any other precautions required.

The WAC will also ban, after July 16th 2005, any wastes containing over 6 % total organic carbon (TOC). This will prevent a significant amount of hydrocarbon impacted soil being disposed of at a landfill site.

Wastes that will be disposed of to hazardous waste landfill sites include those wastes on the hazardous waste list of the EWC or wastes having similar properties. However, this does not include any wastes that constitute short-term occupational risk, environmental risk or prevent waste stabilisation over the projected life of the landfill.

11.3.2 PRE-TREATMENT OF WASTES PRIOR TO LANDFILLING

The Directive requires, from the 16th July 2004, pre-treatment of hazardous waste on all landfill sites.

The various EU and national regulatory bodies refer to 'treatment' as 'the physical, thermal, chemical or biological processes, including sorting, that change the characteristics of the waste in order to reduce its quantity or hazardous nature, facilitate its handling or enhance recovery'.

The Directive states that only waste that has been subject to treatment may be sent to landfill. This provision may not apply to inert waste (pre-treatment of non-hazardous or inert waste will be specified at a later date), where treatment is not technically feasible, or to any other waste for which treatment does not contribute to the protection of the environment or human health by reducing the quantity of the waste or its hazards. Pre-treatment of waste does not include mixing or dilution, both of which are prohibited by the Landfill Directive.

11.3.3 PROHIBITION OF CERTAIN WASTES FROM LANDFILLS

Under the Landfill Directive a number of wastes are banned which are relevant to waste tars found on gasworks sites.

11.3.3.1 Liquid wastes

'Liquid waste' is defined in the Landfill Directive as 'any waste in liquid form, including wastewaters but excluding sludge'. It is not defined elsewhere in UK legislation.

Liquid wastes are banned from landfill due to their propensity to promote instability in the landfill mass; provide a mechanism for the transfer of pollutants off-site via surface water run-off or underground loss of leachate; and assist in the formation of landfill gas. It would appear to be the propensity of liquid waste to flow and be mobile within the landfill that leads to these effects.

The likely definition of 'liquid waste' is:

- Any waste that near instantaneously flows into an indentation void made in the surface of the waste. This test is designed to distinguish between a liquid and a sludge;
- Any waste containing a free-draining liquid substance in excess of 250 litres or 10 %, whichever represents the lesser amount. This test is designed to identify a heterogeneous waste that contains a liquid.

The tar and tarry liquors found on gasworks sites are very variable and can be present in the form of liquids of varying viscosity up to thick highly viscous sludges. It is likely, therefore, that the more liquid fractions would be automatically banned from landfill, with the more viscous sludges requiring pre-treatment at the very least.

11.4 THE WAY FORWARD

It can be concluded, therefore, that the Landfill Directive is going to have a significant effect on the disposal of contaminated tar found on gasworks sites. On the grounds of liquidity, corrosiveness and flammability, certain types of coal tar could easily be banned. Where waste materials do not strictly meet those categories, they will no longer be able to be landfilled by mixing with other materials. Most coal tar contaminated wastes will be classed as hazardous and subject to greatly increased costs, including increased distances to the nearest available landfill site.

Remediation treatments will therefore need to be developed to reduce contaminant concentrations such that the material can be used on-site as engineering fill or sent for disposal as a non-hazardous waste.

It is considered that the work described in this report has shown that slurry-phase bioremediation can be used to degrade contaminants commonly found on gasworks sites to acceptable levels. With further improvements to design, the performance may improve further.

The current system should not be disregarded as a failed or an unsuitable system, it would act as a highly effective treatment process for contaminated silts, clays and fines from dredging. A suitable process could be of a great benefit to specific remediation projects encountering these wastes. In addition to this the current design should be tested coupled to a soil washing process to treat fines contaminated with hydrocarbons.

It is recommended that for the purpose employed during this project, the development of the bioreactor now moves on to a period of redesign, using the lessons learned in these trials. The ultimate goal must be to produce a vessel that can treat the largest volume possible per batch, in order to become commercially viable. Thermal treatment is likely to be the only other treatment that would adequately treat these materials. It is also recommended that costs and options for redesign are sought from specialist process engineers, in order to assist in the decision making process.

It would be envisaged that any such continuing work would take the form of a joint industry project, where expertise from the whole range of specialist areas would be brought together to work in partnership in a follow-on CL:AIRE project.

GLOSSARY OF TERMS

Adsorbed contamination
Contamination that is suspended on the surface of a solid liquid or gas particle.

Aliphatic hydrocarbons
Straight chained hydrocarbons without benzene rings (C_6H_6).

Aquifer
A subsurface permeable unit that is capable of transmitting significant quantities of groundwater.

Aromatic hydrocarbons
Hydrocarbons containing benzene rings (C_6H_6).

Chromatography
The chemical method of separating compounds dissolved in one phase (usually mobile) through its equilibration with a second phase (usually stationary). The mechanism of separation may involve partition, adsorption, permeation or ion exchange.

Coal carbonisation
The process whereby coal is heated in a retort in the absence of air and decomposes into coke and coal gas.

Coal tar
A black viscous acidic liquid containing water and a vast range of hydrocarbon compounds with molecular weights varying from 10 - 4,000.

Contaminant
Any hazardous substance that does not occur naturally, or occurs at greater than natural background levels.

Ex situ
Having been removed from the original place of residence; as in the case with soil that has been excavated for treatment.

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.

Gram negative and Gram positive bacteria
Bacteria are split into Gram positive and Gram negative groups. Gram negative cell walls contain relatively little peptidoglycan (a polymer that consists of polysaccharide) and peptide chains in a strong molecular network) but their outer cell membranes are compose of lipopolysaccharide (any of a group of polysaccharides (a carbohydrates consisting of a number of monosaccharides joined by glycosidic bonds) in which a lipid constitutes a portion of the molecule.), lipoprotein (any of a group of conjugated proteins in which at least one of the components is a lipid) and other complex macromolecules (a very large molecule). Gram-Positive bacteria consist chiefly of peptidoglycan but lack the outer membrane of Gram-Negative bacteria.

In situ
In place, without removal.

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.

pH
pH is an abbreviation for "*pondus hydrogenii*" (translated as potential hydrogen) meaning hydrogen power as acidity is caused by a predominance of hydrogen ions (H^+). The pH scale is a measure of acid/base strength

defined on a logarithmic scale using the molar concentration of H^+ in solution. Pure water autoionizes to produce equal concentrations of H^+ and hydroxide ions (OH^-).

Phenolics
Aromatic compound containing hydroxyl groups attached to a benzene ring.

Polycyclic aromatic hydrocarbons
Hydrocarbon compound with multiple benzene rings. PAH are typical components of tars, asphalts, fuels, oils and greases. These are also called Polynuclear Aromatic Hydrocarbons.

Polymerase chain reaction
The polymerase chain reaction (PCR) can be used for gene cloning and manipulation, gene mutagenesis, DNA sequencing etc. The PCR technique is a primer extension reaction for amplifying specific nucleic acids in vitro. PCR will allow a short stretch of DNA (usually fewer than 3,000 base pairs) to be amplified to about a million fold using a 3-step cycle. This includes melting of DNA, annealing of primers and elongation of the primers. This cycle is repeated more than 20 times to create a sufficient amount of the desired DNA. The particular stretch of DNA to be amplified, called the target sequence, is identified by a specific pair of DNA primers, oligonucleotides (a short polymer of two to twenty nucleotides.) usually about 20 nucleotides (the basic building blocks of nucleic acids) in length.

Proteobacteria

Proteobacteria are one of the many bacteria's found under the Eubacteria bacteria category. Proteobacteria include nitrogen-fixing bacteria in the root nodules of legumes and enteric bacteria that live in the intestinal track of animals. Proteobacteria are split into different subgroups, the alpha, beta, delta/epsilon and gamma subgroups. Each of these subgroups displays similar features.

Ramsar convention protected site
The Convention on Wetlands is an intergovernmental treaty adopted on 2 February 1971 in the Iranian city of Ramsar, on the southern shore of the Caspian Sea. Thus, though nowadays the name of the Convention is usually written "Convention on Wetlands (Ramsar, Iran, 1971)", it has come to be known popularly as the "Ramsar Convention". Ramsar was the first of the modern global intergovernmental treaties on conservation and careful use of natural resources.

Retort
An oven used for the carbonisation of coal.

RNA
RNA is a polymer of nucleotides connected via a phosphate-ribose backbone and it is heavily involved in the synthesis of proteins.

rRNA
rRNA is ribosomal RNA, which is the type of RNA found in the ribosomes (cytoplasmic particles).

16S rRNA and its analysis
The 16S rRNA portion of ribosomal RNA varies according to each species of bacterium. Thus, identifying the composition of the rRNA allows identification of different bacterial species.

Sorption
The processes by which contaminants attached themselves to solid particles, thereby retarding their transport or movement.

Spent oxide
Ferric oxide used as purifying agent within coal gas production. On becoming saturated with gas impurities, principally hydrocyanic and sulphuric acid the ferric oxide was said to be "spent".

Sulphuric acid
A colourless oily liquid acid. It is extremely corrosive, and reacts violently with water, creating heat and can char organic matter. It is used extensively in many processes in the chemical industry.

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APPENDICES

Appendix A: Previous Trials at a Gasworks in Northern England – Field Trial Results

Appendix B: Demonstration Project Trial at a Former Gasworks in Northwest England – Chemical, Geotechnical, Microbiological, Laboratory and Field Trial Results

Appendix C: Telemetry System

Appendix D: Contact Details

APPENDIX A

PREVIOUS TRIALS AT A GASWORKS IN NORTHERN ENGLAND: FIELD TRIAL RESULTS

RESULTS FOR THE BIOREMEDIATION OF COAL TAR CONTAMINATED SOILS DURING THE PREVIOUS TRIAL CARRIED OUT IN NORTHERN ENGLAND

Trial 1.

Table A1: Mean results for Trial 1 of the bioremediation of coal tar contaminated soil

	Sample					
Contaminant in mg/kg	**Feedstock**	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Naphthalene	2	8	5	13	3	12
Acenaphthylene	59	10	13	32	18	34
Acenaphthene	10	9	2	4	2	6
Fluorene	38	30	5	15	8	220
Phenanthrene	183	84	34	71	38	96
Anthracene	104	77	35	48	41	62
Fluoranthene	765	667	189	358	231	428
Pyrene	1194	1047	315	690	424	756
Benzo(a)anthracene	204	307	64	199	93	242
Chrysene	382	377	136	283	196	347
Benzo(b)fluoranthene	BD	169	BD	186	BD	221
Benzo(k)fluoranthene	624	565	256	555	558	733
Benzo(a)pyrene	572	492	153	493	328	638
Indeno(1,2,3-cd)pyrene	317	288	76	292	162	347
Di-benzo(a,h,)anthracene	38	60	21	60	56	70
Benzo(g,h,i)perylene	295	306	94	288	206	353
Anthanthrene	31	113	18	101	38	122
Benzo(e)pyrene	482	296	118	295	262	367
Cyclopenta(c,d)pyrene	88	144	35	105	82	136
Total PAH	5,387	5,049	1,564	4,088	2,742	5,190

Note: BD – Below detection

Table A1 (continued): Mean average results for Trial 1 of the bioremediation of coal tar contaminated soil

	Sample			
Contaminant in mg/kg	**Day 6**	**Day 7**	**Day 8**	**End Product**
Naphthalene	6	9	16	3
Acenaphthylene	33	31	57	5
Acenaphthene	3	3	5	2
Fluorene	1	1	19	8
Phenanthrene	35	37	76	49
Anthracene	39	38	76	49
Fluoranthene	229	248	285	67
Pyrene	419	467	520	95
Benzo(a)anthracene	114	116	175	29
Chrysene	207	235	241	31
Benzo(b)fluoranthene	BD	BD	165	18
Benzo(k)fluoranthene	698	766	554	52
Benzo(a)pyrene	429	473	498	47
Indeno(1,2,3-cd)pyrene	244	278	301	27
Di-benz(a,h,)anthracene	56	63	63	8
Benzo(g,h,i)perylene	271	303	310	29
Anthanthrene	55	58	94	10
Benzo(e)pyrene	331	365	275	27
Cyclopenta(c,d)pyrene	115	125	112	13
Total PAH	3,280	3,612	3,842	570

Note: BD – Below detection

Table A2: Percentage of PAH remaining (according to number of benzene rings) at the end of the remediation trial

Number of Rings in PAH structure	**% remaining in the End Product**
2-Ring PAH	142.9
3-Ring PAH	28.7
4-Ring PAH	8.7
5-Ring PAH	9.3
6-Ring PAH	9.9
Total PAH	10.6

Trial 2.

Table A3: Results for Trial 2 of the bioremediation of coal tar contaminated soil

	Sample					
Contaminant in mg/kg	**Feedstock**	**Feedstock**	**Feedstock**	**Feedstock**	**Feedstock**	**Feedstock**
Naphthalene	5	5	11	5	7	5
Acenaphthylene	19	21	22	20	26	19
Acenaphthene	5	5	5	4	4	4
Fluorene	23	25	25	25	24	22
Phenanthrene	141	144	156	155	147	145
Anthracene	54	59	57	57	61	61
Fluoranthene	318	308	316	340	311	302
Pyrene	483	455	472	502	466	448
Benzo(a)anthracene	146	144	147	158	147	138
Chrysene	185	181	183	198	187	177
Benzo(b)fluoranthene	91	87	83	99	87	77
Benzo(k)fluoranthene	248	238	254	267	261	239
Benzo(a)pyrene	217	209	217	236	231	203
Indeno(1,2,3-cd)pyrene	116	113	121	130	132	114
Di-benzo(a,h,)anthracene	28	25	26	28	27	24
Benzo(g,h,i)perylene	116	111	120	128	136	113
Cyclopenta(c,d)pyrene	47	43	41	48	43	39
Benzo(e)pyrene	132	128	135	145	139	125
Anthanthrene	44	41	44	48	48	44
Total PAH	2,418	2,342	2,435	2,593	2,484	2,299

Table A3 (continued): Results for Trial 2 of the bioremediation of coal tar contaminated soil

	Sample					
Contaminant in mg/kg	**Feedstock**	**Feedstock**	**Feedstock**	**Feedstock**	**Day 0 slurry**	**Day 1 slurry**
Naphthalene	7	7	4	8	12	8
Acenaphthylene	37	25	24	25	25	24
Acenaphthene	4	5	4	4	5	5
Fluorene	23	26	21	24	20	17
Phenanthrene	131	165	143	154	102	72
Anthracene	52	60	60	62	59	56
Fluoranthene	290	327	348	316	373	458
Pyrene	450	485	527	476	584	770
Benzo(a)anthracene	140	151	169	147	188	241
Chrysene	180	191	210	194	234	296
Benzo(b)fluoranthene	95	92	102	92	114	148
Benzo(k)fluoranthene	259	258	286	258	316	430
Benzo(a)pyrene	231	223	251	228	285	378
Indeno(1,2,3-cd)pyrene	130	126	139	131	163	210
Di-benzo(a,h)anthracene	28	27	30	27	34	46
Benzo(g,h,i)perylene	135	126	138	135	160	200
Cyclopenta(c,d)pyrene	25	36	37	42	63	82
Benzo(e)pyrene	140	138	154	139	172	228
Anthanthrene	51	46	52	51	61	78
Total PAH	2,408	2,514	2,699	2,513	2,970	3,747

Table A3 (continued): Results for Trial 2 of the bioremediation of coal tar contaminated soil.

Contaminant in mg/kg	Sample					
	Day 3 Slurry	Day 4 Slurry	Day 5 Slurry	Day 5 Solids	Day 5 Solids	Day 5 Solids
Naphthalene	8	159	10	2	3	3
Acenaphthylene	16	39	6	7	6	8
Acenaphthene	3	4	2	2	1	2
Fluorene	12	14	8	12	9	13
Phenanthrene	56	61	39	75	61	98
Anthracene	41	44	28	23	18	34
Fluoranthene	332	296	183	88	81	140
Pyrene	623	548	336	108	104	180
Benzo(a)anthracene	175	180	118	33	33	56
Chrysene	234	249	162	43	41	74
Benzo(b)fluoranthene	132	145	108	19	22	42
Benzo(k)fluoranthene	363	512	356	62	55	89
Benzo(a)pyrene	322	466	318	51	51	82
Indeno(1,2,3-cd)pyrene	168	270	181	31	30	49
Di-benzo(a,h)anthracene	34	52	34	7	8	12
Benzo(g,h,i)perylene	161	277	192	32	32	52
Cyclopenta(c,d)pyrene	75	105	71	11	10	17
Benzo(e)pyrene	193	265	181	30	28	48
Anthanthrene	65	103	83	12	11	20
Total PAH	3,013	3,789	2,416	648	604	1,019

Table A3 (continued): Results for Trial 2 of the bioremediation of coal tar contaminated soil

	Sample					
Contaminant in mg/kg	**Day 5 solids**	**Day 5 solids**	**Day 5 solids**	**Day 5 solids**	**Day 7 slurry**	**Day 8 slurry**
Naphthalene	2	3	3	4	19	7
Acenaphthylene	7	6	8	11	47	15
Acenaphthene	2	1	2	2	4	2
Fluorene	12	9	13	10	13	8
Phenanthrene	75	61	98	70	62	34
Anthracene	23	18	34	32	44	20
Fluoranthene	88	81	140	148	309	148
Pyrene	108	104	180	216	593	279
Benzo(a)anthracene	33	33	56	75	221	102
Chrysene	43	41	74	103	306	144
Benzo(b)fluoranthene	19	22	42	63	204	112
Benzo(k)fluoranthene	62	55	89	200	803	366
Benzo(a)pyrene	51	51	82	171	712	323
Indeno(1,2,3-cd)pyrene	31	30	49	104	450	192
Di-benzo(a,h)anthracene	7	8	12	22	90	43
Benzo(g,h,i)perylene	32	32	52	105	461	185
Cyclopenta(c,d)pyrene	11	10	17	33	141	60
Benzo(e)pyrene	30	28	48	93	373	171
Anthanthrene	12	11	20	39	184	74
Total PAH	648	604	1,019	1,501	5,036	2,285

Table A3 (continued): Results for Trial 2 of the bioremediation of coal tar contaminated soil

	Sample					
Contaminant in mg/kg	**Day 9 slurry**	**Day 10 slurry**	**Day 10 slurry**	**Day 11 slurry**	**Product**	**Product**
Naphthalene	4	11	9	7	3	2
Acenaphthylene	10	22	18	13	8	5
Acenaphthene	2	2	2	2	3	1
Fluorene	7	10	8	8	11	6
Phenanthrene	42	47	38	35	64	36
Anthracene	23	33	22	20	17	10
Fluoranthene	138	230	173	159	63	38
Pyrene	247	424	331	301	75	48
Benzo(a)anthracene	87	144	125	110	23	15
Chrysene	123	209	176	157	30	20
Benzo(b)fluoranthene	90	159	146	125	18	13
Benzo(k)fluoranthene	296	449	482	407	42	29
Benzo(a)pyrene	253	415	421	351	38	28
Indeno(1,2,3-cd)pyrene	144	242	258	208	24	17
Di-benzo(a,h)anthracene	32	55	54	49	7	7
Benzo(g,h,i)perylene	142	251	263	204	28	19
Cyclopenta(c,d)pyrene	50	89	79	66	7	4
Benzo(e)pyrene	133	237	222	184	23	15
Anthanthrene	57	99	101	83	11	10
Total PAH	1,880	3,128	2,928	2,489	495	323

Table A3 (continued): Results for Trial 2 of the bioremediation of coal tar contaminated soil

	Sample	
Contaminant in mg/kg	**Product**	**Product**
Naphthalene	2	2
Acenaphthylene	7	5
Acenaphthene	2	2
Fluorene	9	8
Phenanthrene	52	47
Anthracene	15	13
Fluoranthene	53	49
Pyrene	65	62
Benzo(a)anthracene	200	19
Chrysene	25	25
Benzo(b)fluoranthene	13	15
Benzo(k)fluoranthene	37	35
Benzo(a)pyrene	33	32
Indeno(1,2,3-cd)pyrene	20	20
Di-benzo(a,h)anthracene	6	5
Benzo(g,h,i)perylene	22	21
Cyclopenta(c,d)pyrene	6	6
Benzo(e)pyrene	18	18
Anthanthrene	9	7
Total PAH	594	391

Trial 3.

Table A4: Mean results for Trial 3 of the bioremediation of coal tar contaminated soil

	Samples					
Contaminant in mg/kg	**Start (day 0)**	**Day 1**	**Day 2**	**Day 3**	**Day 7**	**Day 9**
Naphthalene	5.2	3	4	2	2	2.25
Acenaphthylene	54.4	15	29	5	7	11.25
Acenaphthene	4.2	2	3	2	2	1.75
Fluorene	11.8	4	7	4	4	4.25
Phenanthrene	74.6	34	47	34	31	31.25
Anthracene	51.8	17	23	5	10	9
Fluoranthene	207.4	55	99	32	30	42.5
Pyrene	341.2	88	141	42	42	60
Benzo(a)anthracene	69	20	20	3	7	7.25
Chrysene	109.2	48	75	12	19	19.5
Benzo(b)fluoranthene	117	13	45	3	6	13.75
Benzo(k)fluoranthene	62.4	24	34	6	12	16.25
Benzo(a)pyrene	144.8	17	46	BD	10	11
Indeno(1,2,3-cd)pyrene	77.8	BD	37	3	BD	7.25
Di-benzo(a,h)anthracene	15	BD	BD	BD	BD	BD
Benzo(g,h,i)perylene	66.6	10	36	3	5	11
Anthanthrene	19.6	3	8	BD	1	2
Benzo(e)pyrene	67.6	15	34	6	8	13
Cyclopenta(c,d)pyrene	18.8	BD	BD	BD	BD	1.25
Total PAH	1,518.4	368	688	162	196	264.5

Note: BD – Below detection

Table A4 (continued): Mean results for Trial 3 of the bioremediation of coal tar contaminated soil

	Samples					
Contaminant in mg/kg	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**	**Day 15**
Naphthalene	2.25	2.5	2	1.75	1.75	2
Acenaphthylene	8.5	12.25	10	1.75	1.25	15.25
Acenaphthene	1.5	2	2	1.75	1.25	1.75
Fluorene	3.5	4	3	3	3	2.75
Phenanthrene	28	29.25	27	24.75	19.75	21.5
Anthracene	7.25	6	5.75	5.75	4.5	5.75
Fluoranthene	36	42.25	33.5	39.75	31.5	37.25
Pyrene	49.5	60.5	54.75	62	41	54.25
Benzo(a)anthracene	4.75	7	7.25	8.75	4.75	7.25
Chrysene	13.75	28.5	20	31	20	28.5
Benzo(b)fluoranthene	8	10.25	10.25	17	11.75	22.25
Benzo(k)fluoranthene	12.5	19.5	16.75	22.25	15	23.5
Benzo(a)pyrene	3.5	11.5	8.75	11	3.5	18
Indeno(1,2,3-cd)pyrene	4.75	10.5	6	12.25	11	17
Di-benzo(a,h)anthracene	BD	BD	BD	0.25	BD	2.5
Benzo(g,h,i)perylene	7.5	11.75	9.25	14	12.5	17.75
Anthanthrene	1.25	3	1.5	2.75	2	4
Benzo(e)pyrene	9	14.5	12.75	16.75	11.5	17.25
Cyclopenta(c,d)pyrene	BD	1.5	1	1.5	2	3.25
Total PAH	201.5	276.75	231.5	278	198	301.75

Note: BD – Below detection

Table A4 (continued): Mean results for Trial 3 of the bioremediation of coal tar contaminated soil.

	Sample			
Contaminant in mg/kg	**16**	**17**	**19**	**19 Solid**
Naphthalene	2.5	1.75	1	1.6
Acenaphthylene	12.75	9.75	7.25	11.4
Acenaphthene	1.75	1.5	0.75	1.2
Fluorene	3.25	3.25	2	3
Phenanthrene	24.5	25	15	22.4
Anthracene	16	5.5	5.25	8
Fluoranthene	44	32	27	38.4
Pyrene	62.5	44.5	37.75	53.6
Benzo(a)anthracene	7.5	8	6.75	10.8
Chrysene	25.25	15.5	15.5	21.2
Benzo(b)fluoranthene	17.25	13.25	13.25	19.8
Benzo(k)fluoranthene	19.5	11	8.5	13
Benzo(a)pyrene	12.25	12.25	12.25	19.2
Indeno(1,2,3-cd)pyrene	11.75	9	3.75	9.4
Di-benzo(a,h)anthracene	BD	1.25	BD	1
Benzo(g,h,i)perylene	14.25	8	7.75	11.4
Anthanthrene	2.5	2	2	5
Benzo(e)pyrene	16.25	9.75	9	12.8
Cyclopenta(c,d)pyrene	2	6	0.25	3
Total PAH	295.75	219.25	175	266.2

Note: BD – Below detection

APPENDIX B

DEMONSTRATION PROJECT TRIAL AT A FORMER GASWORKS IN NORTHWEST ENGLAND: CHEMICAL, GEOTECHNICAL, MICROBIOLOGICAL, LABORATORY AND FIELD TRIAL RESULTS

RESULTS FOR THE LABORATORY SCALE TRIALS UNDERTAKEN ON SOILS TAKEN FROM A GASWORKS IN NORTHWEST ENGLAND.

CHEMICAL DATA

Trial 1.

