# Bioremediation of Petroleum-Contaminated Soils: An Innovative, Environmentally Friendly Technology

Dan M. McNicoll and Anar S. Baweja

**The National
Contaminated Sites
Remediation Program**

Canada

Environment Canada Environnement Canada

# Bioremediation of Petroleum-Contaminated Soils: An Innovative, Environmentally Friendly Technology

**Dan M. McNicoll* and Anar S. Baweja†**

* Oliver, Mangione, McCalla & Assoc. Ltd.
154 Colonnade Road South
Nepean, Ontario
K2E 7J5

† Evaluation and Interpretation Branch
Ecosystem Conservation Directorate
Environment Canada
Ottawa, Ontario
K1A 0H3

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# Executive Summary

In 1991, petroleum-contaminated soil was encountered beneath a bulk petroleum storage facility at Canadian Forces Base Petawawa, Petawawa, Ontario. Several conventional soil remediation options were presented to the Department of National Defence (DND). In collaboration with Environment Canada, DND decided to proceed with bioremediating the petroleum-contaminated soils using an aboveground bioreactor system. An innovative bioreactor was subsequently designed to treat the estimated 3600 tonnes of petroleum-contaminated soil. The bioremediation facility was constructed in the late fall of 1992 and operated for a six-month period between May and November 1993.

The bioremediation facility consisted of four aboveground bioreactors, each incorporating a network of aeration pipes and a two-tiered water/nutrient delivery system. The aeration piping was connected to a central vacuum pump that drew air through the bioreactor providing an essential source of oxygen for the proliferation of the hydrocarbon-degrading bacteria. The nutrient delivery system introduced nutrients to the hydrocarbon-degrading bacteria uniformly and allowed the user to control and maintain pH and moisture content within the bioreactors in the optimum range for bacterial growth. An elaborate leachate collection system enabled the leachates to be amended as required and recirculated into the bioreactor from which it originated. The bioreactors were covered with an opaque vapour barrier to minimize volatilization and enhance solar heating.

An elaborate monitoring program, consisting of soil, water, and air sample collection and analysis, was implemented over the six-month operating period. Results showed that the total petroleum hydrocarbon concentration in the bioreactor soils was reduced by about 97%. Mass balance calculations indicated that 99% of the degradation was attributable to biological degradation, with the remaining 1% due to volatilization.

With a reduced monitoring program and taking into account the reuse potential, the cost to treat petroleum-contaminated soils using this technology would be between $20 and $40 per tonne. This project has shown that even soils contaminated with diesel fuel can be efficiently treated to meet the most stringent federal and/or provincial criteria in a cost-effective manner over a typical Canadian summer. Furthermore, these favourable results should encourage the widespread use of this technology on military bases across Canada or at any other sites similarly contaminated.

This project is in keeping with the objectives of the National Contaminated Sites Remediation Program, namely, to remediate contaminated sites, and to develop and demonstrate innovative technologies that reduce or eliminate threats posed to the environment by contaminated sites.

# Acknowledgments

Financial support for this project by the Department of National Defence and by the various branches of Environment Canada, namely, the Hazardous Waste Management Branch and the Office of Environmental Stewardship, is gratefully acknowledged by the authors. Special thanks are due to the District Office of Environmental Protection, particularly to Frank D'Addario, who initiated the interest in this project, and to Peter Fernandes (DND), who managed the day-to-day operations at CFB Petawawa, Ontario.

# Bioremediation of Petroleum-Contaminated Soils: An Innovative, Environmentally Friendly Technology

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## INTRODUCTION

The firm of Oliver, Mangione, McCalla & Associates Limited was retained by Environment Canada and the Department of National Defence to design an innovative aboveground bioremediation facility to treat petroleum-contaminated soils. The objective of the project was to assess whether cost-effective bioremediation could successfully be undertaken in a typical Canadian climate.

The following text presents the conventional soil remediation technologies that were considered, the rationale behind the selection of aboveground bioremediation as the method of choice, the design and objectives of the bioreactor, the monitoring program that was implemented, the results obtained, and the conclusions reached as to the effectiveness and general applicability of this technology.

## BACKGROUND INFORMATION

In June 1991, gasoline and diesel fuel spills occurred at a bulk petroleum storage facility located on Canadian Forces Base (CFB) Petawawa, Petawawa, Ontario (Figure 1). The firm of Oliver, Mangione, McCalla & Associates Limited was retained by the Department of National Defence (DND) to investigate the subsurface to determine the extent of the petrochemical contamination. This investigation revealed that a significant amount of subsoil had been contaminated with diesel fuel and gasoline, and that soil remediation was necessary. The underlying groundwater regime, approximately 23 m below grade, however, was not affected (McNicoll and McKee 1991).

## AVAILABLE SOIL REMEDIATION OPTIONS

Several conventional in situ and ex situ soil remediation technologies were presented to DND. These are discussed briefly below and are summarized in Table 1.

### In Situ Technologies

#### *Soil Vapour Extraction*

Soil vapour extraction promotes the volatilization of contaminants adhering to the soil while simultaneously inducing fresh oxygenated air into the zone of soil contamination. The fresh air becomes an essential source of oxygen for the indigenous hydrocarbon-degrading bacteria and hence promotes natural biological degradation. Soil vapours are withdrawn from the subsurface through several specially designed vapour recovery wells that are connected to one or more vacuum pumps. The contaminated vapours are then treated on site and discharged to the atmosphere.

Average treatment costs range from $35 to $80 per tonne, with an average operating period of 6–36 months (GASReP 1990).

The relatively low cost and the ability of this technology to treat soils under roadways, buildings, and similar structures, make this technology very attractive. The limitation of this technology, however, is that it is heavily dependent on the air permeability of the impacted soils and the degree of homogeneity (U.S. EPA 1991, 1992).