Table B1: Comparison of data before and after treatment of Trial 1, showing percentage change

	Trial 1	Start, concentration in mg/kg	End, concentration in mg/kg	% Degraded
	Cresols	0.10	0.10	0.00
	Xylenols & Ethylphenols	0.10	0.10	0.00
	Naphthols	0.10	0.10	0.00
	Phenol	0.10	0.10	0.00
	Trimethylphenol	0.10	0.10	0.00
	Catechol	13.70	0.10	99.27
	Resorcinol	0.10	0.10	0.00
Number of Benzene rings	Total Phenols	13.70	0.50	96.35
4	Naphthalene	0.50	0.50	0.00
3	Acenaphthylene	3.00	10.30	-243.33
3	Acenaphthene	1.30	0.50	61.54
3	Fluorene	6.30	7.90	-25.40
3	Anthracene	145.80	41.10	71.81
4	Fluoranthene	80.50	31.00	61.49
4	Pyrene	79.60	32.10	59.67
5	Benzo(a)anthracene	39.50	15.60	60.51
4	Chrysene	35.00	15.00	57.14
5	Benzo(b)fluoranthene & Benzo(k)fluoranthene	0.50	0.50	0.00
5	Benzo(a)pyrene	0.50	0.50	0.00
6	Indeno(1,2,3-cd)pyrene &	BD	BD	-
5	Di-benzoo(a,h)anthracene	0.50	0.50	0.00
6	Benzo(g,h,i) Perylene	0.50	0.50	0.00
	Total PAH	391.00	153.00	60.87
	2-ring	0.50	0.50	0.00
	3-ring	156.4	59.8	61.76
	4-ring	195.1	78.1	59.97
	5-ring	40.5	16.6	59.01
	6-ring	0.5	0.5	0.00
	Total Petroleum Hydrocarbons	665.49	32.32	95.14

Note: BD – Below detection

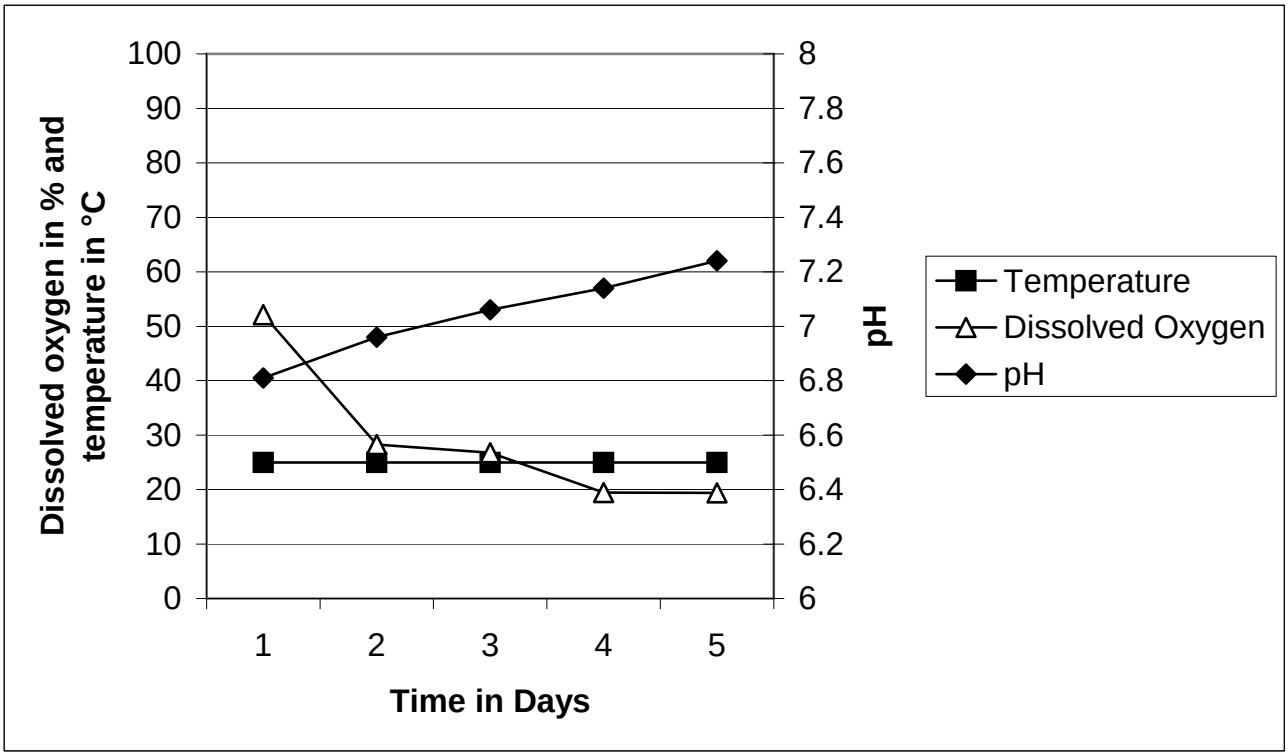

Figure B1: Biotreatment of tarry sand feedstock during Trial 1, showing changes in temperature, dissolved oxygen and pH.

Table B2: Comparison of data before and after treatment of Trial 2, showing percentage change.

	Trial 2	Start, concentration in mg/kg	End, concentration in mg/kg	% Degraded
	Cresols	1.10	0.10	90.91
	Xylenols & Ethylphenols	0.10	0.10	0.00
	Naphthols	0.10	0.10	0.00
	Phenol	0.80	0.10	87.50
	Trimethylphenol	0.10	0.10	0.00
	Catechol	0.20	0.10	50.00
	Resorcinol	0.10	0.10	0.00
Number of Benzene rings	Total Phenols	2.10	0.10	95.24
4	Naphthalene	12.67	10.50	17.11
3	Acenaphthylene	62.73	10.90	82.62
3	Acenaphthene	26.40	4.30	83.71
3	Fluorene	229.30	11.50	94.98
3	Anthracene	246.63	18.10	92.66
4	Fluoranthene	194.13	104.40	46.22
4	Pyrene	189.90	109.00	42.60
5	Benzo(a)anthracene	208.03	112.30	46.02
4	Chrysene	185.00	108.80	41.19
5	'Benzo(b)fluoranthene & Benzo(k)fluoranthene	0.50	0.50	0.00
5	Benzo(a)pyrene	0.50	0.50	0.00
6	Indeno(1,2,3-cd)pyrene &	BD	BD	-
5	Di-benzoo(a,h)anthracene	0.50	0.50	0.00
6	Benzo(g,h,i) Perylene	0.50	0.50	0.00
	Total PAH	1354.80	489.80	63.85
	2-ring	12.67	10.50	17.11
	3-ring	565.1	44.8	92.07
	4-ring	569.0	322.2	43.38
	5-ring	209.0	113.3	45.80
	6-ring	0.5	0.5	0.00
	Total Petroleum Hydrocarbons	1,469.36	700.75	52.31

Note: BD – Below detection

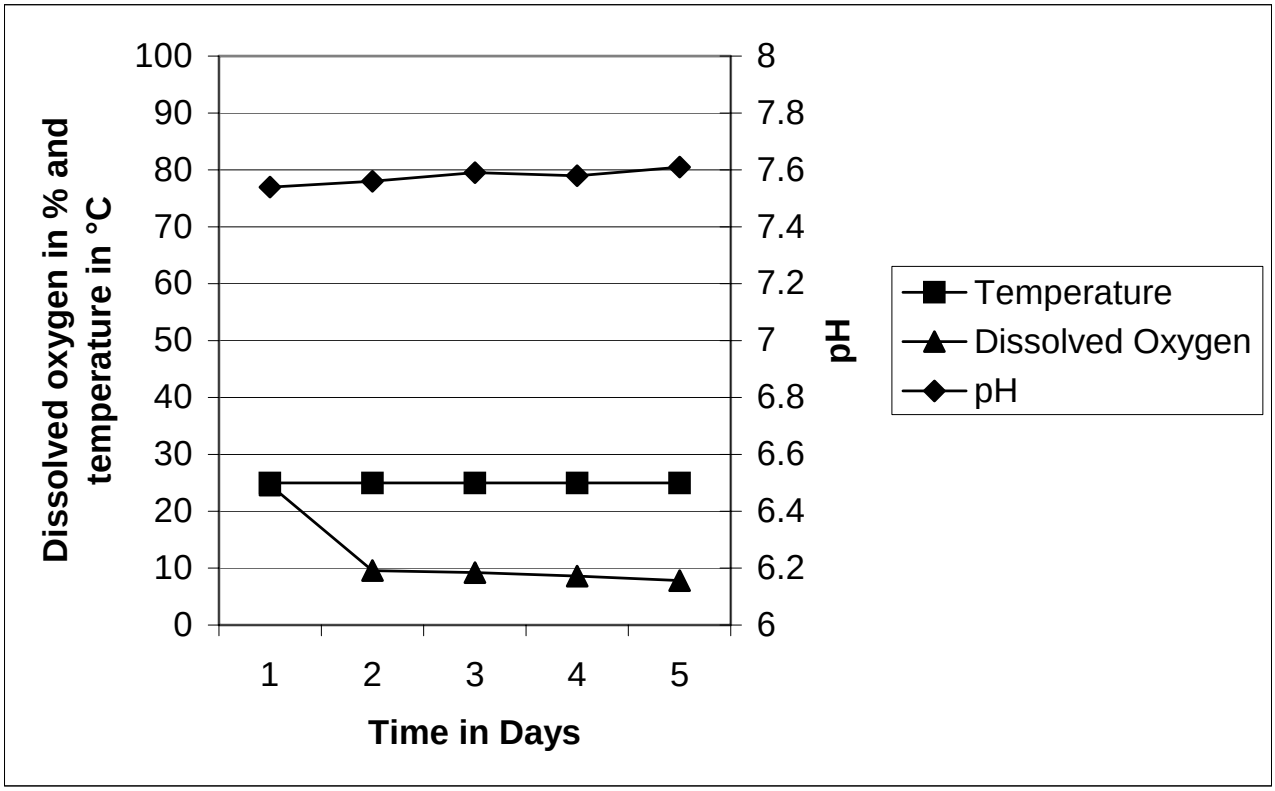

Figure B2: Biotreatment of tarry sand feedstock during Trial 2, showing changes in temperature, dissolved oxygen and pH.

Table B3: Comparison of data before and after treatment of Trial 3, showing percentage change.

	Trial 3	Start, concentration in mg/kg	End, concentration in mg/kg	% degraded
	Cresols	0.10	0.10	0.00
	Xylenols & Ethylphenols	0.10	0.10	0.00
	Naphthols	0.10	0.10	0.00
	Phenol	0.10	0.10	0.00
	Trimethylphenol	0.10	0.10	0.00
	Catechol	3.40	0.10	97.06
	Resorcinol	0.10	0.10	0.00
Number of Benzene rings	Total Phenols	4.00	0.70	82.50
4	Naphthalene	1.85	2.80	-51.35
3	Acenaphthylene	15.10	5.10	66.23
3	Acenaphthene	8.95	2.20	75.42
3	Fluorene	35.60	12.90	63.76
3	Anthracene	247.45	169.50	31.50
4	Fluoranthene	78.70	20.00	74.59
4	Pyrene	93.95	33.70	64.13
5	Benzo(a)anthracene	135.55	40.30	70.27
4	Chrysene	126.30	42.10	66.67
5	Benzo(b)fluoranthene & Benzo(k)fluoranthene	16.95	23.10	-36.28
5	Benzo(a)pyrene	56.30	44.40	21.14
6	Indeno(1,2,3-cd)pyrene &	BD	BD	-
5	Di-benzoo(a,h)anthracene	0.50	0.50	0.00
6	Benzo(g,h,i) Perylene	0.50	0.50	0.00
	Total PAH	815.95	396.10	51.46
	2-ring	1.85	2.80	-51.35
	3-ring	307.1	189.7	38.23
	4-ring	299.0	95.8	67.95
	5-ring	208.8	107.8	48.37
	6-ring	0.5	0.5	0.00
	Total Petroleum Hydrocarbons	501.06	49.18	90.18

Note: BD – Below detection

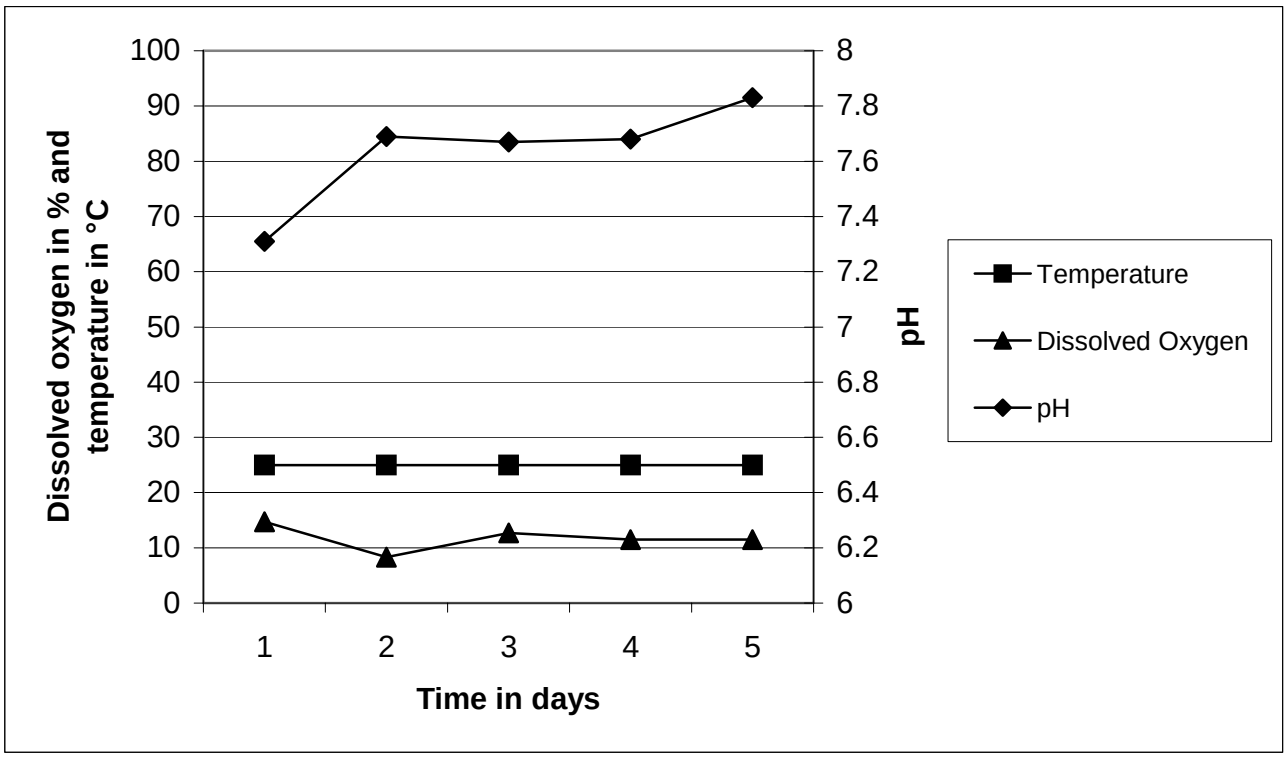

Figure B3: Biotreatment of tarry sand feedstock during Trial 3, showing changes in temperature, dissolved oxygen and pH.

Table B4: Comparison of data before and after treatment of Trial 4, showing percentage change.

	Trial 4	Start, concentration in mg/kg	End, concentration in mg/kg	% degraded
	Cresols	0.10	0.10	0.00
	Xylenols & Ethylphenols	0.10	0.10	0.00
	Naphthols	0.10	0.10	0.00
	Phenol	0.10	1.10	-1000.00
	Trimethylphenol	0.10	0.10	0.00
	Catechol	177.10	0.40	99.77
	Resorcinol	0.10	0.10	0.00
Number of Benzene rings	Total Phenols	177.10	1.50	99.15
4	Naphthalene	0.50	1.10	-120.00
3	Acenaphthylene	20.00	6.10	69.50
3	Acenaphthene	13.00	3.20	75.38
3	Fluorene	46.20	15.70	66.02
3	Anthracene	158.20	111.00	29.84
4	Fluoranthene	122.50	50.90	58.45
4	Pyrene	124.00	49.10	60.40
5	Benzo(a)anthracene	176.20	0.50	99.72
4	Chrysene	164.90	0.50	99.70
5	Benzo(b)fluoranthene & Benzo(k)fluoranthene	0.50	0.50	0.00
5	Benzo(a)pyrene	0.50	0.50	0.00
6	Indeno(1,2,3-cd)pyrene &	BD	BD	-
5	Di-benzoo(a,h)anthracene	0.50	0.50	0.00
6	Benzo(g,h,i) Perylene	0.50	0.50	0.00
	Total PAH	825.00	237.10	71.26
	2-ring	0.50	1.10	-120.00
	3-ring	237.4	136.0	42.71
	4-ring	411.4	100.5	75.57
	5-ring	177.2	1.5	99.15
	6-ring	0.5	0.5	0.00
	Total Petroleum Hydrocarbons	90.00	5.00	94.44

Note: BD – Below detection

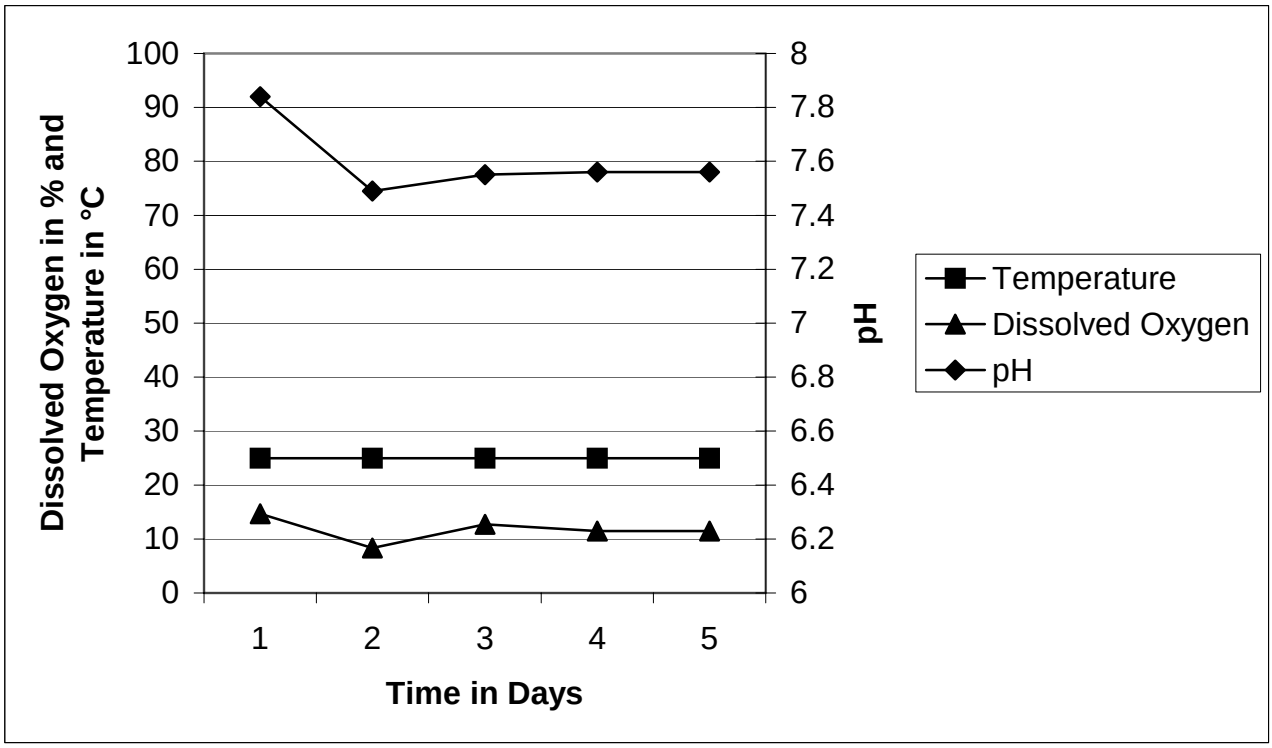

Figure B4: Biotreatment of tarry sand feedstock during Trial 4, showing changes in temperature, dissolved oxygen and pH.

Table B5. Comparison of data before and after treatment of Trial 5, showing percentage change.

	Trial 5	Start, concentration in mg/kg	End, concentration in mg/kg	% degraded
	Cresols	0.10	0.67	-566.67
	Xylenols & Ethylphenols	0.10	0.10	0.00
	Naphthols	0.10	0.10	0.00
	Phenol	0.10	2.10	-2000.00
	Trimethylphenol	0.10	0.10	0.00
	Catechol	88.70	BD	99.9
	Resorcinol	0.10	BD	-
Number of Benzene rings	Total Phenols	88.80	2.97	96.66
4	Naphthalene	1.85	7.43	-301.80
3	Acenaphthylene	15.10	4.23	71.96
3	Acenaphthene	8.95	3.00	66.48
3	Fluorene	35.60	9.37	73.69
3	Anthracene	247.45	94.77	61.70
4	Fluoranthene	78.70	91.50	-16.26
4	Pyrene	93.95	85.63	8.85
5	Benzo(a)anthracene	135.55	44.93	66.85
4	Chrysene	126.30	40.77	67.72
5	Benzo(b)fluoranthene & Benzo(k)fluoranthene	16.95	0.50	97.05
5	Benzo(a)pyrene	56.30	0.50	99.11
6	Indeno(1,2,3-cd)pyrene &	BD	BD	-
5	Di-benzo(a,h)anthracene	0.50	0.50	0.00
6	Benzo(g,h,i) Perylene	0.50	0.50	0.00
	Total PAH	815.95	381.47	53.25
	2-ring	1.85	7.43	-301.80
	3-ring	307.1	111.4	63.74
	4-ring	299.0	217.9	27.11
	5-ring	208.8	45.9	78.00
	6-ring	0.5	0.5	0.00
	Total Petroleum Hydrocarbons	295.53	BD	99.9

Note: BD – Below detection

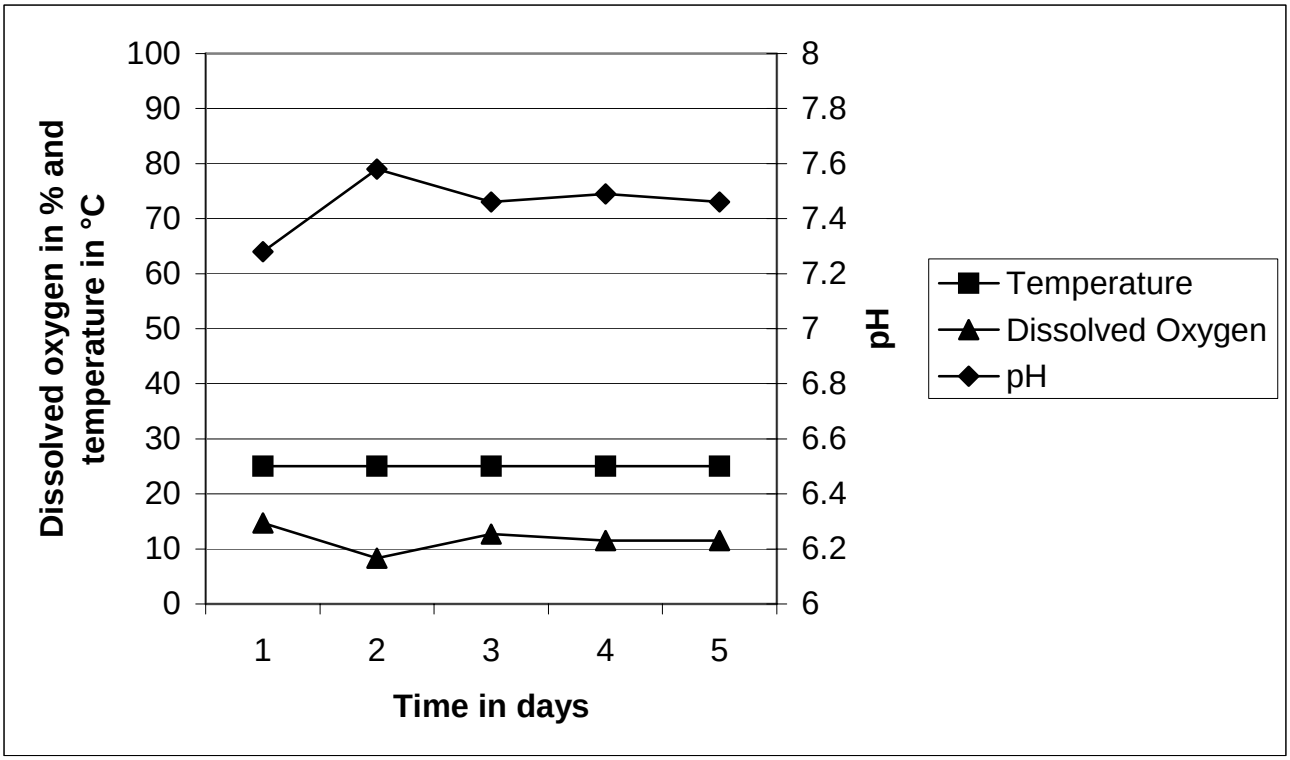

Figure B5: Biotreatment of tarry sand feedstock during Trial 5, showing changes in temperature, dissolved oxygen and pH.

LABORATORY AND FIELD SCALE MICROBIOLOGICAL DATA

Table B6: Health and Safety Laboratory identification from the samples received from slurry-phase bioreactor project.

Colony number	Species and percentage similarity	Source
1	Eubacterium (90 %)	Bacteria grown from a millipede gut and a common soil bacterium.
2	*Variovorax paradoxus* (94 %)	Bacterial Rhizosphere populations of black poplar and herbal plants to be used for phytoremediation of diesel.
3	*Acidovorax delafieldii* (95 %)	Microbial Degradation of PHBV.
4	*Afipia genosp. 9.* (92 %)	This species was formally known as cat scratch fever bacillus but this is not the same genus. The optimal pH value is about 6.8 and showed a strong susceptibility to NaCl and other salts according to the latest research.
5	*Afipia genosp. 9 strain G8990* (96 %)	See above.
6	*Hydrogenophaga taeniospiralis* (98 %)	Geochemistry and microbial diversity of a trichloroethene-contaminated Superfund site undergoing intrinsic *in situ* reductive dechlorination.
7	*Stenotrophomonas maltophilia* (96 %)	Molecular typing of Gram negative bacterial soil isolates from a PAH-contaminated site in Melbourne Australia.
8	Bromate-reducing bacterium (98 %)	Unique bacterial diversity in subseafloor habitats associated with a deep-sea volcanic eruption.
9	*Sphingomonas sp*. (93 %)	Found in several studies including evolution of bacterial diversity during enrichment of PCP-degrading activated soils.
10	Uncultured bacterium clone and Bromate-reducing bacterium B7. (97 %)	Unique bacterial diversity in subseafloor habitats associated with a deep-sea volcanic eruption.
11	*Pseudomonas sp.* (98 %)	Bacterial diversity in water samples of Monticello mill tailings site, the water used was from uranium mining waste. Also a common environmental bacterium.
12	*Pseudomonas gessardii* (98 %)	*Pseudomonas gessardii sp.* and *Pseudomonas migulae sp.* two new species isolated from natural mineral waters.
13	*Pseudomonas marginalis* (99 %)	Identification of *Pseudomonas viridiflava* and *Pseudomonas marginalis* isolates causative of carrot post harvest bacterial soft rot during refrigerated export from New Zealand.
14	*Pseudomonas marginalis* (92 %)	Spatial distribution of total, ammonia oxidizing, and denitrifying bacteria in biological wastewater treatment reactors for bioregenerative life support.
15	*Pseudomonas sp.* (97 %)	Rhizosphere microbial community of glufosinate-tolerant and wildtype oilseed rape.
16	Eubacterium (90 %)	Combined Use of 16S Ribosomal DNA and 16S rRNA To Study the Bacterial Community of Polychlorinated Biphenyl-Polluted Soil.
17	Unidentified bacterium DNA (92 %) or *Alcaligenes sp.* (92 %)	An outbreak of nonflocculating catabolic populations caused the breakdown of a phenol-digesting activated-sludge process.
18	Unidentified bacterium DNA (92 %) or *Alcaligenes sp.* (92 %)	An outbreak of nonflocculating catabolic populations caused the breakdown of a phenol-digesting activated-sludge process.
19	Uncultured bacterium clone (96 %)	Bacterial 16S rDNA clones associated with carbon leader ore samples from a depth of 3.3 km below land surface in the East Driefontein gold mine, South Africa.
20	Uncultured bacterium FukuS93 (94 %)	Comparative 16S rRNA analysis of lake bacterioplankton reveals globally distributed phylogenetic clusters including an abundant group of actinobacteria.
21	*Sphingomonas paucimobilis* (96 %)	Phylogenetic and physiological comparisons of PAH-degrading bacteria from geographically diverse soils.
22	unknown – bad sequence	
23	*Pseudomonas sp.* (92 %)	Diversity and ubiquity of bacteria capable of utilizing humic substances as electron donors for anaerobic respiration.

Table B6 (continued): Health and Safety Laboratory identification from the samples received from slurry-phase bioreactor project.

Colony number	Species and percentage similarity	Source
24	*Sphingomonas sp.* (96 %)	Dominant marine bacterioplankton species found among colony-forming bacteria.
25	*Sphingomonas sp.* (96 %)	Plasmid-mediated mineralization of carbofuran by *Sphingomonas sp.* strain CF06.
26	*Bordetella sp.* (92 %)	Microflora for efficient degradation of cellulolytic substrate.
27	alpha proteobacterium (96 %)	Composition of marine bacterial communities utilizing high and low molecular weight dissolved organic matter.
28	blackwater bioreactor bacterium BW6 (96 %)	Analysis of microbial activity based on 16S rRNA by denaturing gradient gel electrophoresis
29	uncultured eubacterium WR8151 (96 %)	Combined Use of 16S ribosomal DNA and 16S rRNA To Study the Bacterial Community of Polychlorinated Biphenyl-Polluted Soil.
30	*Sphingomonas sp.* (95 %)	Phylogenetic and physiological comparisons of PAH-degrading bacteria from geographically diverse soils.
31	*Azorhizobium sp.* (97 %)	Not known.
32	*Acidovorax sp.* (94 %)	Anaerobic mineralization of quaternary carbon atoms: isolation of denitrifying bacteria on dimethylmalonate.
33	*Acidovorax sp.* (96 %)	Anaerobic mineralization of quaternary carbon atoms: isolation of denitrifying bacteria on dimethylmalonate.
34	uncultured bacterium FukuS36 (91 %).	Comparative 16S rRNA analysis of lake bacterioplankton reveals globally distributed phylogenetic clusters including an abundant group of actinobacteria.
35	uncultured eubacterium. (95 %)	Dependence of wastewater treatment efficiencies on treatment system and its bacterial community composition.
36	Poor sequence – Unknown	n/a.
37	*Sphingopyxis witflariensis.* (98 %)	*Sphingopyxis witflariensis sp.* nov., isolated from activated sludge.
38	*Pseudomonas sp.* (99 %)	Peptide nucleic acid-mediated PCR clamping as a useful supplement in the determination of microbial diversity.
39	*Sphingopyxis witflariensis.* (98 %)	*Sphingopyxis witflariensis sp.* nov., isolated from activated sludge.
40	*Pseudomonas sp.* (97 %)	Phylogeny, ribosomal RNA gene typing and relative abundance of new Pseudomonas species (*sensu stricto*) isolated from two pinyon-juniper woodland soils of the arid southwest U.S.
41	uncultured bacterium. (90 %)	Phylogenetic Composition of Bacterioplankton Assemblages from the Arctic Ocean.
42	unknown – bad sequence	n/a

FIELD SCALE CHEMICAL DATA

Table B7: Trial 1 analytical data and interpretation

Slurry-phase bioreactor Trial 1 Samples of Feedstock Prior to Treatment-- Soil Samples Page 1

Sample Reference:	BT1S/001	BT1S/02	BT1S/03	BT1S/04	BT1S/05	BT1S/006	**Mean Conc.**	**US 95 (upper bound value)**	**Median Conc.**	**Mode Conc.**	**Standard Deviation**
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	Mg/kg	Mg/kg	Mg/kg	Mg/kg	
pH	7.7	7.6	7.7	7.6	7.6	7.3	7.6	7.7	7.6	7.6	0.147
% Loss on Ignition	8.6	9.0	11	12	9.6	11	10	11	10	11	1.333
% Moisture	16	15	16	16	17	17	16	16	16	16	0.753
% Stones	32	26	23	27	22	18	24	28	24	*	4.803
Cresols	4.4	1.9	0.48	0.20	0.56	0.46	1.3	2.7	0.52	*	1.619
Xylenols & Ethylphenols	15	17	16	9.6	12	17	14.4	16.9	15.5	17	3.008
Catechol	0.57	1.0	1.2	0.77	0.94	1.2	0.9	1.1	0.97	1.2	0.247
Phenol	0.80	0.64	0.57	0.43	0.49	0.81	0.6	0.8	0.605	*	0.158
Trimethylphenol	8.0	10	10	6.1	4.5	11	8.3	10.4	9	10	2.547
Total Phenols	28	30	28	17	19	30	25	30	28	28	5.785
Naphthalene	530	470	470	690	530	540	538	604	530	530	80.602
Acenaphthylene	140	160	170	170	200	180	170	186	170	170	20.000
Acenaphthene	30	34	37	34	43	38	36	39	35.5	34	4.427
Fluorene	120	140	150	140	180	160	148	165	145	140	20.412
Phenanthrene	390	420	480	450	570	500	468	520	465	*	63.692
Anthracene	100	130	140	150	160	170	141	162	145	*	24.833
Fluoranthene	230	270	300	290	360	310	293	328	295	*	43.205
Pyrene	220	260	290	280	340	300	281	314	285	*	40.208
Benzo(a)anthracene	74	76	94	82	110	94	88	99	88	94	13.648
Chrysene	61	66	79	75	96	79	76	86	77	79	12.198
Benzo(b)fluoranthene	44	41	65	51	57	53	51	59	52	*	8.727
Benzo(k)fluoranthene	35	44	39	44	61	51	45	53	44	44	9.245
Benzo(a)pyrene	48	53	67	60	81	66	62	72	63	*	11.675
Indeno(1,2,3-cd)pyrene	31	27	42	32	42	37	35	40	34.5	42	6.178
Di-benzoo(a,h)anthracene	6.1	7.6	3.2	9.6	14	8.7	8.2	11	8.15	*	3.623
Benzo(g,h,i)perylene	31	31	40	36	48	39	37	42	37.5	31	6.411
Anthanthrene	14	13	19	15	23	18	17	20	16.5	*	3.742
Benzo(e)pyrene	31	38	44	42	47	50	42	47	43	*	6.782
Cyclopenta(cd)pyrene	3.3	4.3	5.7	4.8	4.6	4.6	4.6	5.2	4.6	4.6	0.777
Total PAH	2138	2285	2535	2655	2967	2698	2546	2792	2595	*	298.83
Easily-liberatable Cyanide	0.81	1	1	1	1	1	1.0	1.0	1	1	0.078
Complex Cyanide	18	22	21	26	21	32	23.3	27.4	21.5	21	4.967
Total Cyanide	19	22	21	26	21	32	23.5	27.4	21.5	21	4.764
Elemental Sulphur	100	100	100	100	100	100	100.0	100.0	100	100	0.000
Water Soluble SO4	2400	2600	2700	2600	2700	3100	2683	2873	2650	2600	231.661
Water Soluble Chloride	62	48	51	62	53	68	57	63	57.5	62	7.789
Exchangeable Ammonium	110	79	170	100	180	150	131	165	130	*	40.957
Nitrate	12	8.7	7.0	6.8	7.0	9.2	8.5	10.1	7.85	7	2.008
Arsenic	62	76	79	69	74	31	65.2	79.8	71.5	*	17.770
Cadmium	1.3	1.6	1.7	1.4	1.6	1.0	1.4	1.6	1.5	1.6	0.258
Chromium	36	43	45	42	46	76	48	59	44	*	14.156
Lead	460	550	530	480	530	420	495	536	505	530	50.100
Mercury	2.0	2.5	3.0	2.9	2.6	3.1	2.7	3.0	2.75	*	0.407
Selenium	1.1	1.2	1.4	1.3	1.2	1.4	1.3	1.4	1.25	1.2	0.121
Copper	62	76	72	65	74	100	74	85	73	*	13.452
Nickel	36	43	42	40	42	27	38	43	41	42	6.088
Zinc	510	610	610	540	610	400	546	615	575	610	83.586
Boron	1.4	1.5	1.4	1.2	1.6	1.7	1.5	1.6	1.45	1.4	0.175
Benzene	1.9	2.6	6.4	1.6	2.9	1.8	2.9	4.3	2.25	*	1.802
Toluene	1.2	1.7	4.4	1.0	1.8	1.4	1.9	2.9	1.55	*	1.253
Ethylbenzene	0.081	0.12	0.27	1.0	0.11	0.12	0.3	0.6	0.12	0.12	0.357
Xylenes	1.1	1.6	3.3	1.0	1.4	1.5	1.7	2.3	1.45	*	0.841
Total Petroleum Hydrocarbons											
C6-C8 (Aliphatic)	5	5	5	5	5	5	5	5	5	5	0
C8-C10 (Aliphatic)	5	5	5	5	5	5	5	5	5	5	0
C10-C12 (Aliphatic)	5	5	5	5	5	5	5	5	5	5	0
C12-C16 (Aliphatic)	10	10	10	10	10	10	10	10	10	10	0
C16-C21 (Aliphatic)	1090	10	696	10	10	10	304	693	10	10	472
C21-C40 (Aliphatic)	25	25	25	25	25	25	25	25	25	25	0
C6-C7 (Aromatic)	5	5	5	5	5	5	5	5	5	5	0
C7-C8 (Aromatic)	5	5	5	5	5	5	5	5	5	5	0
C8-C10 (Aromatic)	5	5	5	5	5	5	5	5	5	5	0
C10-C12 (Aromatic)	1360	1870	5	1450	5	1590	1046	1725	1405	5	825
C12-C16 (Aromatic)	1340	1920	10	1320	10	1630	1038	1717	1330	10	826
C16-C21 (Aromatic)	1500	1700	2180	10	1630	1290	1385	1990	1565	*	735
C21-C40 (Aromatic)	1400	2080	25	1370	25	1650	1091	1802	1385	25	864

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Slurry-phase bioreactor Trial 1 Samples of Feedstock Prior to Treatment-- Soil Samples Page 2											
Sample Reference:	BT1S/031	BT1S/032	BT1S/033	BT1S/034	Mean Conc.	US 95 (upper bound value)	CLEA Soil Guideline Value (SGV)	US95 Higher/Lower than SGV	Median Conc.	Mode Conc.	Standard Deviation
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	Mg/kg	Mg/kg	Mg/kg	Mg/kg	
pH	7.3	7.6	7.4	7.5	7.45	7.6			7.5	*	0.1
% Loss on Ignition	19	16	18	17	17.5	19.0			17.5	*	1.3
% Moisture	21	22	24	25	23	25.1			23.0	*	1.8
% Stones	9.1	22	7.8	2.7	10.4	20.1			8.5	*	8.2
Cresols	1.6	1.8	1.9	1.4	1.675	1.9			1.7	*	0.2
Xylenols & Ethylphenols	9.1	9.2	12	7.4	9.425	11.7			9.2	*	1.9
Catechol	0.1	0.1	0.1	0.1	0.1	0.1			0.1	0.1	0.0
Phenol	1.1	1.0	1.1	1.0	1.05	1.1			1.1	1.1	0.1
Trimethylphenol	10	9.5	12	6.6	9.525	12.1			9.8	*	2.2
Total Phenols	22	22	27	17	22	26.8			22.0	22.0	4.1
Naphthalene	760	360	650	900	667.5	937.0			705.0	*	229.1
Acenaphthylene	890	610	860	840	800	951.0			850.0	*	128.3
Acenaphthene	190	130	190	190	175	210.3			190.0	190.0	30.0
Fluorene	730	500	700	680	652.5	774.5			690.0	*	103.7
Phenanthrene	1900	1400	1900	2000	1800	2118.6			1900.0	1900.0	270.8
Anthracene	710	440	690	650	622.5	768.6			670.0	*	124.2
Fluoranthene	1700	1200	1600	1600	1525	1785.9			1600.0	1600.0	221.7
Pyrene	1500	1100	1500	1500	1400	1635.3			1500.0	1500.0	200.0
Benzo(a)anthracene	720	350	720	570	590	795.8			645.0	720.0	174.9
Chrysene	510	320	520	490	460	570.8			500.0	*	94.2
Benzo(b)fluoranthene	390	230	380	340	335	421.2			360.0	*	73.3
Benzo(k)fluoranthene	420	230	440	360	362.5	473.9			390.0	*	94.6
Benzo(a)pyrene	500	270	500	410	420	547.8	37**	Higher	455.0	500.0	108.6
Indeno(1,2,3-cd)pyrene	240	170	290	240	235	293.0			240.0	240.0	49.3
Di-benzo(a,h)anthracene	61	46	34	95	59	90.1			53.5	*	26.4
Benzo(g,h,i)perylene	270	170	290	260	247.5	310.0			265.0	*	53.2
Anthanthrene	120	70	120	110	105	133.0			115.0	120.0	23.8
Benzo(e)pyrene	400	190	460	270	330	474.1			335.0	*	122.5
Cyclopenta(cd)pyrene	110	< 1.0	83	< 1.0	96.5	119.0			96.5	*	19.1
Total PAH	12000	7900	12000	12000	10975	13386.8			12000.0	12000.0	2050.0
Easily-liberatable Cyanide	1.1	2.0	1	1.3	1.35	1.9			1.2	*	0.5
Complex Cyanide	30	35	43	47	38.75	47.8			39.0	*	7.7
Total Cyanide	31	37	43	48	39.75	48.4			40.0	*	7.4
Elemental Sulphur	400	310	450	170	332.5	477.0			355.0	*	122.8
Water Soluble SO4	600	600	660	680	635	683.5			630.0	600.0	41.2
Water Soluble Chloride	52	45	61	55	53.25	61.1			53.5	*	6.7
Exchangeable Ammonium	57	75	58	140	82.5	128.6			66.5	*	39.2
Nitrate	19	21	19	13	18	22.1			19.0	19.0	3.5
Arsenic	80	67	85	4.8	59.2	102.8	500	Lower	73.5	*	37.1
Cadmium	1.6	1.4	1.7	1.8	1.625	1.8	1400	Lower	1.7	*	0.2
Chromium	45	38	46	50	44.75	50.6	5000	Lower	45.5	*	5.0
Lead	550	450	580	630	552.5	641.8	750	Lower	565.0	*	75.9
Mercury	2.7	2.3	3.2	3.5	2.925	3.6	480	Lower	3.0	*	0.5
Selenium	1.1	1.0	1.4	1.3	1.2	1.4	8000	Lower	1.2	*	0.2
Copper	73	60	76	81	72.5	83.0			74.5	*	9.0
Nickel	44	37	46	48	43.75	49.4	5000	Lower	45.0	*	4.8
Zinc	640	530	670	710	637.5	728.3			655.0	*	77.2
Boron	1.4	1.1	1.4	1.5	1.35	1.6			1.4	1.4	0.2
Benzene	0.50	0.24	0.81	0.51	0.515	0.8			0.5	*	0.2
Toluene	0.48	0.30	0.96	0.83	0.6425	1.0			0.7	*	0.3
Ethylbenzene	0.1	0.1	0.12	0.13	0.1125	0.1			0.1	0.1	0.0
Xylenes	0.84	5.4	1.6	1.7	2.385	4.8			1.7	*	2.0
Total Petroleum Hydrocarbons											
C6-C8 (Aliphatic)	5	41	38	5	22.25	45.7			21.5	5.0	20.0
C8-C10 (Aliphatic)	27	34	26	29	29	33.2			28.0	*	3.6
C10-C12 (Aliphatic)	138	153	130	146	141.75	153.5			142.0	*	9.9
C12-C16 (Aliphatic)	436	461	425	475	449.25	476.1			448.5	*	22.8
C16-C21 (Aliphatic)	351	388	350	406	373.75	406.5			369.5	*	27.8
C21-C40 (Aliphatic)	494	627	511	596	557	633.0			553.5	*	64.6
C6-C7 (Aromatic)	5	5	5	5	5	5.0			5.0	5.0	0.0
C7-C8 (Aromatic)	5	5	5	5	5	5.0			5.0	5.0	0.0
C8-C10 (Aromatic)	159	252	178	189	194.5	241.9			183.5	*	40.3
C10-C12 (Aromatic)	791	2060	1220	1270	1335.25	1957.4			1245.0	*	528.8
C12-C16 (Aromatic)	3170	3280	2940	3230	3155	3331.7			3200.0	*	150.2
C16-C21 (Aromatic)	5220	5020	4680	5170	5022.5	5309.1			5095.0	*	243.6
C21-C40 (Aromatic)	9220	8710	8260	8900	8772.5	9244.6			8805.0	*	401.3

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Table B7 (continued): Trial 1 analytical results and interpretation

Slurry-phase bioreactor Trial 1 Samples of Feedstock Prior to Treatment-- Soil Samples Page 3

Sample Reference:	BT1S/035	BT1S/036	BT1S/037	BT1S/038	BT1S/039	BT1S/040	BT1S/041	BT1S/042	Mean Conc.	US 95 (upper bound value)	CLEA Soil Guideline Value (SGV)
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg			mg/kg
pH	7.6	8.1	7.5	7.6	7.6	7.6	7.7	7.6	7.7	7.8	
% Loss on Ignition	6.4	5.8	5.2	5.9	3.9	5.4	4.3	5.8	5.3	5.9	
% Moisture	17	11	14	13	12	12	11	12	12.8	14.1	
% Stones	20	28	17	22	31	24	24	31	24.6	28.0	
Cresols	0.43	2.4	3.4	2.5	2.2	1.7	2.4	0.94	2.0	2.6	
Xylenols & Ethylphenols	4.6	20	17	16	20	15	15	7.7	14.4	18.1	
Catechol	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Phenol	0.43	1.1	1.7	1.2	0.93	0.84	1.2	0.48	1.0	1.3	
Trimethylphenol	5.9	13	15	13	15	11	13	6.9	11.6	13.9	
Total Phenols	12	37	38	33	38	28	31	16	29.1	35.8	
Naphthalene	58	96	97	75	190	100	67	64	93.4	121.7	
Acenaphthylene	84	82	140	75	100	120	100	58	94.9	112.3	
Acenaphthene	19	19	31	19	22	27	23	14	21.8	25.3	
Fluorene	76	76	120	71	90	100	95	56	85.5	98.8	
Phenanthrene	230	250	350	220	270	330	270	170	261.3	300.4	
Anthracene	75	69	120	63	84	94	88	49	80.3	94.7	
Fluoranthene	170	160	280	150	170	230	190	120	183.8	217.3	
Pyrene	170	150	270	140	170	220	180	120	177.5	209.5	
Benzo(a)anthracene	84	61	130	51	84	87	88	46	78.9	96.8	
Chrysene	58	52	89	44	57	73	57	38	58.5	69.3	
Benzo(b)fluoranthene	42	34	70	31	44	60	45	30	44.5	54.0	
Benzo(k)fluoranthene	48	5.1	73	31	44	36	51	26	39.3	52.7	
Benzo(a)pyrene	56	43	89	37	57	57	61	33	54.1	65.9	37**
Indeno(1,2,3-cd)pyrene	33	30	51	31	34	50	35	27	36.4	42.5	
Di-benzo(a,h)anthracene	3.8	4.1	9.7	1.8	4.8	3.1	5.8	2.1	4.4	6.1	
Benzo(g,h,i)perylene	33	25	52	23	34	38	37	21	32.9	39.6	
Anthanthrene	14	10	23	10	15	17	15	10	14.3	17.2	
Benzo(e)pyrene	45	26	62	24	40	36	50	21	38.0	47.5	
Cyclopenta(cd)pyrene	9.9	1	12	1	9.7	1	15	1	6.3	10.3	
Total PAH	1308.7	1193.2	2068.7	1097.8	1519.5	1679.1	1472.8	906.1	1405.7	1650.0	
Easily-liberatable Cyanide	1	1	1	1	1	1	0.86	1	1.0	1.0	
Complex Cyanide	21	17	19	12	17	22	15	3.1	15.8	19.8	
Total Cyanide	21	17	20	12	17	22	15	3.1	15.9	20.0	
Elemental Sulphur	110	120	280	100	130	150	140	120	143.8	182.1	
Water Soluble SO4	760	540	770	630	640	800	560	710	676.3	742.2	
Water Soluble Chloride	35	24	35	38	25	31	22	24	29.3	33.4	
Exchangeable Ammonium	27	23	66	12	5	10	5	5	19.1	33.0	
Nitrate	13	7.9	5.0	29	6.0	6.4	5.8	9.4	10.3	15.7	
Arsenic	54	47	52	48	45	46	46	44	47.8	50.1	500
Cadmium	0.84	0.82	0.89	0.75	0.77	0.80	0.81	0.77	0.8	0.8	1400
Chromium	42	36	42	37	30	38	36	36	37.1	39.7	5000
Lead	370	330	360	350	320	360	320	330	342.5	355.8	750
Mercury	1.1	1.1	1.5	1.0	0.90	1.0	0.81	0.90	1.0	1.2	480
Selenium	0.61	0.45	0.42	0.42	0.45	0.54	0.31	0.49	0.5	0.5	8000
Copper	56	51	56	47	55	52	45	51	51.6	54.4	
Nickel	36	31	41	32	30	31	30	30	32.6	35.3	5000
Zinc	430	400	430	410	370	400	390	370	400.0	415.6	
Boron	0.84	0.69	0.81	0.75	0.53	0.61	0.63	0.63	0.7	0.8	
Benzene	0.82	1.1	4.7	2.0	4.1	2.7	1.5	0.1	2.1	3.2	
Toluene	0.75	1.1	5.0	2.0	3.2	2.5	1.9	0.1	2.1	3.1	
Ethylbenzene	0.1	0.1	0.51	0.20	0.24	0.22	0.22	0.1	0.2	0.3	
Xylenes	0.82	1.1	6.4	2.5	3.0	2.7	2.8	0.094	2.4	3.7	
Total Petroleum Hydrocarbons											
C6-C8 (Aliphatic)	5	5	5	5	5	5	5	5	5.0	5.0	
C8-C10 (Aliphatic)	5	5	5	5	5	5	5	5	5.0	5.0	
C10-C12 (Aliphatic)	5	38	52	106	81	58	68	45	56.6	76.8	
C12-C16 (Aliphatic)	71	117	159	313	218	170	200	175	177.9	225.9	
C16-C21 (Aliphatic)	82	111	156	258	195	174	179	176	166.4	202.0	
C21-C40 (Aliphatic)	146	175	239	451	292	262	277	275	264.6	325.9	
C6-C7 (Aromatic)	5	5	5	5	5	5	5	5	5.0	5.0	
C7-C8 (Aromatic)	5	5	5	5	5	5	5	5	5.0	5.0	
C8-C10 (Aromatic)	5	5	5	248	228	5	140	5	80.1	152.6	
C10-C12 (Aromatic)	5	173	210	1700	764	233	444	248	472.1	837.1	
C12-C16 (Aromatic)	424	774	976	2500	1690	1080	1400	1090	1241.8	1666.7	
C16-C21 (Aromatic)	760	1300	1760	3600	2410	1760	2120	1900	1951.3	2510.4	
C21-C40 (Aromatic)	1300	2230	2930	6450	3910	3060	3570	3230	3335.0	4338.4	

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Table B7 (continued): Trial 1 analytical results and interpretation.

Slurry-phase bioreactor Trial 1 Samples of Feedstock Prior to Treatment-- Soil Samples Page 4

Sample Reference: Units	US95 Higher/Lower than SGV	Median Conc.	Mode Conc.	Standard Deviation	Mean feedstock conc.	Mean product conc.	US 95 (upper bound value) of mean product conc.	CLEA Soil Guideline Value (SGV) mg/kg	US95 Higher/Lower than SGV	%Change
pH		7.6	7.6	0.2	7.6	7.65	7.78			-0.88
% Loss on Ignition		5.6	5.8	0.8	10.2	6.07	6.69			40.52
% Moisture		12.0	12.0	2.0	16.2	13.37	14.74			17.33
% Stones		24.0	31.0	5.1	24.7	23.77	27.54			3.63
Cresols		2.3	2.4	0.9	1.3	1.98	2.59			-48.27
Xylenols & Ethylphenols		15.5	20.0	5.5	14.4	14.11	17.73			2.22
Catechol		0.1	0.1	0.0	0.9	0.10	0.10			89.44
Phenol		1.0	1.2	0.4	0.6	0.99	1.25			-58.65
Trimethylphenol		13.0	13.0	3.5	8.3	11.48	13.81			-38.82
Total Phenols		32.0	38.0	10.0	25.3	28.70	35.31			-13.28
Naphthalene		85.5	*	42.3	538.3	127.82	170.66			76.26
Acenaphthylene		92.0	100.0	26.1	170.0	137.18	162.66			19.30
Acenaphthene		20.5	19.0	5.3	36.0	30.95	36.41			14.04
Fluorene		83.0	76.0	19.9	148.3	119.52	139.37			19.42
Phenanthrene		260.0	270.0	58.4	468.3	353.58	409.48			24.50
Anthracene		79.5	*	21.6	141.7	112.79	135.17			20.39
Fluoranthene		170.0	170.0	50.1	293.3	264.23	311.45			9.92
Pyrene		170.0	170.0	47.7	281.7	250.85	295.03			10.94
Benzo(a)anthracene		84.0	84.0	26.7	88.3	109.54	138.71			-24.01
Chrysene		57.0	57.0	16.1	76.0	82.59	99.39			-8.67
Benzo(b)fluoranthene		43.0	*	14.1	51.8	61.93	76.01			-19.48
Benzo(k)fluoranthene		40.0	*	20.0	45.7	58.66	77.93			-28.45
Benzo(a)pyrene	Higher	56.5	57.0	17.5	62.5	76.08	94.77	37**	Higher	-21.72
Indeno(1,2,3-cd)pyrene		33.5	*	9.1	35.2	48.29	57.49			-37.32
Di-benzo(a,h)anthracene		4.0	*	2.5	8.2	7.68	11.13			6.39
Benzo(g,h,i)perylene		33.5	*	10.1	37.5	45.75	55.85			-22.01
Anthanthrene		14.5	10.0	4.5	17.0	19.70	24.19			-15.85
Benzo(e)pyrene		38.0	*	14.2	42.0	55.52	73.09			-32.19
Cyclopenta(cd)pyrene		5.4	1.0	5.9	4.6	11.74	16.81			-157.92
Total PAH		1390.8	*	364.6	2546.4	1979.89	2354.25			22.25
Easily-liberatable Cyanide		1.0	1.0	0.0	1.0	1.00	1.07			-3.74
Complex Cyanide		17.0	17.0	6.0	23.3	17.14	21.48			26.54
Total Cyanide		17.0	17.0	6.1	23.5	17.32	21.69			26.30
Elemental Sulphur		125.0	120.0	57.3	100.0	155.08	199.84			-55.08
Water Soluble SO4		675.0		98.4	2683.3	673.78	738.66			74.89
Water Soluble Chloride		28.0	35.0	6.2	57.3	30.69	35.08			46.47
Exchangeable Ammonium		11.0	5.0	20.7	131.5	22.93	38.75			82.56
Nitrate		7.2		8.0	8.5	10.77	16.04			-27.50
Arsenic	Lower	46.5	46.0	3.5	65.2	48.44	53.25	500	Lower	25.67
Cadmium	Lower	0.8	0.8	0.0	1.4	0.86	0.90	1400	Lower	40.32
Chromium	Lower	36.5	36.0	3.8	48.0	37.58	40.35	5000	Lower	21.70
Lead	Lower	340.0	330.0	19.8	495.0	355.10	372.94	750	Lower	28.26
Mercury	Lower	1.0	1.1	0.2	2.7	1.15	1.32	480	Lower	57.07
Selenium	Lower	0.5	0.5	0.1	1.3	0.51	0.57	8000	Lower	60.09
Copper		51.5	56.0	4.1	74.8	52.88	56.07			29.34
Nickel	Lower	31.0	30.0	3.9	38.3	33.29	36.10	5000	Lower	13.15
Zinc		400.0	430.0	23.3	546.7	414.25	434.37			24.22
Boron		0.7	0.6	0.1	1.5	0.73	0.81			50.49
Benzene		1.8	*	1.6	2.9	2.03	3.06			29.16
Toluene		2.0	*	1.5	1.9	1.98	2.98			-3.47
Ethylbenzene		0.2	0.1	0.1	0.3	0.21	0.29			27.57
Xylenes		2.6	*	1.9	1.7	2.42	3.79			-46.92
Total Petroleum Hydrocarbons										
C6-C8 (Aliphatic)		5.0	5.0	0.0	5.0	6.04	7.44			-20.70
C8-C10 (Aliphatic)		5.0	5.0	0.0	5.0	6.44	6.69			-28.80
C10-C12 (Aliphatic)		55.0	*	30.1	5.0	61.73	81.38			-1134.65
C12-C16 (Aliphatic)		172.5	*	71.6	10.0	194.16	240.88			-1841.58
C16-C21 (Aliphatic)		175.0	*	53.2	304.3	178.82	214.29			41.24
C21-C40 (Aliphatic)		268.5	*	91.4	25.0	282.17	344.31			-1028.67
C6-C7 (Aromatic)		5.0	5.0	0.0	5.0	5.00	5.00			0.00
C7-C8 (Aromatic)		5.0	5.0	0.0	5.0	5.00	5.00			0.00
C8-C10 (Aromatic)		5.0	5.0	108.1	5.0	86.99	157.93			-1639.75
C10-C12 (Aromatic)		240.5	*	544.8	1046.7	523.91	904.33			49.94
C12-C16 (Aromatic)		1085.0	*	634.3	1038.3	1356.55	1766.63			-30.65
C16-C21 (Aromatic)		1830.0	1760.0	834.6	1385.0	2135.53	2678.36			-54.19
C21-C40 (Aromatic)		3145.0		1497.7	1091.7	3661.25	4632.81			-235.38

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Table B7 (continued): Trial 1 analytical results and interpretation.

Table B8: Trial 1 slurry analytical results

Sample Reference	BT1S/008	BT1S/011	BT1S/015	BT1S/018	BT1S/021	BT1S/024	BT1S/027	Percentage change from Day 1 of Trial
Day of Bioreactor Trial	1	4	5	6	7	8	11	
Date Sampled:	06/09/02	09/09/02	10/09/02	11/09/02	12/09/02	13/09/02	16/09/02	
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	
pH	.	7.1	7.6	.	.	.	.	-
% Loss on Ignition	.	25	26	21	23	24	23	-
% Moisture	57	54	58	55	51	49	53	-
% Stones	1.8	0.30	1.3	1.1	0.42	0.49	0.79	-
Cresols	.	2.1	1.2	.	.	.	.	-
Xylenols & Ethylphenols	.	22	5.6	.	.	.	.	-
Catechol	.	0.1	0.1	.	.	.	.	-
Phenol	.	0.66	0.79	.	.	.	.	-
Trimethylphenol	.	24	20	.	.	.	.	-
Total Phenols	.	48	28	.	.	.	.	-
Naphthalene	4100	780	290	330	400	1300	550	86.6
Acenaphthylene	1200	950	720	1200	1200	1100	980	18.3
Acenaphthene	240	210	160	270	300	280	270	-12.5
Fluorene	1100	900	680	1300	1300	1200	750	31.8
Phenanthrene	3200	2800	2000	3800	3800	2500	560	82.5
Anthracene	950	740	600	960	1100	990	940	1.1
Fluoranthene	2100	1800	1400	2500	2800	2600	2900	-38.1
Pyrene	1900	1700	1300	2300	2600	2500	2700	-42.1
Benzo(a)anthracene	650	530	390	620	900	740	920	-41.5
Chrysene	510	410	310	590	860	660	880	-72.5
Benzo(b)fluoranthene	350	310	210	430	570	490	580	-65.7
Benzo(k)fluoranthene	390	330	250	410	640	420	650	-66.7
Benzo(a)pyrene	460	390	280	510	720	560	760	-65.2
Indeno(1,2,3-cd)pyrene	290	220	160	300	390	330	410	-41.4
Di-benzo(a,h)anthracene	36	43	29	89	120	130	120	-233.3
Benzo(g,h,i)perylene	300	260	170	350	470	380	480	-60.0
Anthanthrene	120	110	71	140	190	170	200	-66.7
Benzo(e)pyrene	310	260	230	300	560	350	550	-77.4
Cyclopenta(cd)pyrene	48	60	36	26	64	35	82	-70.8
Total PAH	18254	12803	9286	16425	18984	16735	15282	16.3
Easily-liberatable Cyanide	.	2.2	1	.	.	.	.	.
Complex Cyanide	.	170	180	.	.	.	.	.
Total Cyanide	.	170	180	.	.	.	.	.
Elemental Sulphur	.	100	100	390	370	450	440	.
Water Soluble Sulphate as SO4	.	7700	5000	7400	7700	7700	7300	.
Water Soluble Chloride	.	210	250	220	200	170	190	.
Exchangeable Ammonium	.	140	120	.	.	.	.	.
Nitrate	.	22	30	.	.	.	.	.
Arsenic	.	190	160	180	170	150	170	.
Cadmium	.	3.7	3.2	3.6	3.3	3.0	3.2	.
Chromium	.	91	83	82	76	69	80	.
Lead	.	1400	1300	1300	1200	990	1200	.
Mercury	.	8.8	7.9	7.9	7.4	6.8	7.7	.
Selenium	.	3.3	2.9	3.1	3.0	2.5	2.8	.
Copper	.	190	160	170	160	140	160	.
Nickel	.	81	70	70	67	64	72	.
Zinc	.	1500	1400	1400	1300	1100	1300	.
Boron	.	2.7	2.5	2.7	2.8	2.9	3.7	.
Benzene	.	0.48	0.1	44	.	.	.	.
Toluene	.	0.50	0.1	41	.	.	.	.
Ethylbenzene	.	0.1	0.1	10	.	.	.	.
Xylenes	.	1.0	0.1	130	.	.	.	.
Total Petroleum Hydrocarbons	18871	10967	9341	9615	10515	11233	9665	48.8
C6-C8 (Aliphatic)	5	5	5	5	5	5	5	0.0
C8-C10 (Aliphatic)	5	5	5	5	5	5	5	0.0
C10-C12 (Aliphatic)	162	5	127	5	5	5	5	96.9
C12-C16 (Aliphatic)	483	399	450	326	352	397	409	15.3
C16-C21 (Aliphatic)	317	235	255	208	237	258	267	15.8
C21-C40 (Aliphatic)	425	354	149	133	152	159	377	11.3
C6-C7 (Aromatic)	5	5	5	5	5	5	5	0.0
C7-C8 (Aromatic)	5	5	5	5	5	5	5	0.0
C8-C10 (Aromatic)	234	50	29	5	25	62	27	88.5
C10-C12 (Aromatic)	3130	484	241	218	194	172	320	89.8
C12-C16 (Aromatic)	2880	1650	1320	1390	1360	1630	1210	58.0
C16-C21 (Aromatic)	4570	3290	2860	3130	3420	3310	2450	46.4
C21-C40 (Aromatic)	6650	4480	3890	4180	4750	5220	4580	31.1

Notes:1) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

2) Dashed borders denote % change in concentrations each day compared with the first slurry sample. Negative sign denotes concentration higher than first day sample

3) Where results are absent, the centrifuged sample was insufficient for the full testing suite

Table B9: Trial 2 analytical data and interpretation

Slurry-phase bioreactor Trial 2 Samples of Feedstock Prior to Treatment–- Soil Samples Page 1

Sample Reference:	BT2S/001	BT2S/002	BT2S/003	BT2S/004	BT2S/005	BT2S/006	Mean Conc.	US 95 (upper bound value)	Median Conc.	Mode Conc.
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg				
pH	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
% Loss on Ignition	9.1	10	9.6	9.7	9.2	9.1	9.5	9.8	9.4	9.1
% Moisture	12	11	13	12	11	13	12.0	12.7	12.0	12
% Stones	35	35	41	31	34	38	35.7	38.5	35.0	35
Cresols	1.4	1.9	130	1.4	0.89	3.4	23.2	66.2	1.7	1.4
Xylenols & Ethylphenols	26	21	160	14	3.4	33	42.9	90.8	23.5	*
Catechol	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Phenol	1.5	1.9	45	1.3	0.55	1.4	8.6	23.3	1.5	*
Trimethylphenol	19	17	68	11	3.0	21	23.2	42.0	18.0	*
Total Phenols	47	42	410	28	7.4	59	98.9	225.1	44.5	*
Naphthalene	220	730	2400	610	190	960	851.7	1521.9	670.0	*
Acenaphthylene	190	350	520	250	150	250	285.0	394.8	250.0	250
Acenaphthene	43	73	120	50	34	51	61.8	87.6	50.5	*
Fluorene	160	290	480	200	130	220	246.7	350.9	210.0	*
Phenanthrene	510	850	1400	630	370	680	740.0	1037.3	655.0	*
Anthracene	140	260	390	210	120	190	218.3	298.8	200.0	*
Fluoranthene	340	590	900	510	290	420	508.3	690.0	465.0	*
Pyrene	320	520	850	410	270	400	461.7	633.2	405.0	*
Benzo(a)anthracene	120	200	340	170	98	140	178.0	249.7	155.0	*
Chrysene	100	190	290	170	92	130	162.0	222.5	150.0	*
Benzo(b)fluoranthene	73	120	210	100	68	110	113.5	155.9	105.0	*
Benzo(k)fluoranthene	79	130	210	120	80	91	118.3	159.1	105.5	*
Benzo(a)pyrene	91	150	260	140	86	120	141.2	193.5	130.0	*
Indeno(1,2,3-cd)pyrene	44	73	130	64	58	48	69.5	95.4	61.0	*
Di-benzo(a,h)anthracene	18	21	43	21	5.5	26	22.4	32.5	21.0	21
Benzo(g,h,i)perylene	57	85	160	71	49	68	81.7	114.8	69.5	*
Anthanthrene	22	26	74	22	1.5	32	29.6	49.4	24.0	22
Benzo(e)pyrene	67	120	150	110	55	79	96.8	126.5	94.5	*
Cyclopenta(cd)pyrene	1	16	13	16	1	28	12.5	21.0	14.5	1
Total PAH	2600	4800	9000	3900	2100	4000	4400.0	6423.7	3950.0	*
Easily-liberatable Cyanide	1	1	1	1	1	1	1.0	1.0	1.0	*
Complex Cyanide	12	5.2	5.4	11	8.9	11	8.9	11.4	10.0	11
Total Cyanide	12	5.2	5.4	11	8.9	11	8.9	11.4	10.0	11
Elemental Sulphur	61	61	110	100	100	91	87.2	104.6	95.5	61
Water Soluble SO4	670	550	690	710	2300	2400	1220.0	1942.0	700.0	*
Water Soluble Chloride	32	35	85	30	32	62	46.0	64.6	33.5	32
Exchangeable Ammonium	40	28	140	94	130	31	77.2	119.0	67.0	*
Nitrate	5.6	5	5	5	5.3	5	5.2	5.4	5.0	*
Arsenic	56	57	48	60	61	53	55.8	59.8	56.5	*
Cadmium	0.79	0.92	0.90	0.91	0.92	0.96	0.9	0.9	0.9	0.92
Chromium	32	34	31	36	36	31	33.3	35.3	33.0	31
Lead	410	420	360	430	420	380	403.3	425.8	415.0	420
Mercury	1.6	1.6	2.3	1.8	1.7	1.7	1.8	2.0	1.7	1.6
Selenium	0.91	1.0	0.90	0.97	1.0	1.0	1.0	1.0	1.0	1
Copper	60	67	47	60	61	53	58.0	63.7	60.0	60
Nickel	33	34	28	36	35	31	32.8	35.2	33.5	*
Zinc	470	480	410	490	490	440	463.3	489.7	475.0	490
Boron	1.2	1.2	0.90	1.4	1.3	1.3	1.2	1.4	1.3	1.2
Benzene	1.3	2.7	14	0.20	0.081	5.0	3.9	8.2	2.0	*
Toluene	1.5	3.0	8.8	0.27	0.089	7.2	3.5	6.5	2.3	*
Ethylbenzene	0.17	0.32	0.75	0.1	0.1	0.72	0.4	0.6	0.2	0.1
Xylenes	2.3	2.1	8.8	0.86	0.28	9.3	3.9	7.3	2.2	*
Total Petroleum Hydrocarbons										
C6-C8 (Aliphatic)	25	25	25	25	25	25	25.0	25.0	25.0	25
C8-C10 (Aliphatic)	25	25	25	25	25	25	25.0	25.0	25.0	25
C10-C12 (Aliphatic)	25	25	25	25	25	25	25.0	25.0	25.0	25
C12-C16 (Aliphatic)	50	50	50	50	50	50	50.0	50.0	50.0	50
C16-C21 (Aliphatic)	50	50	50	50	50	50	50.0	50.0	50.0	50
C21-C40 (Aliphatic)	125	125	125	125	125	125	125.0	125.0	125.0	125
C6-C7 (Aromatic)	25	25	25	25	25	25	25.0	25.0	25.0	25
C7-C8 (Aromatic)	25	25	25	25	25	25	25.0	25.0	25.0	25
C8-C10 (Aromatic)	25	25	25	25	25	25	25.0	25.0	25.0	25
C10-C12 (Aromatic)	583	454	3980	2540	25	921	1417.2	2672.1	752.0	*
C12-C16 (Aromatic)	1050	652	2620	1970	367	890	1258.2	1966.0	970.0	*
C16-C21 (Aromatic)	1400	1060	3510	2740	809	1620	1856.5	2720.1	1510.0	*
C21-C40 (Aromatic)	1220	898	7050	6090	680	1230	2861.3	5243.7	1225.0	*

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Slurry-phase bioreactor Trial 2 Samples of Feedstock Prior to Treatment–- Soil Samples Page 2

Sample Reference:	Standard Deviation	BT2S/020	BT2S/021	BT2S/022	BT2S/023	Mean Conc.	US 95 (upper bound value)	CLEA Soil Guideline Value (SGV)	US95 Higher/Lower than SGV	Median Conc.
Units		mg/kg	mg/kg	mg/kg	mg/kg			mg/kg		
PH	0.052	7.9	8.0	8.0	7.8	7.925	8.0			8.0
% Loss on Ignition	0.373	9.8	12	8.6	12	10.6	12.6			10.9
% Moisture	0.894	26	21	20	23	22.5	25.6			22.0
% Stones	3.445	42	39	50	29	40	50.2			40.5
Cresols	52.345	0.24	0.18	0.35	0.47	0.31	0.5			0.3
Xylenols & Ethylphenols	58.260	0.1	0.51	0.35	1.7	0.665	1.5			0.4
Catechol	0.000	0.1	0.1	0.1	0.1	0.1	0.1			0.1
Phenol	17.834	0.1	0.1	0.1	0.1	0.1	0.1			0.1
Trimethylphenol	22.912	0.1	0.29	0.1	1.3	0.4475	1.1			0.2
Total Phenols	153.431	0.5	1.0	0.74	3.4	1.41	3.0			0.9
Naphthalene	814.749	94	130	56	470	187.5	411.9			112.0
Acenaphthylene	133.529	100	120	79	190	122.25	178.9			110.0
Acenaphthene	31.288	12	18	8.6	33	17.9	30.6			15.0
Fluorene	126.754	36	70	28	130	66	120.6			53.0
Phenanthrene	361.442	90	170	68	340	167	312.2			130.0
Anthracene	97.860	72	85	56	140	88.25	131.2			78.5
Fluoranthene	220.854	150	170	120	290	182.5	270.2			160.0
Pyrene	208.559	300	290	240	390	305	378.5			295.0
Benzo(a)anthracene	87.178	120	75	79	110	96	122.3			94.5
Chrysene	73.485	110	70	75	110	91.25	116.8			92.5
Benzo(b)fluoranthene	51.497	98	75	79	110	90.5	109.8			88.5
Benzo(k)fluoranthene	49.609	120	70	90	75	88.75	115.2			82.5
Benzo(a)pyrene	63.575	140	90	120	120	117.5	141.8	37**	Higher	120.0
Indeno(1,2,3-cd)pyrene	31.456	68	65	56	75	66	75.3			66.5
Di-benzo(a,h)anthracene	12.216	29	21	27	26	25.75	29.8			26.5
Benzo(g,h,i)perylene	40.307	90	55	75	75	73.75	90.6			75.0
Anthanthrene	24.063	43	27	49	24	35.75	50.0			35.0
Benzo(e)pyrene	36.041	110	50	83	75	79.5	108.6			79.0
Cyclopenta(cd)pyrene	10.291	1	1	1	1	1	1.0			1.0
Total PAH	2460.081	1800	1700	1400	2800	1925	2639.8			1750.0
Easily-liberatable Cyanide	0.000	1	1	1.2	1.8	1.25	1.7			1.1
Complex Cyanide	2.979	38	36	27	29	32.5	38.8			32.5
Total Cyanide	2.979	39	37	29	31	34	39.6			34.0
Elemental Sulphur	21.142	110	130	100	140	120	141.5			120.0
Water Soluble SO4	877.633	900	1000	900	1500	1075	1412.9			950.0
Water Soluble Chloride	22.565	47	50	53	58	52	57.5			51.5
Exchangeable Ammonium	50.898	94	77	81	110	90.5	108.0			87.5
Nitrate	0.251	20	40	29	45	33.5	46.7			34.5
Arsenic	4.792	47	48	37	59	47.75	58.3	500	Lower	47.5
Cadmium	0.058	0.55	0.65	0.53	0.75	0.62	0.7	1400	Lower	0.6
Chromium	2.338	22	28	19	38	26.75	36.6	5000	Lower	25.0
Lead	27.325	320	360	270	460	352.5	447.3	750	Lower	340.0
Mercury	0.264	1.4	1.5	1.2	2.1	1.55	2.0	480	Lower	1.5
Selenium	0.047	0.81	0.75	0.64	1.0	0.8	1.0	8000	Lower	0.8
Copper	6.986	41	46	36	61	46	58.7			43.5
Nickel	2.927	22	26	19	34	25.25	32.9	5000	Lower	24.0
Zinc	32.042	330	370	280	460	360	449.6			350.0
Boron	0.172	1.0	1.4	1.1	1.7	1.3	1.7			1.3
Benzene	5.286	0.1	0.1	0.1	0.44	0.185	0.4			0.1
Toluene	3.690	0.1	0.1	0.1	0.52	0.205	0.5			0.1
Ethylbenzene	0.302	0.1	0.1	0.1	0.1	0.1	0.1			0.1
Xylenes	4.033	0.20	0.1	0.1	0.61	0.2525	0.5			0.2
Total Petroleum Hydrocarbons										
C6-C8 (Aliphatic)	0.000	5	5	5	5	5	5.0			5.0
C8-C10 (Aliphatic)	0.000	5	5	5	5	5	5.0			5.0
C10-C12 (Aliphatic)	0.000	59	61	46	46	53	62.6			52.5
C12-C16 (Aliphatic)	0.000	233	242	203	214	223	243.8			223.5
C16-C21 (Aliphatic)	0.000	182	186	177	171	179	186.6			179.5
C21-C40 (Aliphatic)	0.000	25	25	141	25	54	122.2			25.0
C6-C7 (Aromatic)	0.000	5	5	5	5	5	5.0			5.0
C7-C8 (Aromatic)	0.000	5	5	5	5	5	5.0			5.0
C8-C10 (Aromatic)	0.000	201	193	171	5	142.5	251.4			182.0
C10-C12 (Aromatic)	1525.562	333	402	309	191	308.75	412.1			321.0
C12-C16 (Aromatic)	860.441	1010	1160	972	720	965.5	1180.4			991.0
C16-C21 (Aromatic)	1049.822	1580	1670	1440	1400	1522.5	1669.6			1510.0
C21-C40 (Aromatic)	2896.112	534	595	480	307	479	624.8			507.0

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Table B9 (continued): Trial 2 analytical results and interpretation.

Slurry-phase bioreactor Trial 2 Samples of Feedstock Prior to Treatment–- Soil Samples Page 3

Sample Reference:	Mode Conc.	Standard Deviation	BT2S/024	BT2S/025	Mean Conc.	US 95 (upper bound value)	CLEA Soil Guideline Value (SGV)	US95 Higher/Lower than SGV	Median Conc.	Mode Conc.
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
PH	8.0	0.1	7.9	7.9	7.9	7.9			7.9	7.9
% Loss on Ignition	12.0	1.7	3.6	2.4	3.0	6.8			3.0	*
% Moisture	*	2.6	15	11	13.0	25.6			13.0	*
% Stones	*	8.7	50	61	55.5	90.2			55.5	*
Cresols	*	0.1	0.33	0.1	0.2	0.9			0.2	*
Xylenols & Ethylphenols	*	0.7	0.83	0.1	0.5	2.8			0.5	*
Catechol	0.1	0.0	0.1	0.1	0.1	0.1			0.1	0.1
Phenol	0.1	0.0	0.10	0.1	0.1	0.1			0.1	0.1
Trimethylphenol	0.1	0.6	1.1	0.1	0.6	3.8			0.6	*
Total Phenols	*	1.3	2.4	0.5	1.5	7.4			1.5	*
Naphthalene	*	190.7	29	18	23.5	58.2			23.5	*
Acenaphthylene	*	48.2	39	30	34.5	62.9			34.5	*
Acenaphthene	*	10.8	8.6	7.3	8.0	12.1			8.0	*
Fluorene	*	46.4	35	28	31.5	53.6			31.5	*
Phenanthrene	*	123.4	99	73	86.0	168.1			86.0	*
Anthracene	*	36.5	40	28	34.0	71.9			34.0	*
Fluoranthene	*	74.6	91	60	75.5	173.4			75.5	*
Pyrene	*	62.4	91	64	77.5	162.7			77.5	*
Benzo(a)anthracene	*	22.4	1	23	12.0	81.5			12.0	*
Chrysene	110.0	21.7	37	19	28.0	84.8			28.0	*
Benzo(b)fluoranthene	*	16.4	24	13	18.5	53.2			18.5	*
Benzo(k)fluoranthene	*	22.5	26	11	18.5	65.9			18.5	*
Benzo(a)pyrene	120.0	20.6	33	16	24.5	78.2	37**	Higher	24.5	*
Indeno(1,2,3-cd)pyrene	*	7.9	18	9.2	13.6	41.4			13.6	*
Di-benzo(a,h)anthracene	*	3.4	4.9	3.2	4.1	9.4			4.1	*
Benzo(g,h,i)perylene	75.0	14.4	19	9.2	14.1	45.0			14.1	*
Anthanthrene	*	12.1	9.9	6.0	8.0	20.3			8.0	*
Benzo(e)pyrene	*	24.7	20	9.2	14.6	48.7			14.6	*
Cyclopenta(cd)pyrene	1.0	0.0	45	1	23.0	161.9			23.0	*
Total PAH	*	607.6	660	410	535.0	1324.3			535.0	*
Easily-liberatable Cyanide	1.0	0.4	1.2	1	1.1	1.7			1.1	*
Complex Cyanide	*	5.3	11	6.2	8.6	23.8			8.6	*
Total Cyanide	*	4.8	12	7.1	9.6	25.0			9.6	*
Elemental Sulphur	*	18.3	100	100	100.0	100.0			100.0	100.0
Water Soluble SO4	900.0	287.2	410	350	380.0	569.4			380.0	*
Water Soluble Chloride	*	4.7	19	16	17.5	27.0			17.5	*
Exchangeable Ammonium	*	14.9	71	62	66.5	94.9			66.5	*
Nitrate	*	11.2	15	7.5	11.3	34.9			11.3	*
Arsenic	*	9.0	30	20	25.0	56.6	500	Lower	25.0	*
Cadmium	*	0.1	0.50	0.50	0.5	0.5	1400	Lower	0.5	0.5
Chromium	*	8.4	26	17	21.5	49.9	5000	Lower	21.5	*
Lead	*	80.6	220	150	185.0	406.0	750	Lower	185.0	*
Mercury	*	0.4	0.66	0.38	0.5	1.4	480	Lower	0.5	*
Selenium	*	0.2	0.45	0.24	0.3	1.0	8000	Lower	0.3	*
Copper	*	10.8	32	21	26.5	61.2			26.5	*
Nickel	*	6.5	21	15	18.0	36.9	5000	Lower	18.0	*
Zinc	*	76.2	230	160	195.0	416.0			195.0	*
Boron	*	0.3	0.74	0.25	0.5	2.0			0.5	*
Benzene	0.1	0.2	0.13	0.1	0.1	0.2			0.1	*
Toluene	0.1	0.2	0.15	0.1	0.1	0.3			0.1	*
Ethylbenzene	0.1	0.0	0.1	0.1	0.1	0.1			0.1	0.1
Xylenes	0.1	0.2	0.22	0.1	0.2	0.5			0.2	*
Total Petroleum Hydrocarbons										
C6-C8 (Aliphatic)	5.0	0.0	5	5	5.0	5.0			5.0	5.0
C8-C10 (Aliphatic)	5.0	0.0	5	5	5.0	5.0			5.0	5.0
C10-C12 (Aliphatic)	46.0	8.1	66	48	57.0	113.8			57.0	*
C12-C16 (Aliphatic)	*	17.7	190	142	166.0	317.5			166.0	*
C16-C21 (Aliphatic)	*	6.5	143	103	123.0	249.3			123.0	*
C21-C40 (Aliphatic)	25.0	58.0	25	25	25.0	25.0			25.0	25.0
C6-C7 (Aromatic)	5.0	0.0	5	5	5.0	5.0			5.0	5.0
C7-C8 (Aromatic)	5.0	0.0	5	5	5.0	5.0			5.0	5.0
C8-C10 (Aromatic)	*	92.5	288	272	280.0	330.5			280.0	*
C10-C12 (Aromatic)	*	87.8	1170	885	1027.5	1927.2			1027.5	*
C12-C16 (Aromatic)	*	182.7	2330	1740	2035.0	3897.6			2035.0	*
C16-C21 (Aromatic)	*	125.0	1580	1270	1425.0	2403.7			1425.0	*
C21-C40 (Aromatic)	*	123.9	1460	1160	1310.0	2257.1			1310.0	*

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Table B9 (continued): Trial 2 analytical results and interpretation.

Slurry-phase bioreactor Trial 2 Samples of Feedstock Prior to Treatment–- Soil Samples Page 4										
Sample Reference:	Standard Deviation	BT2S/026	BT2S/027	BT2S/028	BT2S/029	BT2S/030	BT2S/031	BT2S/032	BT2S/033	Mean Conc.
Units		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	
PH	0.0	7.9	8.0	7.9	8.0	7.9	7.8	7.8	8.0	7.9
% Loss on Ignition	0.8	5.7	4.3	6.3	3.4	4.7	4.9	20	4.1	6.7
% Moisture	2.8	10	11	13	15	18	12	4.3	9.6	11.6
% Stones	7.8	33	25	24	29	22	35	43	40	31.4
Cresols	0.2	0.21	0.28	0.44	0.21	0.1	0.13	0.29	0.092	0.2
Xylenols & Ethylphenols	0.5	2.3	2.4	2.7	1.7	1.7	1.3	2.4	1.1	2.0
Catechol	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Phenol	0.0	0.1	0.1	0.11	0.1	0.1	0.1	0.060	0.1	0.1
Trimethylphenol	0.7	2.5	2.4	3.1	1.8	1.8	1.3	2.3	1.4	2.1
Total Phenols	1.3	3.7	5.2	6.4	3.8	3.7	2.7	5.1	2.6	4.2
Naphthalene	7.8	33	34	48	35	38	50	37	25	37.5
Acenaphthylene	6.4	83	79	100	66	71	91	78	55	77.9
Acenaphthene	0.9	18	18	23	15	16	22	18	13	17.9
Fluorene	4.9	70	70	94	61	69	85	72	52	71.6
Phenanthrene	18.4	220	190	280	160	200	240	210	140	205.0
Anthracene	8.5	76	65	94	56	68	79	72	49	69.9
Fluoranthene	21.9	160	130	200	110	140	160	160	100	145.0
Pyrene	19.1	160	120	200	110	140	160	150	100	142.5
Benzo(a)anthracene	15.6	76	50	94	45	66	67	72	40	63.8
Chrysene	12.7	64	39	80	37	55	53	61	33	52.8
Benzo(b)fluoranthene	7.8	43	27	50	24	33	35	39	20	33.9
Benzo(k)fluoranthene	10.6	46	22	57	22	38	33	43	20	35.1
Benzo(a)pyrene	12.0	59	32	70	30	48	43	53	27	45.3
Indeno(1,2,3-cd)pyrene	6.2	31	19	37	16	27	25	30	17	25.3
Di-benzo(a,h)anthracene	1.2	10	6.2	12	7.2	7.4	9.1	7.8	4.7	8.1
Benzo(g,h,i)perylene	6.9	33	18	40	16	28	24	31	14	25.5
Anthanthrene	2.8	15	8.6	20	7.9	13	13	14	7.8	12.4
Benzo(e)pyrene	7.6	41	19	56	18	35	25	42	16	31.5
Cyclopenta(cd)pyrene	31.1	3.4	1	5.4	1	2.7	1	4.0	1	2.4
Total PAH	176.8	1200	930	1500	850	1100	1200	1200	720	1087.5
Easily-liberatable Cyanide	0.1	3.0	3.4	1.8	1.7	2.9	1.5	1	0.66	2.0
Complex Cyanide	3.4	11	17	15	15	17	12	11	8.6	13.3
Total Cyanide	3.5	14	20	17	22	20	13	11	9.2	15.8
Elemental Sulphur	0.0	100	100	110	66	88	91	61	100	89.5
Water Soluble SO4	42.4	830	790	940	720	1100	790	660	660	811.3
Water Soluble Chloride	2.1	24	24	32	24	41	22	25	18	26.3
Exchangeable Ammonium	6.4	40	5	51	63	76	37	15	17	38.0
Nitrate	5.3	13	19	19	18	33	16	8.4	18	18.1
Arsenic	7.1	40	48	44	43	49	45	35	34	42.3
Cadmium	0.0	0.50	0.50	0.49	0.43	0.51	0.43	0.38	0.40	0.5
Chromium	6.4	34	37	33	38	41	32	28	33	34.5
Lead	49.5	310	380	340	350	350	280	250	300	320.0
Mercury	0.2	0.60	0.70	0.73	0.57	0.74	0.58	0.61	0.61	0.6
Selenium	0.1	0.59	0.54	0.58	0.49	0.45	0.43	1.1	0.43	0.6
Copper	7.8	47	47	45	47	50	49	36	43	45.5
Nickel	4.2	30	33	32	33	35	27	25	28	30.4
Zinc	49.5	340	400	360	380	410	320	280	320	351.3
Boron	0.3	0.83	0.86	0.80	0.72	0.96	0.53	0.66	0.61	0.7
Benzene	0.0	0.43	0.57	0.66	0.83	1.1	1.1	1.2	0.36	0.8
Toluene	0.0	0.43	0.55	0.96	1.1	1.1	1.3	1.3	0.38	0.9
Ethylbenzene	0.0	0.38	0.1	0.12	0.13	0.11	0.10	0.11	0.1	0.1
Xylenes	0.1	0.48	0.76	1.6	1.7	1.3	1.4	1.4	0.50	1.1
Total Petroleum Hydrocarbons										
C6-C8 (Aliphatic)	0.0	5	5	5	5	5	5	5	5	5.0
C8-C10 (Aliphatic)	0.0	5	5	5	5	5	5	5	5	5.0
C10-C12 (Aliphatic)	12.7	58	51	63	40	35	54	74	38	51.6
C12-C16 (Aliphatic)	33.9	153	131	161	98	82	145	193	90	131.6
C16-C21 (Aliphatic)	28.3	108	108	117	76	65	109	143	71	99.6
C21-C40 (Aliphatic)	0.0	25	25	25	25	25	25	25	25	25.0
C6-C7 (Aromatic)	0.0	5	5	5	5	5	5	5	5	5.0
C7-C8 (Aromatic)	0.0	5	5	5	5	5	5	5	5	5.0
C8-C10 (Aromatic)	11.3	238	310	290	153	5	235	350	133	214.3
C10-C12 (Aromatic)	201.5	958	994	1040	638	491	940	1360	580	875.1
C12-C16 (Aromatic)	417.2	1970	1940	1940	1210	938	1820	2650	1150	1702.3
C16-C21 (Aromatic)	219.2	1290	1310	1350	852	602	1270	1770	767	1151.4
C21-C40 (Aromatic)	212.1	1200	1300	1330	791	613	1170	1710	714	1103.5

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Table B9 (continued): Trial 2 analytical results and interpretation.

Slurry-phase bioreactor Trial 2 Samples of Feedstock Prior to Treatment–- Soil Samples Page 5

Sample Reference:	US 95 (upper bound value)	CLEA Soil Guideline Value (SGV)	US95 Higher/ Lower than SGV	Median Conc.	Mode Conc.	Standard Deviation	Mean Feedstock Conc.	Mean Product Conc.	CLEA Soil Guideline Value (SGV)	US95 Higher/ Lower than SGV	% Change
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	
PH	13.2			7.9	7.9	0.1	7.6	7.9			-4.5
% Loss on Ignition	11.1			4.8	*	5.5	9.5	6.2			34.7
% Moisture	19.4			11.5	*	4.1	12.0	12.5			-4.5
% Stones	52.4			31.0	*	7.7	35.7	36.7			-2.9
Cresols	0.4			0.2	0.2	0.1	23.2	0.2			99.0
Xylenols & Ethylphenols	3.3			2.0	2.4	0.6	42.9	1.6			96.3
Catechol	0.2			0.1	0.1	0.0	0.1	0.1			0.0
Phenol	0.2			0.1	0.1	0.0	8.6	0.1			98.9
Trimethylphenol	3.5			2.1	1.8	0.6	23.2	1.7			92.7
Total Phenols	6.9			3.8	3.7	1.3	98.9	3.4			96.5
Naphthalene	62.6			36.0	*	8.1	851.7	43.7			94.9
Acenaphthylene	130.0			78.5	*	14.1	285.0	71.9			74.8
Acenaphthene	29.9			18.0	18.0	3.4	61.8	15.9			74.3
Fluorene	119.6			70.0	70.0	13.0	246.7	63.3			74.4
Phenanthrene	342.3			205.0	*	44.1	740.0	178.9			75.8
Anthracene	116.7			70.0	*	14.0	218.3	63.8			70.8
Fluoranthene	242.1			150.0	160.0	32.1	508.3	133.4			73.8
Pyrene	238.0			145.0	160.0	32.4	461.7	139.3			69.8
Benzo(a)anthracene	106.5			66.5	*	17.9	178.0	55.3			68.9
Chrysene	88.1			54.0	*	15.9	162.0	50.1			69.1
Benzo(b)fluoranthene	56.6			34.0	*	10.1	113.5	34.2			69.9
Benzo(k)fluoranthene	58.7			35.5	22.0	13.3	118.3	35.0			70.4
Benzo(a)pyrene	75.6	37**	Higher	45.5	*	15.2	141.2	45.4	37**	Higher	67.8
Indeno(1,2,3-cd)pyrene	42.2			26.0	*	7.5	69.5	25.4			63.5
Di-benzo(a,h)anthracene	13.4			7.6	*	2.3	22.4	8.3			62.9
Benzo(g,h,i)perylene	42.6			26.0	*	9.1	81.7	26.1			68.0
Anthanthrene	20.7			13.0	13.0	4.2	29.6	12.9			56.3
Benzo(e)pyrene	52.6			30.0	*	14.3	96.8	31.0			68.0
Cyclopenta(cd)pyrene	4.1			1.9	1.0	1.7	12.5	6.5			48.3
Total PAH	1816.1			1150.0	1200.0	246.3	4400.0	1027.3			76.7
Easily-liberatable Cyanide	3.3			1.8	*	1.0	1.0	1.8			-77.1
Complex Cyanide	22.3			13.5	11.0	3.1	8.9	13.5			-51.7
Total Cyanide	26.3			15.5	20.0	4.7	8.9	15.6			-75.2
Elemental Sulphur	149.5			95.5	100.0	17.4	87.2	93.4			-7.2
Water Soluble SO4	1354.8			790.0	790.0	148.9	1220.0	740.8			39.3
Water Soluble Chloride	43.8			24.0	24.0	7.1	46.0	26.0			43.4
Exchangeable Ammonium	63.5			38.5	*	24.8	77.2	46.9			39.3
Nitrate	30.1			18.0	19.0	7.1	5.2	17.6			-242.1
Arsenic	70.6	500	Lower	43.5	*	5.5	55.8	39.1	500	Lower	29.9
Cadmium	0.8	1400	Lower	0.5	0.5	0.1	0.9	0.5	1400	Lower	47.3
Chromium	57.6	5000	Lower	33.5	33.0	4.0	33.3	31.4	5000	Lower	5.7
Lead	534.4	750	Lower	325.0	350.0	42.8	403.3	295.0	750	Lower	26.9
Mercury	1.1	480	Lower	0.6	0.6	0.1	1.8	0.7	480	Lower	62.3
Selenium	1.0	8000	Lower	0.5	0.4	0.2	1.0	0.5	8000	Lower	43.6
Copper	76.0			47.0	47.0	4.4	58.0	41.7			28.1
Nickel	50.7	5000	Lower	31.0	33.0	3.5	32.8	27.6	5000	Lower	16.0
Zinc	586.6			350.0	320.0	44.5	463.3	320.5			30.8
Boron	1.2			0.8	*	0.1	1.2	0.7			40.1
Benzene	1.3			0.7	1.1	0.3	3.9	0.6			84.2
Toluene	1.5			1.0	1.1	0.4	3.5	0.7			80.0
Ethylbenzene	0.2			0.1	0.1	0.1	0.4	0.1			63.2
Xylenes	1.9			1.4	1.4	0.5	3.9	0.9			77.3
Total Petroleum Hydrocarbons											
C6-C8 (Aliphatic)	8.3			5.0	5.0	0.0	25.0	5.0			80.0
C8-C10 (Aliphatic)	8.3			5.0	5.0	0.0	25.0	5.0			80.0
C10-C12 (Aliphatic)	86.2			52.5	*	13.5	25.0	52.8			-111.1
C12-C16 (Aliphatic)	219.8			138.0	*	38.9	50.0	144.0			-188.0
C16-C21 (Aliphatic)	166.4			108.0	108.0	26.7	50.0	109.1			-118.1
C21-C40 (Aliphatic)	41.7			25.0	25.0	0.0	125.0	26.7			78.6
C6-C7 (Aromatic)	8.3			5.0	5.0	0.0	25.0	5.0			80.0
C7-C8 (Aromatic)	8.3			5.0	5.0	0.0	25.0	5.0			80.0
C8-C10 (Aromatic)	357.8			236.5	*	112.4	25.0	223.1			-792.4
C10-C12 (Aromatic)	1461.4			949.0	*	287.4	1417.2	871.6			38.5
C12-C16 (Aromatic)	2842.7			1880.0	1940.0	564.2	1258.2	1724.6			-37.1
C16-C21 (Aromatic)	1922.8			1280.0	*	381.7	1856.5	1228.4			33.8
C21-C40 (Aromatic)	1842.8			1185.0	*	370.6	2861.3	1107.3			61.3

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Table B9 (continued): Trial 2 analytical results and interpretation.

Table B10: Trial 2 slurry analytical results.

Sample Reference	BT2S/016	BT2S/017	BT2S/018	BT2S/019	Percentage change from Day 1 of trial
Day of Bioreactor Trial	1	4	6	7	
Date Sampled:	27/09/02	30/09/02	02/10/02	03/10/02	
Units	mg/kg	mg/kg	mg/kg	mg/kg	
pH	.	.	7.5	.	.
% Loss on Ignition	17	15	17	17	.
% Moisture	48	51	48	47	.
% Stones	4.9	8.1	1.1	2.6	.
Cresols	0.1	0.1	1.1	.	.
Xylenols & Ethylphenols	3.9	0.66	1.9	.	.
Catechol	0.1	0.1	0.1	.	.
Phenol	0.1	0.1	0.25	.	.
Trimethylphenol	3.0	0.79	1.6	.	.
Total Phenols	6.8	1.6	4.9	.	.
Naphthalene	57	37	39	100	-75.4
Acenaphthylene	180	92	84	120	33.3
Acenaphthene	41	29	11	17	58.5
Fluorene	170	61	2.9	52	69.4
Phenanthrene	500	50	34	85	83.0
Anthracene	160	80	37	86	46.3
Fluoranthene	360	320	270	220	38.9
Pyrene	350	320	400	410	-17.1
Benzo(a)anthracene	160	92	83	100	37.5
Chrysene	140	92	88	100	28.6
Benzo(b)fluoranthene	100	54	78	100	0.0
Benzo(k)fluoranthene	89	53	63	69	22.5
Benzo(a)pyrene	120	69	90	110	8.3
Indeno(1,2,3-cd)pyrene	63	41	51	71	-12.7
Di-benzo(a,h)anthracene	16	14	18	16	0.0
Benzo(g,h,i)perylene	70	45	53	70	0.0
Anthanthrene	29	21	3.9	36	-24.1
Benzo(e)pyrene	81	43	55	72	11.1
Cyclopenta(cd)pyrene	6.9	5.8	5.9	1	85.5
Total PAH	2692.9	1518.8	1466.7	1835	31.9
Easily-liberatable Cyanide	.	.	3.8	.	.
Complex Cyanide	.	.	100	.	.
Total Cyanide	.	.	110	.	.
Elemental Sulphur	160	100	100	140	.
Water Soluble Sulphate as SO4	2600	2300	2400	2200	.
Water Soluble Chloride	240	220	240	190	.
Exchangeable Ammonium	.	.	130	.	.
Nitrate	.	.	85	.	.
Arsenic	100	.	130	100	.
Cadmium	1.9	.	1.4	1.2	.
Chromium	56	.	72	53	.
Lead	730	.	810	750	.
Mercury	3.7	3.4	4.3	3.3	.
Selenium	1.9	1.7	2.3	1.7	.
Copper	100	.	130	100	.
Nickel	48	.	66	52	.
Zinc	810	.	870	800	.
Boron	3.8	2.8	4.1	2.9	.
Benzene	3.0	0.1	0.25	.	.
Toluene	2.6	0.1	0.1	.	.
Ethylbenzene	0.57	0.1	0.1	.	.
Xylenes	3.7	0.1	0.1	.	.
Total Petroleum Hydrocarbons	9181	5268	3415	2023	78.0
C6-C8 (Aliphatic)	5	5	5	5	0.0
C8-C10 (Aliphatic)	32	5	5	5	84.4
C10-C12 (Aliphatic)	126	75	57	52	58.7
C12-C16 (Aliphatic)	361	226	262	232	35.7
C16-C21 (Aliphatic)	330	162	191	158	52.1
C21-C40 (Aliphatic)	651	25	25	25	96.2
C6-C7 (Aromatic)	5	5	5	5	0.0
C7-C8 (Aromatic)	5	5	5	5	0.0
C8-C10 (Aromatic)	5	169	5	5	0.0
C10-C12 (Aromatic)	281	651	152	5	98.2
C12-C16 (Aromatic)	1430	1600	929	506	64.6
C16-C21 (Aromatic)	2220	1520	1550	995	55.2
C21-C40 (Aromatic)	3730	820	224	25	99.3

Notes:1) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

2) Dashed borders denote % change in concentrations each day compared with the first slurry sample. Negative sign denotes concentration higher than first day sample

3) Where results are absent, the centrifuged sample was insufficient for the full testing suite

Table B11: Trial 3 analytical data and interpretation

Slurry-phase bioreactor Trial 3 Samples of Feedstock Prior to Treatment–- Soil Samples Page 1

Sample Reference:	BT3S/004	BT3S/005	BT3S/006	BT3S/007	BT3S/008	BT3S/009	**Mean Conc.**	**US 95 (upper bound value)**	**Median Conc.**	**Mode Conc.**	**Standard Deviation**
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
PH	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	0.0
% Loss on Ignition	11	9.5	11	10	11	9.3	10.3	11.0	10.5	11	0.8
% Moisture	14	17	14	16	16	14	15.2	16.3	15.0	14	1.3
% Stones	28	27	27	26	28	36	28.7	31.7	27.5	28	3.7
Cresols	1.3	4.5	9.4	22	22	51	18.4	33.3	15.7	22	18.2
Xylenols & Ethylphenols	10	7.8	17	23	28	44	21.6	32.6	20.0	*	13.3
Catechol	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Phenol	1.3	3.4	4.3	12	12	24	9.5	16.4	8.2	12	8.4
Trimethylphenol	7.0	5.5	7.5	11	12	16	9.8	13.0	9.3	*	3.9
Total Phenols	20	21	38	67	73	130	58.2	92.5	52.5	*	41.7
Naphthalene	150	320	400	360	870	930	505.0	766.7	380.0	*	318.2
Acenaphthylene	120	81	100	96	210	150	126.2	165.2	110.0	*	47.5
Acenaphthene	27	19	23	21	48	33	28.5	37.4	25.0	*	10.8
Fluorene	100	75	83	82	190	130	110.0	146.1	91.5	*	43.9
Phenanthrene	280	210	220	250	520	390	311.7	411.1	265.0	*	120.9
Anthracene	94	75	76	82	170	130	104.5	135.8	88.0	*	38.1
Fluoranthene	180	150	160	160	310	240	200.0	251.8	170.0	160	62.9
Pyrene	170	140	150	150	290	230	188.3	237.3	160.0	150	59.5
Benzo(a)anthracene	64	66	59	69	110	99	77.8	95.3	67.5	*	21.2
Chrysene	55	43	52	53	100	81	64.0	81.9	54.0	*	21.8
Benzo(b)fluoranthene	40	40	32	35	67	53	44.5	55.3	40.0	40	13.2
Benzo(k)fluoranthene	29	41	30	40	49	56	40.8	49.5	40.5	*	10.5
Benzo(a)pyrene	43	47	40	49	74	76	54.8	67.9	48.0	*	15.9
Indeno(1,2,3-cd)pyrene	24	28	21	28	44	45	31.7	40.1	28.0	28	10.3
Di-benzo(a,h)anthracene	8.1	6.8	8.3	7.5	10	7.6	8.1	8.9	7.9	*	1.1
Benzo(g,h,i)perylene	28	31	22	31	41	46	33.2	40.4	31.0	31	8.8
Anthanthrene	11	16	9.6	16	18	25	15.9	20.5	16.0	16	5.5
Benzo(e)pyrene	26	29	28	29	43	43	33.0	39.4	29.0	29	7.8
Cyclopenta(cd)pyrene	1	2.6	1	2.3	1.7	5.8	2.4	3.9	2.0	1	1.8
Total PAH	1500	1400	1500	1600	3200	2800	2000.0	2647.7	1550.0	1500	787.4
Easily-liberatable Cyanide	0.83	1	0.85	0.88	0.86	0.74	0.9	0.9	0.9	*	0.1
Complex Cyanide	34	18	15	18	25	0.74	18.5	27.5	18.0	18	11.1
Total Cyanide	35	18	15	18	26	1.5	18.9	28.1	18.0	18	11.2
Elemental Sulphur	74	75	100	75	100	81	84.2	94.5	78.0	75	12.5
Water Soluble SO4	2600	2800	2800	160	2600	2100	2176.7	3016.3	2600.0	2600	1020.6
Water Soluble Chloride	62	65	44	12	55	76	52.3	70.8	58.5	*	22.4
Exchangeable Ammonium	32	50	44	37	79	37	46.5	60.6	40.5	37	17.1
Nitrate	9.1	14	4.5	18	6.6	5	9.5	14.0	7.9	*	5.4
Arsenic	64	68	68	75	74	55	67.3	73.3	68.0	68	7.3
Cadmium	0.81	0.88	0.83	0.82	0.87	0.76	0.8	0.9	0.8	*	0.0
Chromium	37	41	42	44	43	33	40.0	43.5	41.5	*	4.2
Lead	480	530	500	510	510	400	488.3	526.4	505.0	510	46.2
Mercury	1.9	2.2	2.1	2.1	2.3	1.8	2.1	2.2	2.1	2.1	0.2
Selenium	1.3	1.4	1.3	1.3	1.3	1.0	1.3	1.4	1.3	1.3	0.1
Copper	74	75	69	75	74	56	70.5	76.6	74.0	74	7.4
Nickel	36	40	38	40	39	31	37.3	40.2	38.5	40	3.4
Zinc	540	610	580	600	580	460	561.7	607.1	580.0	580	55.3
Boron	1.7	2.2	1.7	1.8	1.7	1.3	1.7	2.0	1.7	1.7	0.3
Benzene	0.30	0.1	1.8	1.8	5.9	15	4.2	8.8	1.8	1.8	5.7
Toluene	0.66	0.1	1.3	1.4	3.0	7.4	2.3	4.5	1.4	*	2.7
Ethylbenzene	0.1	0.1	0.1	0.088	0.17	0.63	0.2	0.4	0.1	0.1	0.2
Xylenes	0.79	0.16	1.1	1.2	2.2	7.4	2.1	4.3	1.2	*	2.7
Total Petroleum Hydrocarbons											
C6-C8 (Aliphatic)	5	5	5	5	5	5	5.0	5.0	5.0	5	0.0
C8-C10 (Aliphatic)	5	5	5	5	5	5	5.0	5.0	5.0	5	0.0
C10-C12 (Aliphatic)	5	5	5	5	5	230	42.5	118.1	5.0	5	91.9
C12-C16 (Aliphatic)	129	10	10	156	203	468	162.7	301.6	142.5	10	168.9
C16-C21 (Aliphatic)	10	10	10	10	139	342	86.8	198.1	10.0	10	135.2
C21-C40 (Aliphatic)	25	25	25	25	25	555	113.3	291.3	25.0	25	216.4
C6-C7 (Aromatic)	5	5	60	75	77	195	69.5	126.8	67.5	5	69.6
C7-C8 (Aromatic)	33	5	40	106	131	371	114.3	224.9	73.0	*	134.4
C8-C10 (Aromatic)	290	131	192	593	772	1680	609.7	1086.2	441.5	*	579.3
C10-C12 (Aromatic)	1460	382	1200	4200	5760	13200	4367.0	8301.0	2830.0	*	4782.3
C12-C16 (Aromatic)	2690	1240	1050	3290	4470	8710	3575.0	5897.7	2990.0	*	2823.5
C16-C21 (Aromatic)	3230	1900	1270	3980	5080	10200	4276.7	6919.4	3605.0	*	3212.6
C21-C40 (Aromatic)	3180	2170	1330	4220	4950	9700	4258.3	6703.9	3700.0	*	2972.9

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Slurry-phase bioreactor Trial 3 Samples of Feedstock Prior to Treatment–- Soil Samples Page 2											
Sample Reference:	BT3S/013	BT3S/014	BT3S/015	**Mean Conc.**	**US 95 (upper bound value)**	**CLEA Soil Guideline Value (SGV)**	**US95 Higher/ Lower than SGV**	**Median Conc.**	**Mode Conc.**	**Standard Deviation**	BT3S/016
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
PH	7.6	7.7	7.7	7.7	7.8			7.7	7.7	0.1	7.4
% Loss on Ignition	14	17	5.3	12.1	22.3			14.0	*	6.1	5.9
% Moisture	36	35	34	35.0	36.7			35.0	*	1.0	15
% Stones	0.50	0.95	2.1	1.2	2.6			1.0	*	0.8	20
Cresols	0.45	0.1	0.64	0.4	0.9			0.5	*	0.3	0.36
Xylenols & Ethylphenols	8.4	3.7	7.9	6.7	11.0			7.9	*	2.6	5.8
Catechol	0.1	0.1	0.1	0.1	0.1			0.1	0.1	0.0	0.1
Phenol	0.1	0.1	0.1	0.1	0.1			0.1	0.1	0.0	0.1
Trimethylphenol	5.2	2.5	5.3	4.3	7.0			5.2	*	1.6	5.3
Total Phenols	14	6.1	14	11.4	19.1			14.0	14.0	4.6	11
Naphthalene	110	65	97	90.7	129.7			97.0	*	23.2	52
Acenaphthylene	220	160	150	176.7	240.5			160.0	*	37.9	84
Acenaphthene	52	35	35	40.7	57.2			35.0	35.0	9.8	18
Fluorene	210	140	140	163.3	231.5			140.0	140.0	40.4	75
Phenanthrene	570	420	380	456.7	625.5			420.0	*	100.2	220
Anthracene	180	140	130	150.0	194.6			140.0	*	26.5	76
Fluoranthene	330	280	220	276.7	369.5			280.0	*	55.1	180
Pyrene	320	270	220	270.0	354.3			270.0	*	50.0	140
Benzo(a)anthracene	170	110	120	133.3	187.5			120.0	*	32.1	63
Chrysene	150	83	120	117.7	174.2			120.0	*	33.6	56
Benzo(b)fluoranthene	92	54	64	70.0	103.2			64.0	*	19.7	59
Benzo(k)fluoranthene	82	54	54	63.3	90.6			54.0	54.0	16.2	76
Benzo(a)pyrene	99	71	69	79.7	107.9	37**	Higher	71.0	*	16.8	40
Indeno(1,2,3-cd)pyrene	49	38	22	36.3	59.2			38.0	*	13.6	18
Di-benzo(a,h)anthracene	24	14	7.1	15.0	29.4			14.0	*	8.5	6.6
Benzo(g,h,i)perylene	59	47	40	48.7	64.9			47.0	*	9.6	24
Anthanthrene	23	25	2.7	16.9	37.7			23.0	*	12.3	9.9
Benzo(e)pyrene	62	43	46	50.3	67.6			46.0	*	10.2	44
Cyclopenta(cd)pyrene	1	1	1	1.0	1.0			1.0	1.0	0.0	1
Total PAH	2800	2100	1900	2266.7	3063.4			2100.0	*	472.6	1200
Easily-liberatable Cyanide	1.6	1.5	1	1.4	1.9			1.5	*	0.3	1
Complex Cyanide	52	57	56	55.0	59.5			56.0	*	2.6	17
Total Cyanide	53	58	56	55.7	59.9			56.0	*	2.5	17
Elemental Sulphur	170	140	140	150.0	179.2			140.0	140.0	17.3	99
Water Soluble SO4	5600	5400	5300	5433.3	5690.9			5400.0	*	152.8	1400
Water Soluble Chloride	150	150	140	146.7	156.4			150.0	150.0	5.8	40
Exchangeable Ammonium	130	580	460	390.0	782.8			460.0	*	233.0	150
Nitrate	130	54	110	98.0	164.4			110.0	*	39.4	9.4
Arsenic	110	110	120	113.3	123.1	500	Lower	110.0	110.0	5.8	60
Cadmium	1.4	1.4	1.5	1.4	1.5	1400	Lower	1.4	1.4	0.1	0.71
Chromium	58	54	65	59.0	68.4	5000	Lower	58.0	*	5.6	50
Lead	760	760	810	776.7	825.3	750	Higher	760.0	760.0	28.9	430
Mercury	2.5	2.7	2.8	2.7	2.9	480	Lower	2.7	*	0.2	1.6
Selenium	1.3	1.1	1.5	1.3	1.6	8000	Lower	1.3	*	0.2	0.69
Copper	110	99	130	113.0	139.5			110.0	*	15.7	69
Nickel	52	50	69	57.0	74.6	5000	Lower	52.0	*	10.4	47
Zinc	780	770	850	800.0	873.5			780.0	*	43.6	530
Boron	3.9	3.9	3.3	3.7	4.3			3.9	3.9	0.3	0.99
Benzene	1.0	0.72	0.18	0.6	1.3			0.7	*	0.4	0.42
Toluene	0.72	0.48	0.1	0.4	1.0			0.5	*	0.3	0.58
Ethylbenzene	0.1	0.1	0.1	0.1	0.1			0.1	0.1	0.0	0.1
Xylenes	2.0	1.1	0.39	1.2	2.5			1.1	*	0.8	0.94
Total Petroleum Hydrocarbons											
C6-C8 (Aliphatic)	5	5	5	5.0	5.0			5.0	5.0	0.0	5
C8-C10 (Aliphatic)	5	5	5	5.0	5.0			5.0	5.0	0.0	5
C10-C12 (Aliphatic)	25	26	24	25.0	26.7			25.0	*	1.0	20
C12-C16 (Aliphatic)	97	107	121	108.3	128.7			107.0	*	12.1	114
C16-C21 (Aliphatic)	70	79	74	74.3	81.9			74.0	*	4.5	81
C21-C40 (Aliphatic)	47	50	47	48.0	50.9			47.0	47.0	1.7	55
C6-C7 (Aromatic)	5	5	5	5.0	5.0			5.0	5.0	0.0	5
C7-C8 (Aromatic)	5	5	5	5.0	5.0			5.0	5.0	0.0	5
C8-C10 (Aromatic)	43	40	35	39.3	46.1			40.0	*	4.0	27
C10-C12 (Aromatic)	183	183	162	176.0	196.4			183.0	183.0	12.1	152
C12-C16 (Aromatic)	931	944	883	919.3	973.5			931.0	*	32.1	961
C16-C21 (Aromatic)	1680	1740	1600	1673.3	1791.7			1680.0	*	70.2	2140
C21-C40 (Aromatic)	1890	1870	1810	1856.7	1926.9			1870.0	*	41.6	2810

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Table B11 (continued): Trial 3 analytical results and interpretation.

Slurry-phase bioreactor Trial 3 Samples of Feedstock Prior to Treatment–- Soil Samples Page 3

Sample Reference:	BT3S/017	BT3S/018	Mean Conc.	US 95 (upper bound value)	CLEA Soil Guideline Value (SGV)	US95 Higher/ Lower than SGV	Median Conc.	Mode Conc.	Standard Deviation	Mean Feedstock Conc.	Mean Product Conc.
Units	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	Mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
PH	7.4	7.4	7.4	7.4			7.4	7.4	0.0	7.9	7.5
% Loss on Ignition	5.5	5.9	5.8	6.2			5.9	5.9	0.2	10.3	7.7
% Moisture	17	17	16.3	18.3			17.0	17.0	1.2	15.2	21.9
% Stones	15	18	17.7	21.9			18.0	*	2.5	28.7	12.7
Cresols	0.30	0.27	0.3	0.4			0.3	*	0.0	18.4	0.34
Xylenols & Ethylphenols	5.8	3.5	5.0	7.3			5.8	5.8	1.3	21.6	5.5
Catechol	0.1	0.1	0.1	0.1			0.1	0.1	0.0	0.1	0.10
Phenol	0.1	0.1	0.1	0.1			0.1	0.1	0.0	9.5	0.10
Trimethylphenol	5.2	4.8	5.1	5.5			5.2	*	0.3	9.8	4.9
Total Phenols	11	8.7	10.2	12.5			11.0	11.0	1.3	58.2	10.6
Naphthalene	56	38	48.7	64.6			52.0	*	9.5	505	61.3
Acenaphthylene	91	87	87.3	93.3			87.0	*	3.5	126	114
Acenaphthene	22	20	20.0	23.4			20.0	*	2.0	28.5	26.2
Fluorene	91	79	81.7	95.7			79.0	*	8.3	110	106
Phenanthrene	230	240	230.0	246.9			230	*	10.0	312	298
Anthracene	82	87	81.7	91.0			82.0	*	5.5	105	102
Fluoranthene	170	180	176.7	186.4			180	180	5.8	200	207
Pyrene	170	160	156.7	182.4			160	*	15.3	188	191
Benzo(a)anthracene	82	68	71.0	87.6			68.0	*	9.8	77.8	89.7
Chrysene	91	64	70.3	101.3			64.0	*	18.3	64.0	84.5
Benzo(b)fluoranthene	48	35	47.3	67.6			48.0	*	12.0	44.5	54.1
Benzo(k)fluoranthene	39	49	54.7	86.9			49.0	*	19.1	40.8	57.3
Benzo(a)pyrene	49	44	44.3	51.9	37**	Higher	44.0	*	4.5	54.8	54.9
Indeno(1,2,3-cd)pyrene	18	24	20.0	25.8			18.0	18.0	3.5	31.7	24.9
Di-benzo(a,h)anthracene	4.0	6.3	5.6	8.0			6.3	*	1.4	8.1	8.5
Benzo(g,h,i)perylene	24	33	27.0	35.8			24.0	24.0	5.2	33.2	33.5
Anthanthrene	1.5	13	8.1	18.2			9.9	*	6.0	15.9	10.8
Benzo(e)pyrene	36	29	36.3	49.0			36.0	*	7.5	33.0	40.5
Cyclopenta(cd)pyrene	1	1	1.0	1.0			1.0	1.0	0.0	2.4	1.00
Total PAH	1300	1300	1266.7	1364.0			1300	1300	57.7	2000	1567
Easily-liberatable Cyanide	1	1	1.0	1.0			1.0	1.0	0.0	0.9	1.1
Complex Cyanide	26	31	24.7	36.6			26.0	*	7.1	18.5	33.8
Total Cyanide	26	31	24.7	36.6			26.0	*	7.1	18.9	34.0
Elemental Sulphur	120	140	119.7	154.2			120.0	*	20.5	84.2	128.8
Water Soluble SO4	1200	1500	1366.7	1624.2			1400	*	153	2177	2587
Water Soluble Chloride	32	42	38.0	46.9			40.0	*	5.3	52.3	70.6
Exchangeable Ammonium	67	52	89.7	178.7			67.0	*	52.8	46.5	180
Nitrate	7.6	30	15.7	36.6			9.4	*	12.4	9.5	40.4
Arsenic	62	63	61.7	64.2	500	Lower	62.0	*	1.5	67.3	77.2
Cadmium	0.76	0.70	0.7	0.8	1400	Lower	0.7	*	0.0	0.8	0.94
Chromium	55	50	51.7	56.5	5000	Lower	50.0	50.0	2.9	40.0	53.9
Lead	470	430	443.3	482.3	750	Lower	430	430	23.1	488	543
Mercury	1.2	1.0	1.3	1.8	480	Lower	1.2	*	0.3	2.1	1.7
Selenium	0.60	0.76	0.7	0.8	8000	Lower	0.7	*	0.1	1.3	0.87
Copper	77	74	73.3	80.1			74.0	*	4.0	70.5	85.2
Nickel	50	47	48.0	50.9	5000	Lower	47.0	47.0	1.7	37.3	50.7
Zinc	510	490	510.0	543.7			510	*	20.0	562	597
Boron	0.91	0.87	0.9	1.0			0.9	*	0.1	1.7	1.8
Benzene	0.43	0.26	0.4	0.5			0.4	*	0.1	4.2	0.45
Toluene	0.54	0.39	0.5	0.7			0.5	*	0.1	2.3	0.48
Ethylbenzene	0.1	0.1	0.1	0.1			0.1	0.1	0.0	0.2	0.10
Xylenes	0.71	0.61	0.8	1.0			0.7	*	0.2	2.1	0.88
Total Petroleum Hydrocarbons											
C6-C8 (Aliphatic)	5	5	5.0	5.0			5.0	5.0	0.0	5.0	5.0
C8-C10 (Aliphatic)	5	5	5.0	5.0			5.0	5.0	0.0	5.0	5.0
C10-C12 (Aliphatic)	25	36	27.0	40.8			25.0	*	8.2	42.5	26.4
C12-C16 (Aliphatic)	127	159	133.3	172.4			127	*	23.2	163	125.8
C16-C21 (Aliphatic)	89	115	95.0	125.0			89.0	*	17.8	86.8	88.8
C21-C40 (Aliphatic)	60	79	64.7	86.0			60.0	*	12.7	113	59.7
C6-C7 (Aromatic)	5	5	5.0	5.0			5.0	5.0	0.0	69.5	5.0
C7-C8 (Aromatic)	5	5	5.0	5.0			5.0	5.0	0.0	114	5.0
C8-C10 (Aromatic)	31	39	32.3	42.6			31.0	*	6.1	610	34.4
C10-C12 (Aromatic)	181	323	218.7	372.9			181	*	91.5	4367	206
C12-C16 (Aromatic)	1040	1610	1203.7	1800.6			1040	*	354	3575	1118
C16-C21 (Aromatic)	2260	3250	2550.0	3577.0			2260	*	609	4277	2287
C21-C40 (Aromatic)	2700	3890	3133.3	4242.0			2810	*	658	4258	2750

1) *= Mode not possible due to degree of variation in results.

2) Where minus sign is shown, product results are greater than the feedstock.

3) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

4) Dashed borders denotes average results for feedstock and product.

5) US95 upper bound value based on formula in DEFRA/EA R&D publication CLR 7 Appendix A.

6) Zig zag borders indicate the more contaminated fines, where this has been separated.

Table B11 (continued): Trial 3 analytical results and interpretation.

Table B12: Trial 3 slurry analytical results.

Sample Reference	BT3S/010	BT3S/011	BT3S/012	Percentage change from Day 2 of Trial
Day of Bioreactor Trial	2	3	5	
Date Sampled:	14/10/02	15/10/02	17/10/02	
Units	mg/kg	mg/kg	mg/kg	
pH	-	-	-	-
% Loss on Ignition	-	-	-	-
% Moisture	50	46	47	-
% Stones	2.4	11.0	1.5	-
Cresols	1.9	2.5	3.7	-
Xylenols & Ethylphenols	29	33	36	-
Catechol	0.10	0.10	0.1	-
Phenol	0.10	0.10	1.3	-
Trimethylphenol	15	26	34	-
Total Phenols	47	61	75	-
Naphthalene	290	250	68	76.6
Acenaphthylene	150	110	170	-13.3
Acenaphthene	32	25	34	-6.3
Fluorene	130	95	170	-30.8
Phenanthrene	430	280	570	-32.6
Anthracene	140	88	180	-28.6
Fluoranthene	280	160	400	-42.9
Pyrene	270	160	380	-40.7
Benzo(a)anthracene	100	54	130	-30.0
Chrysene	87	53	120	-37.9
Benzo(b)fluoranthene	54	29	70	-29.6
Benzo(k)fluoranthene	57	27	72	-26.3
Benzo(a)pyrene	71	31	89	-25.4
Indeno(1,2,3-cd)pyrene	46	15	52	-13.0
Di-benzo(a,h)anthracene	5.8	5.2	16	-175.9
Benzo(g,h,i)perylene	41	16	63	-53.7
Anthanthrene	18	4.9	27	-50.0
Benzo(e)pyrene	46	21	63	-37.0
Cyclopenta(cd)pyrene	4.9	2.2	9.5	-93.9
Total PAH	2300	1400	2600	-13.0
Benzene	2.3	0.74	0.1	95.7
Toluene	5.5	1.4	0.1	98.2
Ethylbenzene	1.4	0.31	0.1	92.9
Xylenes	21	4.9	0.1	99.5
Total Petroleum Hydrocarbons	3454	4328	4409	
C6-C8 (Aliphatic)	5	5	5	0.0
C8-C10 (Aliphatic)	5	5	5	0.0
C10-C12 (Aliphatic)	5	5	19	-280.0
C12-C16 (Aliphatic)	10	10	79	-690.0
C16-C21 (Aliphatic)	10	10	55	-450.0
C21-C40 (Aliphatic)	25	25	38	-52.0
C6-C7 (Aromatic)	5	5	5	0.0
C7-C8 (Aromatic)	5	5	5	0.0
C8-C10 (Aromatic)	80	104	44	45.0
C10-C12 (Aromatic)	610	674	163	73.3
C12-C16 (Aromatic)	785	1060	821	-4.6
C16-C21 (Aromatic)	973	1250	1420	-45.9
C21-C40 (Aromatic)	941	1170	1750	-86.0

Notes:1) Grey highlight denotes results that were below the detection limit (shown) of the determinand.

2) Dashed borders denote % change in concentrations each day compared with the first slurry sample. Negative sign denotes concentration higher than first day sample

3) Where results are absent, the centrifuged sample was insufficient for the full testing suite

Table B13: Analysis of activated carbon from the slurry-phase bioreactor air filter.

Sample reference	BT1S/030	Activated Carbon 1	Activated Carbon 2
Comments	**Sample taken at end of Trial 1**	**Samples taken when all 4 trials completed**	
Date Sampled	24/09/2002	29/10/2002	29/10/2002
Units	mg/kg	mg/kg	mg/kg
pH	.		
% Loss on Ignition	.		
% Moisture	4.3	3.5	4.5
% Stones	75	36	47
Cresols	< 0.10	< 0.10	< 0.10
Xylenols & Ethylphenols	< 0.10	< 0.10	< 0.10
Catechol	< 0.10	< 0.10	< 0.10
Phenol	< 0.10	< 0.10	< 0.10
Trimethylphenol	< 0.10	< 0.10	< 0.10
Total Phenols	< 0.50	< 0.50	< 0.50
Naphthalene	< 1.0	< 1.0	< 1.0
Acenaphthylene	< 1.0	< 1.0	< 1.0
Acenaphthene	< 1.0	< 1.0	< 1.0
Fluorene	< 1.0	< 1.0	< 1.0
Phenanthrene	< 1.0	< 1.0	< 1.0
Anthracene	< 1.0	< 1.0	< 1.0
Fluoranthene	< 1.0	< 1.0	< 1.0
Pyrene	< 1.0	< 1.0	< 1.0
Benzo(a)anthracene	< 1.0	< 1.0	< 1.0
Chrysene	< 1.0	< 1.0	< 1.0
Benzo(b)fluoranthene	< 1.0	< 1.0	< 1.0
Benzo(k)fluoranthene	< 1.0	< 1.0	< 1.0
Benzo(a)pyrene	< 1.0	< 1.0	< 1.0
Indeno(1,2,3-cd)pyrene	< 1.0	< 1.0	< 1.0
Di-benzo(a,h)anthracene	< 1.0	< 1.0	< 1.0
Benzo(g,h,i)perylene	< 1.0	< 1.0	< 1.0
Anthanthrene	< 1.0	< 1.0	< 1.0
Benzo(e)pyrene	< 1.0	< 1.0	< 1.0
Cyclopenta(cd)pyrene	< 1.0	< 1.0	< 1.0
Total PAH	< 10	< 10	< 10
Benzene	< 0.10	< 0.10	< 0.10
Toluene	< 0.10	< 0.10	< 0.10
Ethylbenzene	< 0.10	< 0.10	< 0.10
Xylene's	< 0.10	< 0.10	< 0.10

Table B14: Contaminant mass balance for the water phase in Trial 1.

		Bioreactor Trial 1 (volume of water added 27200 litres)				
	Units	Inoculum and water. Pre-trial 1	Mass Balance Pre-Trial 1 (g)	Average at end of Trial 1	Mass Balance end of Trial 1 (g)	Percentage change in Mass Balance (%)
Cresols	µg/l	0.5	0.01	0.5	0.01	0.0
Xylenols & Ethylphenols	µg/l	0.5	0.01	3.4	0.09	-573.3
Catechol	µg/l	0.5	0.01	0.5	0.01	0.0
Phenol	µg/l	0.5	0.01	0.5	0.01	0.0
Trimethylphenol	µg/l	0.5	0.01	2.8	0.08	-453.3
Total Phenols	µg/l	2.5	0.07	6.3	0.17	-152.0
Naphthalene	ng/l	290	0.01	2600.0	0.07	-796.6
Acenaphthylene	ng/l					
Acenaphthene	ng/l	280	0.01	8233.3	0.22	-2840.5
Fluorene	ng/l	100	0.00	5633.3	0.15	-5533.3
Phenanthrene	ng/l	30	0.00	10000.0	0.27	-33233.3
Anthracene	ng/l	120	0.00	746.7	0.02	-522.2
Fluoranthene	ng/l	67	0.00	986.7	0.03	-1372.6
Pyrene	ng/l	67	0.00	1800.0	0.05	-2586.6
Benzo(a)anthracene	ng/l	20	0.00	37.3	0.00	-86.7
Chrysene	ng/l	20	0.00	123.3	0.00	-516.7
Benzo(b)fluoranthene	ng/l	20	0.00	36.3	0.00	-81.7
Benzo(k)fluoranthene	ng/l	20	0.00	20.0	0.00	0.0
Benzo(a)pyrene	ng/l	20	0.00	65.0	0.00	-225.0
Indeno(1,2,3-cd)pyrene	ng/l	20	0.00	22.0	0.00	-10.0
Di-benzo(a,h)anthracene	ng/l	20	0.00	20.0	0.00	0.0
Benzo(g,h,i)perylene	ng/l	20	0.00	27.0	0.00	-35.0
Anthanthrene	ng/l	20	0.00	20.0	0.00	0.0
Benzo(e)pyrene	ng/l	20	0.00	62.3	0.00	-211.7
Cyclopenta(cd)pyrene	ng/l					
Benzene	µg/l	-	-	0.0	0.00	-
Toluene	µg/l	-	-	10.0	0.00	-
Ethylbenzene	µg/l	-	-	10.0	0.27	-
Xylenes	µg/l	-	-	53	0.27	-
TOTALS:			**0.10**		**1.58**	-1489.1

Table B15: Contaminant mass balance for the soil phase in Trial 1.

SOILS		Bioreactor Trial 1 (volume of soil feedstock added 10460 kg)				
Units		Average of Feedstock Trial 1	Mass Balance Pre-trial 1 (g)	Average of Product End of Trial 1	Mass Balance Post Trial 1 (g)	Percentage change in Mass Balance (%)
Cresols	mg/kg	1.3	1.3	13.9	2.4	25.6
Xylenols & Ethylphenols	mg/kg	14.4	14.4	151.0	16.9	176.9
Catechol	mg/kg	0.9	0.9	9.9	0.1	1.0
Phenol	mg/kg	0.6	6.5	1.2	12.5	-91.6
Trimethylphenol	mg/kg	8.3	86.5	13.3	138.9	-60.7
Total Phenols	mg/kg	25.3	265.0	33.8	353.6	-33.5
Naphthalene	mg/kg	538.3	5631.0	160.8	1682.0	70.1
Acenaphthylene	mg/kg	170.0	1778.2	156.8	1640.2	7.8
Acenaphthene	mg/kg	36.0	376.6	35.2	367.7	2.4
Fluorene	mg/kg	148.3	1551.6	134.8	1410.1	9.1
Phenanthrene	mg/kg	468.3	4898.8	396.6	4148.8	15.3
Anthracene	mg/kg	141.7	1481.8	130.0	1359.9	8.2
Fluoranthene	mg/kg	293.3	3068.3	300.6	3144.3	-2.5
Pyrene	mg/kg	281.7	2946.2	284.9	2979.9	-1.1
Benzo(a)anthracene	mg/kg	88.3	924.0	132.0	1380.5	-49.4
Chrysene	mg/kg	76.0	795.0	95.5	999.1	-25.7
Benzo(b)fluoranthene	mg/kg	51.8	542.2	72.8	761.2	-40.4
Benzo(k)fluoranthene	mg/kg	45.7	477.7	73.5	768.8	-60.9
Benzo(a)pyrene	mg/kg	62.5	653.8	90.5	946.3	-44.7
Indeno(1,2,3-cd)pyrene	mg/kg	35.2	367.8	55.4	579.2	-57.5
Di-benzo(a,h)anthracene	mg/kg	8.2	85.8	10.3	108.0	-25.9
Benzo(g,h,i)perylene	mg/kg	37.5	392.3	53.5	559.9	-42.7
Anthanthrene	mg/kg	17.0	177.8	23.2	242.2	-36.2
Benzo(e)pyrene	mg/kg	42.0	439.3	69.0	722.0	-64.3
Cyclopenta(cd)pyrene	mg/kg	4.6	47.6	15.6	163.7	-243.9
Benzene	mg/kg	2.9	30.0	2.0	21.2	29.2
Toluene	mg/kg	1.9	20.0	2.0	20.7	-3.5
Ethylbenzene	mg/kg	0.3	3.0	0.2	2.1	27.6
Xylenes	mg/kg	1.7	17.3	2.4	25.4	-46.9
TOTAL MASS:			**27238.6**		**24741.8**	**9.2**

Table B16: Overall contaminant mass balance for Trial 1.

Mass Balance of Organic Analytes in the Bioreactor				
	Units	Pre-trial 1	Post Trial 1	% change
Waters	g	0.10	1.58	-1489.13
Soils	g	27239	24742	9.17
Total	g	27239	24743	9.16

Table B17: Contaminant mass balance for the water phase in Trial 2.

		Bioreactor Trial 2 (volume of water added 26980 litres)				
	Units	Inoculum and water. Pre-trial 2	Mass Balance Pre-Trial 2 (g)	Average at end of Trial 2	Mass Balance end of Trial 2 (g)	Percentage change in Mass Balance (%)
Cresols	µg/l	0.5	0.01	140	3.78	-27900.0
Xylenols & Ethylphenols	µg/l	4900	132.20	150	4.05	96.9
Catechol	µg/l	87.0	2.35	0.5	0.01	99.4
Phenol	µg/l	56.0	1.51	76	2.05	-35.7
Trimethylphenol	µg/l	3333	89.93	0.5	0.01	100.0
Total Phenols	µg/l	8400	226.63	360	9.71	95.7
Naphthalene	ng/l	10767	0.29	1700	0.05	84.2
Acenaphthylene	ng/l					
Acenaphthene	ng/l	10433	0.28	330	0.01	96.8
Fluorene	ng/l	4367	0.12	220	0.01	95.0
Phenanthrene	ng/l	2600	0.07	360	0.01	86.2
Anthracene	ng/l	703	0.02	630	0.02	10.4
Fluoranthene	ng/l	313	0.01	35	0.00	88.8
Pyrene	ng/l	193	0.01	220	0.01	-13.8
Benzo(a)anthracene	ng/l	41.3	0.00	20	0.00	51.6
Chrysene	ng/l	30.7	0.00	20	0.00	34.8
Benzo(b)fluoranthene	ng/l	28.0	0.00	20	0.00	28.6
Benzo(k)fluoranthene	ng/l	22.3	0.00	20	0.00	10.4
Benzo(a)pyrene	ng/l	82.7	0.00	20	0.00	75.8
Indeno(1,2,3-cd)pyrene	ng/l	44.3	0.00	20	0.00	54.9
Di-benzo(a,h)anthracene	ng/l	20.0	0.00	20	0.00	0.0
Benzo(g,h,i)perylene	ng/l	20.0	0.00	20	0.00	0.0
Anthanthrene	ng/l	20.0	0.00	20	0.00	0.0
Benzo(e)pyrene	ng/l	30.3	0.00	20	0.00	34.1
Cyclopenta(cd)pyrene	ng/l					
Benzene	µg/l	0.0	0.00	-	-	-
Toluene	µg/l	10.7	0.00	-	-	-
Ethylbenzene	µg/l	21.0	0.29	-	-	-
Xylenes	µg/l	183	0.57	-	-	-
TOTALS:			**227.66**		**10.00**	**95.6**

Table B18: Contaminant mass balance for the soil phase in Trial 2.

SOILS		Bioreactor Trial 2 (volume of soil feedstock added 7050 kg)				
Units		Average of Feedstock Trial 2	Mass Balance Pre-trial 2 (g)	Average of Product End of Trial 2	Mass Balance Post Trial 2 (g)	Percentage change in Mass Balance (%)
Cresols	mg/kg	23.2	163.3	0.2	1.6	99.0
Xylenols & Ethylphenols	mg/kg	42.9	302.4	1.6	11.1	96.3
Catechol	mg/kg	0.1	0.7	0.1	0.7	0.0
Phenol	mg/kg	8.6	60.7	0.1	0.7	98.9
Trimethylphenol	mg/kg	23.2	163.3	1.7	11.9	92.7
Total Phenols	mg/kg	98.9	697.2	3.4	24.3	96.5
Naphthalene	mg/kg	851.7	6004.3	43.7	308.1	94.9
Acenaphthylene	mg/kg	285.0	2009.3	71.9	506.6	74.8
Acenaphthene	mg/kg	61.8	435.9	15.9	112.0	74.3
Fluorene	mg/kg	246.7	1739.0	63.3	446.0	74.4
Phenanthrene	mg/kg	740.0	5217.0	178.9	1261.4	75.8
Anthracene	mg/kg	218.3	1539.3	63.8	449.8	70.8
Fluoranthene	mg/kg	508.3	3583.8	133.4	940.1	73.8
Pyrene	mg/kg	461.7	3254.8	139.3	981.7	69.8
Benzo(a)anthracene	mg/kg	178.0	1254.9	55.3	390.1	68.9
Chrysene	mg/kg	162.0	1142.1	50.1	353.3	69.1
Benzo(b)fluoranthene	mg/kg	113.5	800.2	34.2	241.1	69.9
Benzo(k)fluoranthene	mg/kg	118.3	834.3	35.0	246.9	70.4
Benzo(a)pyrene	mg/kg	141.2	995.2	45.4	320.3	67.8
Indeno(1,2,3-cd)pyrene	mg/kg	69.5	490.0	25.4	178.8	63.5
Di-benzo(a,h)anthracene	mg/kg	22.4	158.0	8.3	58.6	62.9
Benzo(g,h,i)perylene	mg/kg	81.7	575.8	26.1	184.1	68.0
Anthanthrene	mg/kg	29.6	208.6	12.9	91.1	56.3
Benzo(e)pyrene	mg/kg	96.8	682.7	31.0	218.6	68.0
Cyclopenta(cd)pyrene	mg/kg	12.5	88.1	6.5	45.6	48.3
Benzene	mg/kg	3.9	27.4	0.6	4.3	84.2
Toluene	mg/kg	3.5	24.5	0.7	4.9	80.0
Ethylbenzene	mg/kg	0.4	2.5	0.1	0.9	63.2
Xylenes	mg/kg	3.9	27.8	0.9	6.3	77.3
TOTAL MASS:			**32482.9**		**7400.9**	**77.2**

Table B19: Overall contaminant mass balance for Trial 2.

Mass Balance of Organic Analytes in the Bioreactor				
	Units	Pre-trial 2	Post Trial 2	% change
Waters	g	227.66	10.00	95.61
Soils	g	32483	7401	77.22
Total	g	32711	7411	**77.34**

Table B20: Contaminant mass balance for the water phase in Trial 3.

		Bioreactor Trial 3 (volume of water added 20880 litres)				
	Units	Inoculum and water. Pre-trial 3	Mass Balance Pre-Trial 3 (g)	Average at end of Trial 3	Mass Balance end of Trial 3 (g)	Percentage change in Mass Balance (%)
Cresols	µg/l	86	1.79	0.5	0.01	99.4
Xylenols & Ethylphenols	µg/l	120	2.51	3800	79.34	-3066.7
Catechol	µg/l	0.5	0.01	0.5	0.01	0.0
Phenol	µg/l	0.5	0.01	0.5	0.01	0.0
Trimethylphenol	µg/l	128	2.67	0.5	0.01	99.6
Total Phenols	µg/l	403	8.42	3800	79.34	-842.1
Naphthalene	ng/l	601	12.56	10633	0.22	98.2
Acenaphthylene	ng/l					
Acenaphthene	ng/l	149	0.00	2200	0.05	-1379.8
Fluorene	ng/l	82	0.00	5567	0.12	-6661.1
Phenanthrene	ng/l	91	0.00	6700	0.14	-7235.8
Anthracene	ng/l	333	0.01	713	0.01	-114.2
Fluoranthene	ng/l	560	0.01	450	0.01	19.6
Pyrene	ng/l	2943	0.06	240	0.01	91.8
Benzo(a)anthracene	ng/l	77	0.00	27.3	0.00	64.3
Chrysene	ng/l	117	0.00	20.0	0.00	83.0
Benzo(b)fluoranthene	ng/l	347	0.01	20.0	0.00	94.2
Benzo(k)fluoranthene	ng/l	277	0.01	20.0	0.00	92.8
Benzo(a)pyrene	ng/l	886	0.02	20.0	0.00	97.7
Indeno(1,2,3-cd)pyrene	ng/l	451	0.01	32.7	0.00	92.8
Di-benzo(a,h)anthracene	ng/l	53	0.00	20.0	0.00	62.5
Benzo(g,h,i)perylene	ng/l	447	0.01	20.0	0.00	95.5
Anthanthrene	ng/l	140	0.00	20.0	0.00	85.7
Benzo(e)pyrene	ng/l	515	0.01	20.0	0.00	96.1
Cyclopenta(cd)pyrene	ng/l					
Benzene	µg/l	10	0.21	29.3	0.00	
Toluene	µg/l	10	0.21	30.0	0.61	-193.0
Ethylbenzene	µg/l	10	0.21	10.0	0.63	-200.0
Xylenes	µg/l	10	0.21	42	0.21	0.0
TOTALS:			**20.53**		**81.39**	-296.4

Table B21: Contaminant mass balance for the soil phase in Trial 3.

SOILS		Bioreactor Trial 3 (volume of soil feedstock added 7060 kg)				
Units		Average of Feedstock Trial 3	Mass Balance Pre-trial 3 (g)	Average of Product End of Trial 3	Mass Balance Post Trial 3 (g)	Percentage change in Mass Balance (%)
Cresols	mg/kg	18.4	129.7	0.3	2.4	98.2
Xylenols & Ethylphenols	mg/kg	21.6	152.7	5.5	39.0	74.5
Catechol	mg/kg	0.1	0.7	0.1	0.7	0.0
Phenol	mg/kg	9.5	67.1	0.1	0.7	98.9
Trimethylphenol	mg/kg	9.8	69.4	4.9	34.4	50.5
Total Phenols	mg/kg	58.2	410.7	10.6	74.6	81.8
Naphthalene	mg/kg	505.0	3565.3	61.3	432.5	87.9
Acenaphthylene	mg/kg	126.2	890.7	114.1	805.8	9.5
Acenaphthene	mg/kg	28.5	201.2	26.2	185.0	8.1
Fluorene	mg/kg	110.0	776.6	106.2	749.5	3.5
Phenanthrene	mg/kg	311.7	2200.4	298.0	2103.9	4.4
Anthracene	mg/kg	104.5	737.8	102.2	721.3	2.2
Fluoranthene	mg/kg	200.0	1412.0	206.7	1459.1	-3.3
Pyrene	mg/kg	188.3	1329.6	190.7	1346.1	-1.2
Benzo(a)anthracene	mg/kg	77.8	549.5	89.7	633.3	-15.2
Chrysene	mg/kg	64.0	451.8	84.5	596.8	-32.1
Benzo(b)fluoranthene	mg/kg	44.5	314.2	54.1	382.2	-21.6
Benzo(k)fluoranthene	mg/kg	40.8	288.3	57.3	404.3	-40.2
Benzo(a)pyrene	mg/kg	54.8	387.1	54.9	387.8	-0.2
Indeno(1,2,3-cd)pyrene	mg/kg	31.7	223.6	24.9	175.8	21.4
Di-benzo(a,h)anthracene	mg/kg	8.1	56.8	8.5	59.7	-5.0
Benzo(g,h,i)perylene	mg/kg	33.2	234.2	33.5	236.5	-1.0
Anthanthrene	mg/kg	15.9	112.5	10.8	76.0	32.4
Benzo(e)pyrene	mg/kg	33.0	233.0	40.5	286.2	-22.8
Cyclopenta(cd)pyrene	mg/kg	2.4	16.9	1.0	7.1	58.3
Benzene	mg/kg	4.2	29.3	0.4	3.2	89.2
Toluene	mg/kg	2.3	16.3	0.5	3.4	79.1
Ethylbenzene	mg/kg	0.2	1.4	0.1	0.7	49.5
Xylenes	mg/kg	2.1	15.1	0.9	6.2	59.1
TOTAL MASS:			32482.9		7400.9	24.6

Table B22: Overall contaminant mass balance for Trial 3.

Mass Balance of Organic Analytes in the Bioreactor				
	Units	Pre-trial 3	Post Trial 3	% change
Waters	g	20.53	81.39	-296.35
Soils	g	14874	11214	24.61
Total	g	14894	11295	**24.16**

APPENDIX C
TELEMETRY SYSTEM

Telemetry Data Stream Summary: All Trials

Bioreactor Trial 1

The first of three bioreactor trials was started at 16:00 on Thursday 5th September 2002. The trial ran for ten and a half days, with unloading starting on the morning of Monday 16th September 2002. A summary of changes in pH, temperature and dissolved oxygen levels within the bioreactor during the trial are recorded below.

Dissolved Oxygen

Day 1: 16:00 on 5th September to 16:00 6th September

Initial dissolved oxygen (DO) readings were in the range 19 % to 22 %, with a 'jump' up to 37 % approximately an hour into the trial. DO levels then steadily decreased, fluctuating between 10 % and 16 % throughout the evening before dropping below 10 % at approximately 02:00. DO levels were then consistently in the range 7 % to 10 % until 14:00 on the 6th September. From 14:00 the DO levels started to increase, initially fluctuating between 9 % and 15 % and then developing peaks and troughs with DO levels in the range of 12 % to 36 % until the end of Day 1.

Day 2: 16:00 on 6th September to 16:00 7th September

DO levels steadily decreased throughout the evening, falling below 10 % at approximately 22:00. DO levels were in the range 7 % to 10 % throughout the night and through the remainder of Day 2, only occasionally rising above 10 %.

Day 3: 16:00 on 7th September to 16:00 8th September

DO levels remained below 10 % until approximately 01:00 on the 8th September when DO levels started to gradually increase, reaching 30 % by 08:00 and consistently exceeding 40 % by 09:30. DO levels peaked in the high 40 %s around 13:00 and remained at this level throughout the remainder of Day 3.

Day 4: 16:00 on 8th September to 16:00 9th September

DO levels dropped to the low 40 %s at 17:00 on the 8th September and remained steady until 05:00 on the 9th September when they started to increase again. DO levels reached 50 % at approximately 11:00 and remained in the range 48 % to 52 % throughout the remainder of Day 4.

Day 5: 16:00 on 9th September to 16:00 10th September

DO levels remained in the range 48 % to 52 % until 21:00 when they started to steadily increase, reaching 60 % by 23:30 and further increasing to 70 % during the night. DO levels remained in the range 67 % to 71 % throughout Day 5.

Day 6: 16:00 on 10th September to 16:00 11th September

DO levels remained in the range 67 % to 71 % until early am on the 11th September when levels steadily increased, rising to the high 70 %s. From 07:00 on September 11th, DO levels started to decrease very steadily, dropping below 75 % around 10:00 and below 70 % by 16:00.

Day 7: 16:00 on 11th September to 16:00 12th September

DO levels continued to drop very steadily throughout the day before stabilising in the range 58 % to 61 % at around 03:00 on September 12th and remaining at this level throughout Day 7.

Day 8: 16:00 on 12th September to 16:00 13th September

At the start of Day 8 DO levels started dropping slowly, falling below 45 % at midnight and below 25 % by 10:30 on the 13th September. DO levels then stabilised in the range 24 % to 27 % for the remainder of Day 8.

Day 9: 16:00 on 13th September to 16:00 14th September

At the start of Day 9 DO levels started increasing, rising above 60 % at 23:00 and peaking at 76.5 % at 07:00 on the 14th September. DO levels remained in the range 74 % to 76.5 % throughout the remainder of Day 9.

Day 10: 16:00 on 14th September to 16:00 15th September

DO levels remained in the mid 70 %s until the evening when they started to rise very slowly throughout the night, reaching 85 % at approximately 10:00 on the 15th September. DO levels remained steady in the range 84 % to 86 % throughout Day 10.

Day 11: 16:00 on 15th September to 07:30 16th September

DO levels were in the range 84 % to 86 % throughout Day 11.

Anomalies:

Only one anomaly was noted in DO readings during Trial 1. At 16.57 on Day 1 DO levels dropped from the low 20 %s to 3 %. Quickly corrected. This is likely to have been a problem with the generator.

Summary

The DO results indicate that the most intense biological activity took place on days 1 and 2.

Temperatures

The temperatures recorded by the three probes in the bioreactor were very stable throughout Trial 1. The range of temperatures typically recorded by each probe were:

- Probe 1: 23 ºC to 29 ºC
- Probe 2: 26 ºC to 30 ºC
- Probe 3: 21 ºC to 23 ºC

Temperatures recorded by probe 1, which was located approximately 1.5 m from the top of the bioreactor, fluctuated the greatest. Temperatures recorded by probe 3, which was located in the cone at the bottom of the bioreactor were the most stable and were also the lowest of the three probes.

The average temperature range was 24 ºC to 27 ºC throughout the Trial.

The temperatures recorded by each probe remained within the acceptable limits throughout the trial with the exception of a number of anomalies thought to have been a result of the generator stalling. These 'blips' usually involved probe 3 and resulted in the temperature recorded by probe 3 dropping by between 4 ºC and 13 ºC. The temperatures returned to acceptable levels immediately. On each occasion the temperature dropped below the acceptable low limit of 20 ºC. On most occasions the average temperature remained within the acceptable range so no call out was made via the telemetry system. A few anomalies also took place involving probe 2 and typically involved the temperature jumping up to between 31 ºC and 33 ºC.

pH

Day 1: 16:00 on 5th September to 16:00 6th September

When the first trial started pH probe 1 was reading between 10.0 and 10.1 and probe 2 was reading between 7.0 and 7.1. The pH read by probe 1 was therefore well above the acceptable upper limit of 8.5.The average pH was slightly above 8.5.

Both pH probes recorded a gradual increase in pH within the bioreactor overnight with probe 1 reaching a peak of 10.5 and probe 2 reaching a peak level of 7.13. The average pH increased to 8.8, which is above

the acceptable range. It is unclear whether the high pH recorded by probe 1 was due to a technical problem or whether the pH in the bioreactor was actually that high.

At 08:34 on September 6th the reading from pH probe 2 dropped instantly down to pH 6.45 and then started slowly increasing again, stabilising around pH 6.6 to pH 6.8 throughout the morning. It is unclear why the pH recorded by probe 2 dropped in this way. The pH recorded by probe 1 dropped slightly during the morning and stabilised around pH 10.2 to pH 10.4.

At 14:13 pH probe 1 showed an immediate drop in pH of approximately 1 and at 14:17 showed a second drop in pH from pH 8.94 to pH 6.81, quickly rising to pH 7.3. At 14:23 pH probe 1 dropped again, this time from pH 7.3 to pH 5.5 but quickly increasing to 6.71. pH probe 2 also showed an immediate drop at 14:23 to pH 6.77. It is possible that this reduction in pH levels was due to an injection of acid.

For about 2 hours probe 1 fluctuated with readings ranging from pH 12.93 (average of the 2 probes, pH 9.8) to pH 4.5 (average of the 2 probes, pH 5.6) until the readings settled down at between pH 7.2 and pH 7.3. probe 2 remained stable throughout the remainder of Day 1 with readings in the range pH 6.7 to pH 6.9.

Remainder of Trial 1

pH levels remained very stable from Day 2 to the end of Trial 1. In general pH levels slowly increased throughout the Trial with pH levels only dropping slightly on Days 7 and 8. pH levels recorded by probe 1 ranged from pH 7.3 to pH 7.94 during the remainder of Trial 1. The pH values recorded by probe 2, during the same period, ranged from pH 6.9 to pH 7.6. The pH changes recorded during Trial 1 are summarised in Table C.1, below.

Table C1: Summary of pH levels from day 2 to day 11 during Trial 1.

Day	Comments on pH	pH readings recorded by probe 1	pH readings recorded by probe 2
2	Rising slightly	pH 7.3 to pH 7.5 (range through day)	pH 6.9 to pH 7.1 (range through day)
3	Steadily rising	pH 7.5 to pH 7.65 (range through day)	pH 7.1 to pH 7.25 (range through day)
4	Rising slowly	pH 7.65 to pH 7.8 (range through day)	pH 7.2 to pH7.4 (range through day)
5	Very stable	pH 7.8 to pH 7.85 (range through day)	pH 7.4 to pH7.46 (range through day)
6	Very stable	pH 7.8 to pH7.83 (range through day)	pH 7.4 to pH7.47 (range through day)
7	Dropping slightly	Reading at 07:45: pH 7.76	Reading at 07:45: pH 7.38
8	Dropping slightly	Reading at 07:45: pH 7.61	Reading at 07:45: pH 7.22
9	Rising steadily	Reading at 07:45: pH 7.8	Reading at 07:45: pH 7.45
10	Rising slowly	Reading at 07:45: pH 7.89	Reading at 07:45: pH 7.54
11	Rising slowly	Reading at 07:45: pH 7.94	Reading at 07:45: pH 7.6

The graph titled 'Bioreactor Trial 1: Data Stream Summary' shows the variation in temperature, pH and dissolved oxygen during Trial 1.

Bioreactor Trial 2

The second bioreactor trial was started at 14:00 on the 27th September. The trail ran for 7 days with unloading starting at 11:45 on 4th October. A summary of changes in pH, temperature and dissolved oxygen levels within the bioreactor during the trial are recorded below.

Dissolved Oxygen

Day 1: 14:00 on 27th September to 14:00 on 28th September
Initial DO readings showed significant peaks and troughs. Peaks were in the high 70 %s and low 80 %s and the troughs in the low 20 %s and 30 %s. No particular timescale or pattern emerged from these peaks and troughs. At 18:00 the peaks and troughs started to flatten out and the DO levels were in the range 50 % to 60 %. DO levels had fallen below 50 % by 19:00 and were dropping into the 30 %s by 22:30. Throughout the night and during the morning of the 28th September DO levels were in the range of 30 % to 55 % with noticeable peaks and troughs developing after 02:00. This may be a temperature related feature.

Day 2: 14:00 on 28th September to 14:00 on 29th September
During the afternoon of the 28th[th] September DO levels remained fairly steady, ranging from 30 % to 40 % and then gradually increasing to 30 % to 50 % during the evening and further increasing to 40 % to 65 % (with indistinct peaks) from 02:00 onwards. The peaks started to level out from 08:00 onwards with the DO levels steadily decreasing, falling below 20 % by 13:00.

Day 3: 14:00 on 29th September to 14:00 on 30th September
DO levels continued to drop slowly throughout the afternoon, falling below 10 % at around 18:00, to 6.5 % by 21:45, to 6.0 % by 01:00 and to 5.5 % by 03:24. DO levels remained at 5.5 % throughout the remainder of Day 3.

Day 4: 14:00 on 30th September to 14:00 on 1st October
DO levels were steady at 5.5 % until 11:15 on October 1st when DO levels started to slowly rise. DO levels had reached 7 % by 11:15 and 21.5 % by 13:15.

Day 5: 14:00 on 1st October to 14:00 on 2ndt October
DO levels ranged from 20 % to 30 % throughout the afternoon and steadily increased overnight until all readings started to exceed 30 % at around 07:00 on October 2nd. DO levels ranged from 30 % to 40 % throughout the morning with a few peaks and troughs developing from 12:00 and the range of DO levels changing to 20 % to 40 %.

Day 6: 14:00 on 2ndt October to 14:00 on 3rdt October
From 14:00 on October 2nd DO levels ranged from 30 % to 50 %. After 16:00 the range of DO readings was 40 % to 60 % with peaks and troughs developing around 19:00. DO levels remained in the high 50 %s/low 60 %s throughout the night until approximately 10:30 on October 3rd when the range of DO readings fell to 40 % to 55 %.

Day7: 14:00 on 3rdt October to 11:45 on 4th October
Throughout the afternoon DO levels ranged from 40 % to 55 % although they were generally gradually decreasing. At around 23:00 DO levels started to drop below 30 % and DO levels remained in the high 20 %s to low 30 %s throughout the night. After 08:00 on October 4th DO levels started to rise again, ranging from 40 % to 50 % until the Trial was ended at 11:45.

Summary

The most intense biological activity took place between days 2 and 4, with a later peak in day 7.

Temperature

It must be noted that throughout Trial 2 temperature probe 3 was not working. All comments in this section are therefore based on temperatures recorded by Probes 1 and 2.

Temperatures recorded by both probes were very stable throughout the trial. Temperatures recorded by probe 1, which was located towards the top of the bioreactor, showed a slightly higher degree of fluctuation than probe 2. Average temperatures recorded by probe 2 were generally 4 ºC to 5 ºC higher than those recorded by probe 1. Temperatures recorded by probe 1 during the trial ranged from 22 ºC to 28 ºC. Temperatures recorded by probe 2 during the trial ranged from 25 ºC to 33 ºC.

During the night of day 4 temperatures recorded by probe 1 started rising above the acceptable maximum temperature of 32 ºC. The average temperature was still within acceptable limits. This rise in temperature was attributed to the fact that 4 of the air inlets had been closed the previous evening in order to try and control the production of foam. The air inlets were opened again next morning and this seemed to drop the temperatures recorded by probe 1 back to acceptable levels.

On the morning on the 4th October (Day 7) a large number of 'blips' occurred, with up to 10 jumps in temperature occurring in 10 minutes. The temperatures either dropped or increased suddenly. The reason for these blips is unclear, but may be related to the problems encountered with the generator.

A summary of temperatures recorded within the bioreactor during Trial 2 can be seen in Table C2.

Table C2: Summary of temperatures recorded during Bioreactor Trial 2

Day of trial	Range of temperatures recorded (ºC)		Comments
	Probe 1	Probe 2	
1	23 to 26	28 to 31	Temperatures higher overnight by approx. 1 ºC
2	23 to 26	29 to 31	Temperatures very stable
3	23 to 27	28 to 31	Temperatures very stable
4	22 to 27	28 to 33	Temperatures recorded by probe 2 rising above 32 ºC during the night
5	23 to 37	29 to 31	Temperatures rising by 1 ºC overnight
6	23 to 28	29 to 32	Temperatures slightly higher overnight. probe 1 only reaching 28 ºC on rare occasions
7	23 to 26	25 to 29	Both probes giving very similar readings from 06:00 to 08:00

pH

The pH values were fairly stable throughout Trial 2 with the average pH value ranging from pH 7.0 to pH 7.3 from day 1 to day 6 of the Trial. PH levels recorded by probe 1 from day 1 to day 6 ranged from pH 7.2 to pH 7.5 and values recorded by probe 2, during the same period, ranged from pH 6.8 to pH 7.1. The pH levels recorded by probe 2 were consistently 0.3 to 0.4 pH units above those recorded by probe 1.

Between 10:33 and 10:39 on Day 6 pH values recorded by both probes started to show a series of peaks and troughs. probe 1 gave a maximum reading of pH 8.6 during this period and probe 2 gave a maximum reading of pH 7.9. The highest average reading during this period was pH 7.9, which is within the allowable pH range. After 10:39 pH readings settled down but levels recorded by both pH probes were approximately half a pH unit higher than prior to this unsettled period.

The pH values steadily increased during the remainder of Day 6 and throughout Day 7. At 11:30 on day 7, just prior to ending the trial, the following pH levels were recorded: probe 1 = pH 8.52, probe 2 = pH 8.04, Average = pH 8.28.

A summary of pH, temperature and dissolved oxygen levels is shown on the graph titled 'Bioreactor Trial 2: Data Stream Summary'.

Bioreactor Trial 3

The third bioreactor trial ran for 5.75 days, starting at 14:00 on the 11th October and finishing at 07:30 on October 17th. A summary of changes in pH, temperature and dissolved oxygen levels within the bioreactor during the trial are recorded below.

Dissolved Oxygen

Day 1: 14:00 on 11th October to 14:00 on 12th October

From 14:00 to 16:00 DO levels were in the high 20 %s and low 30 %s. At 16:00 DO levels jumped up to the high 70 %s and low 80 %s. DO levels remained fairly stable within this range throughout the night and until 11:00 on October 12th. From 11:00 slight peaks and troughs developed with the DO troughs in the high 70 %s and the peaks ranging from 85-90 %.

Day 2: 14:00 on 12th October to 14:00 on 13th October

DO levels continued to show these slight peaks and troughs throughout the afternoon on October 12th. DO levels settled out at 75.5 % at 17:00 and remained stable throughout the night increasing to a maximum level of 78.5 % at approximately 13:00 on October 13th.

Day 3: 14:00 on 13th October to 14:00 on 14th October

DO levels remained stable at 78.5 % throughout Day 3.

Day 4: 14:00 on 14th October to 14:00 on 15th October

DO levels remained in the high 70 %s throughout Day 4, reaching a peak of 79.5 % around 22:00 on October 14th.

Day 5: 14:00 on 15th October to 14:00 on 16th October

DO levels remained in the high 70 %s throughout Day 5

Day 6: 14:00 on 16th October to 07:30 on 17th October

DO levels remained in the high 70 %s throughout the afternoon of October 16th but increased slightly during the evening to 80-81 %. DO level stabilised at 80 % until the third bioreactor trial was finished at 07:30 on October 17th.

Summary

The DO readings indicate that biological activity may have been lower than the other trials.

Temperature

Temperatures were fairly stable throughout Trial 3. The average temperature in the bioreactor ranged from 27 ºC to 31 ºC during the trial. The range of temperatures recorded by each individual probe during the trial were:

Probe 1, 19 ºC to 27 ºC

Probe 2, 29 ºC to 32 ºC

Probe 3, 30 ºC to 34 ºC

Temperatures recorded by probe 1, which was located towards the top of the bioreactor were the lowest of the three probes and also recorded the greatest fluctuations in temperature.

The temperature in the bioreactor appears to increase from top to bottom with probe 3, which was located in the cone at the base of the bioreactor recording the highest temperatures. Temperatures recorded by probe 3 frequently exceeded 32 ºC rising to a maximum of 34 ºC. A summary of temperature levels within the Bioreactor during Trial 3 is included in Table C3.

Table C3: Summary of temperatures in the bioreactor during Trial 3

Day	**Range of temperatures recorded (ºC)**			
	Probe 1	**Probe 2**	**Probe 3**	**Average**
1	19 ºC to 24 ºC rising to 23 ºC to 26 ºC in the evening	29 ºC to 31 ºC	30 ºC to 31 ºC rising to 31 ºC to 34 ºC in the evening	27 ºC to 29 ºC rising to 28 ºC to 30 ºC in the evening
2	21 ºC to 25 ºC	29 ºC to 31 ºC	31 ºC to 34 ºC	28 ºC to 30 ºC
3	12 ºC to 26 ºC	29 ºC to 32 ºC	32 ºC to 34 ºC	28 ºC to 31 ºC
4	22 ºC to 25 ºC	30 ºC to 32 ºC	31 ºC to 34 ºC	28 ºC to 31 ºC
5	24 ºC to 27 ºC	29 ºC to 32 ºC	31 ºC to 33 ºC	29 ºC to 31 ºC
6	19 ºC to 27 ºC	29 ºC to 32 ºC	30 ºC to 34 ºC	27 ºC to 31 ºC

pH

Day 1: 14:00 on 11th October to 14:00 on 12th October

Initial pH readings for both probes were above 8 with probe 1 reading above the maximum allowable pH of 8.5. The pH levels increased steadily during the first 2 hours of the trial and although the pH levels recorded by probe 1 were above the maximum allowable pH of 8.5 the average pH remained within acceptable limits. The table below summarises the pH readings during the first 2 hours of Trial 3:

Table C4: pH levels recorded in the Bioreactor during the first 2 hours of Trial 3

	Time (Trial started at approx. 14:00)		
Probe	14:00	15:30	16:04
1	pH 8.70	pH 8.77	pH 8.79
2	pH 8.04	pH 8.08	pH 8.14
Average	pH 8.38	pH 8.42	pH 8.46

Two 'blips' occurred just after 16:00. At 16:06 the pH recorded by probe 2 dropped from pH 8.14 to pH 7.44. The pH recorded by probe 1 remained stable. At 16:09 the pH recorded by probe 1 dropped from pH 8.79 to pH 7.13. The pH recorded by probe 2 remained stable. It is likely that this drop in pH was due to an injection of acid.

The pH levels recorded by both probes remained fairly stable throughout the remainder of Day 1. The pH levels recorded by probe 1 were between pH 7.0 and pH 7.3. The pH levels recorded by probe 2 dropped slowly through the evening and night with pH levels in the range pH 6.9 to pH 7.2 from approximately 18:00 on October 11th.

Remainder of Trial 3

From Day 2 onwards the pH levels in the bioreactor increased very slowly. PH levels were very stable throughout the remainder of Trial 3. pH levels in the bioreactor from day 2 onwards are summarised in Table 3.3.

Table C5: Summary of pH levels during Trial 3 from day 2 onwards.

Day	Range of pH readings		
	Probe 1	Probe 2	Probe 3
2	pH 7.3 to pH 7.45	pH 6.9 to pH 7.25	pH 7.1 to pH 7.35
3	pH 7.4 to pH 7.5	pH 7.1 to pH 7.3	pH 7.3 to pH 7.35
4	pH 7.45 to pH 7.6	pH 7.15 to pH 7.35	pH 7.3 to pH 7.45
5	pH 7.6 to pH 7.7	pH 7.35 to pH 7.5	pH 7.45 to pH 7.6
6	pH 7.7 to pH 7.75	pH 7.5 to pH 7.65	pH 7.6 to pH 7.7

Foam Production

Trial 1

Antifoam was not required during Trial 1. No significant production of foam took place.

Trial 2

On Wednesday 25th September water, half a bag of fertiliser and 2.6 tonnes of soil feedstock were loaded into the bioreactor. The remainder of the soil along with 6 bags of fertiliser were loaded into the bioreactor on the 26th of September, which was when the trial officially started.

During the night of the 25th/26th of September (i.e. before the bioreactor was fully loaded) the foam probe was triggered and foam started spilling out of the top of the bioreactor. The foam was controlled by attempting to dose the bioreactor with antifoam from the top (difficult as there was around 1 metre of foam at the top of the bioreactor) and by setting the dose of antifoam on manual for 45 minutes.

Foam production continued throughout the loading of the bioreactor on the 26th September.

Day 1 (Thurs/Fri)

A 1 hr dose of antifoam was given to the bioreactor during the afternoon of day 1.

The bioreactor was dosed for 40 minutes at 08:30 on September 27th in order to control the flow of foam out of the top of the bioreactor.

At 14:00 foam started spilling out of the top of the bioreactor again. Continual dose of antifoam given to the bioreactor for 45 minutes.

Foam probe continually triggered during Day 1 so the computer was automatically dosing the bioreactor all day. The continual dosing periods mentioned above were in addition to the auto dose.

Day 2 (Fri/Sat)

At 17:00 foam started escaping from the top of the bioreactor again. Dosed for 10 minutes, which seemed to get the problem under control. In addition, to try and help control foam production, the 4 highest positioned air inlets on the cone were closed.

At 18:00 on the 27th September foam started spilling out of the bioreactor again. Continual dose of antifoam for 70 minutes and foam continued. The auto dose of anti foam was reset to a 1 minute dose every 3 minutes.

Foam production continued, but was controlled by the auto dose on the computer, throughout Day 2.

Day 3 (Sat/Sun)

Foam production continued but was controlled by the auto dose. Foam levels may have dropped during Day 3 as the foam probe was re-triggered at the end of Day 3/Start of Day 4.

Day 4 (Sun/Mon)

Foam probe still triggered but foam production was controlled by the auto dose.

Day 5 (Mon/Tues)

Foam dropped off during the evening then started to be produced again, foam probe triggered at 00:20. Foam production controlled by the auto dose throughout the rest of Day 5.

Day 6 (Tues/Weds)

Foam sensor off throughout the majority of Day 6.

Day 7 (Weds/Thurs)

No problems with foam production, foam sensor off.

Trial 3

The only addition of antifoam was when a 25 minute dose of antifoam was added to the bioreactor prior to loading the soil feedstock.

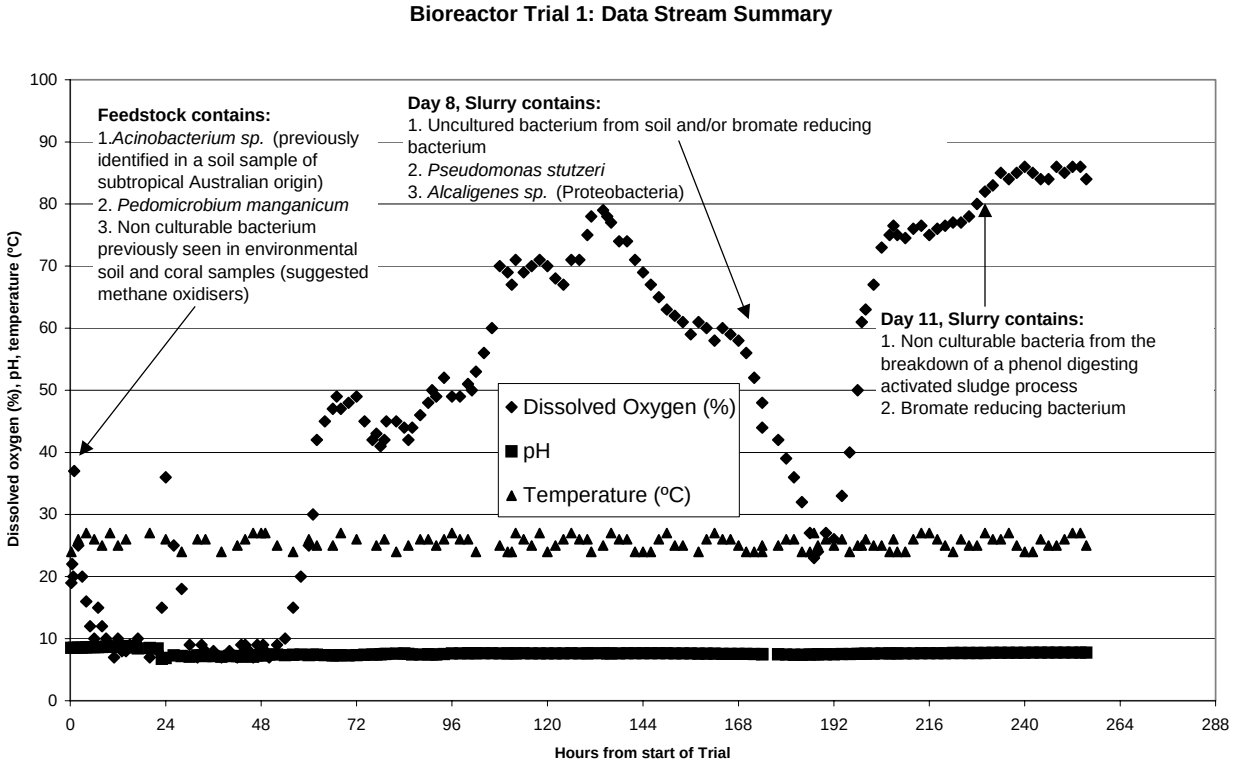

Figure C1: Telemetry data for Trial 1.

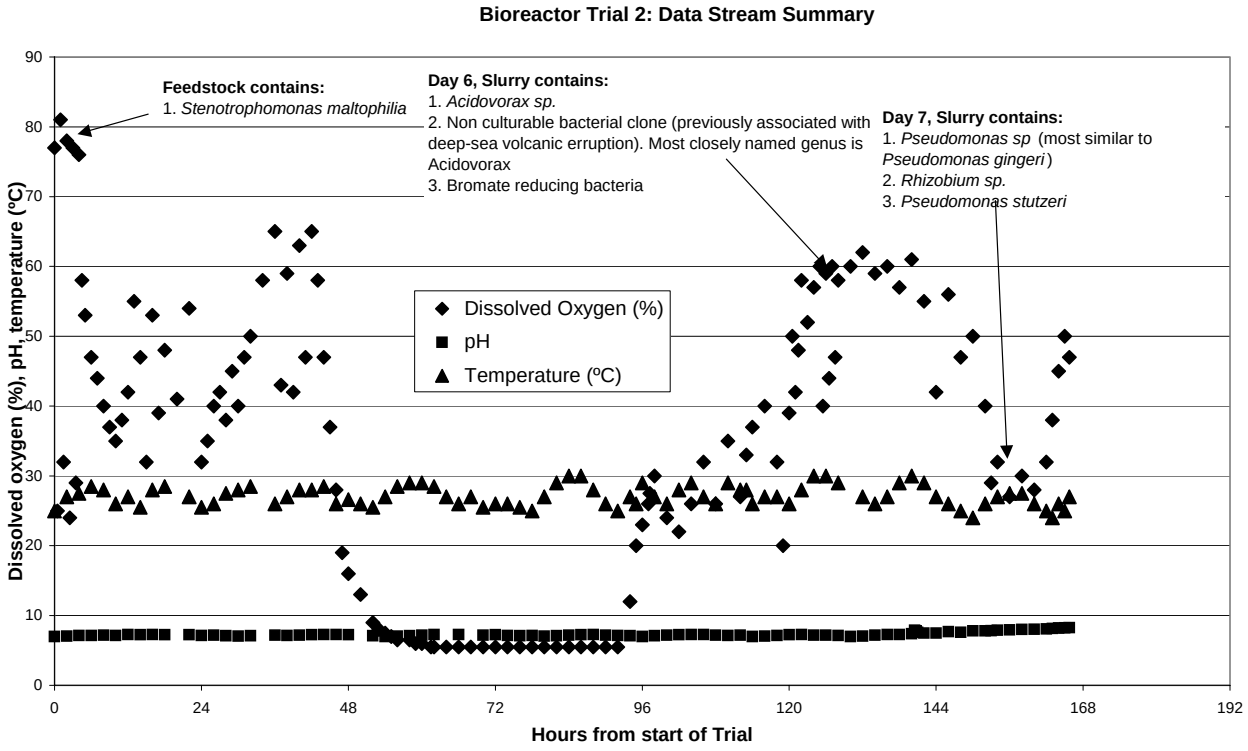

Figure C2: Telemetry data for Trial 2.

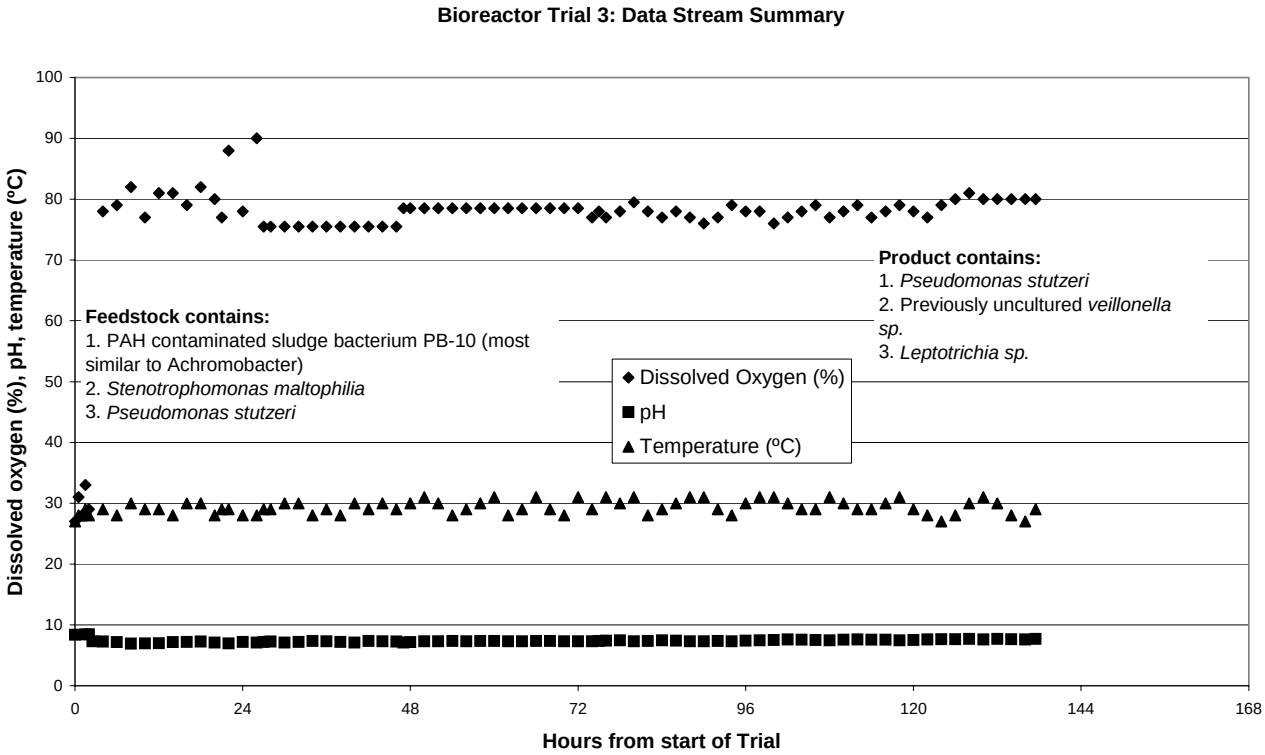

Figure C3: Telemetry data for Trial 3.

Figure C4: Data format from telemetry system – graph view.

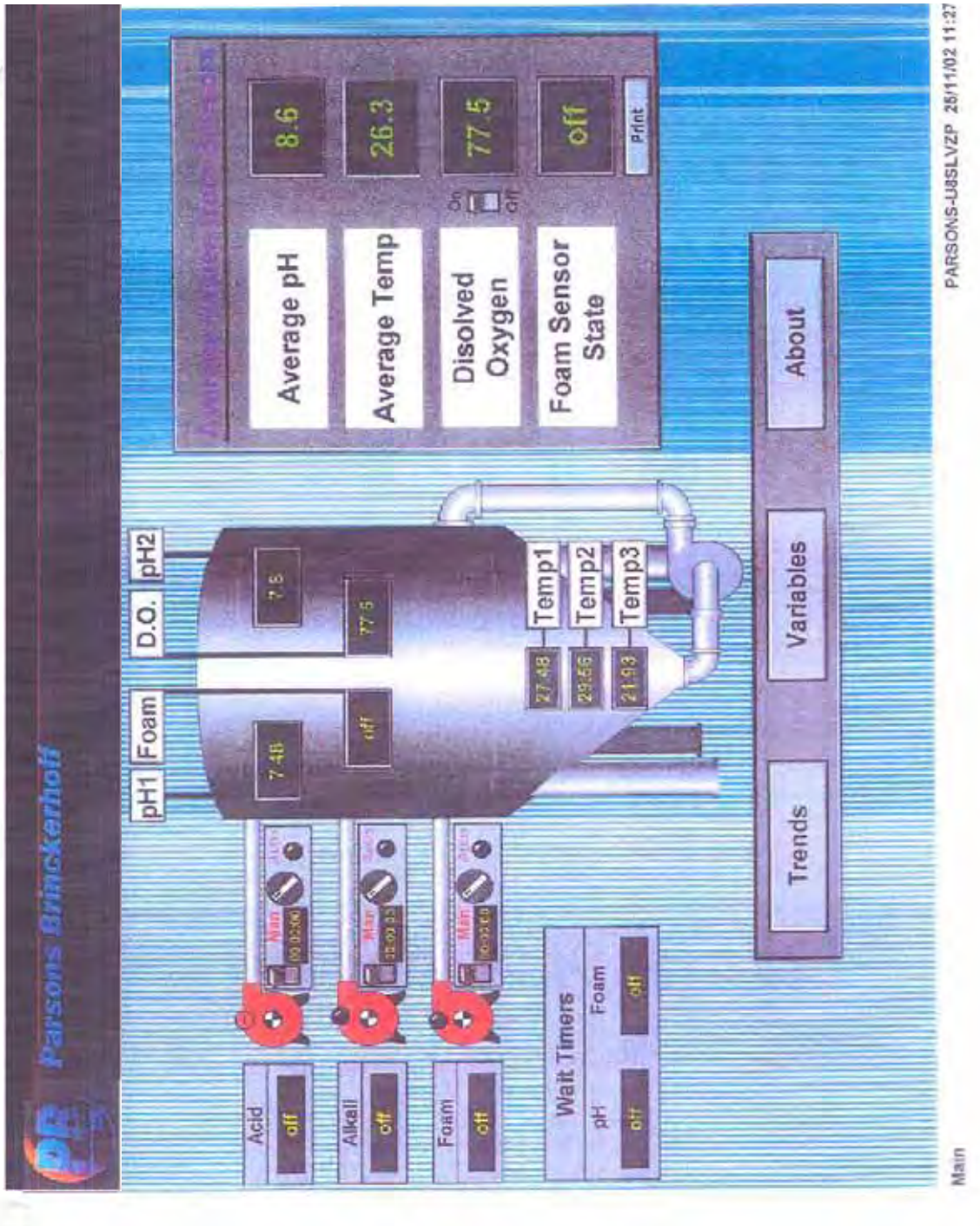

Figure C5: Telemetry system control screen 1.

Figure C6: Telemetry system control screen 2.

APPENDIX D

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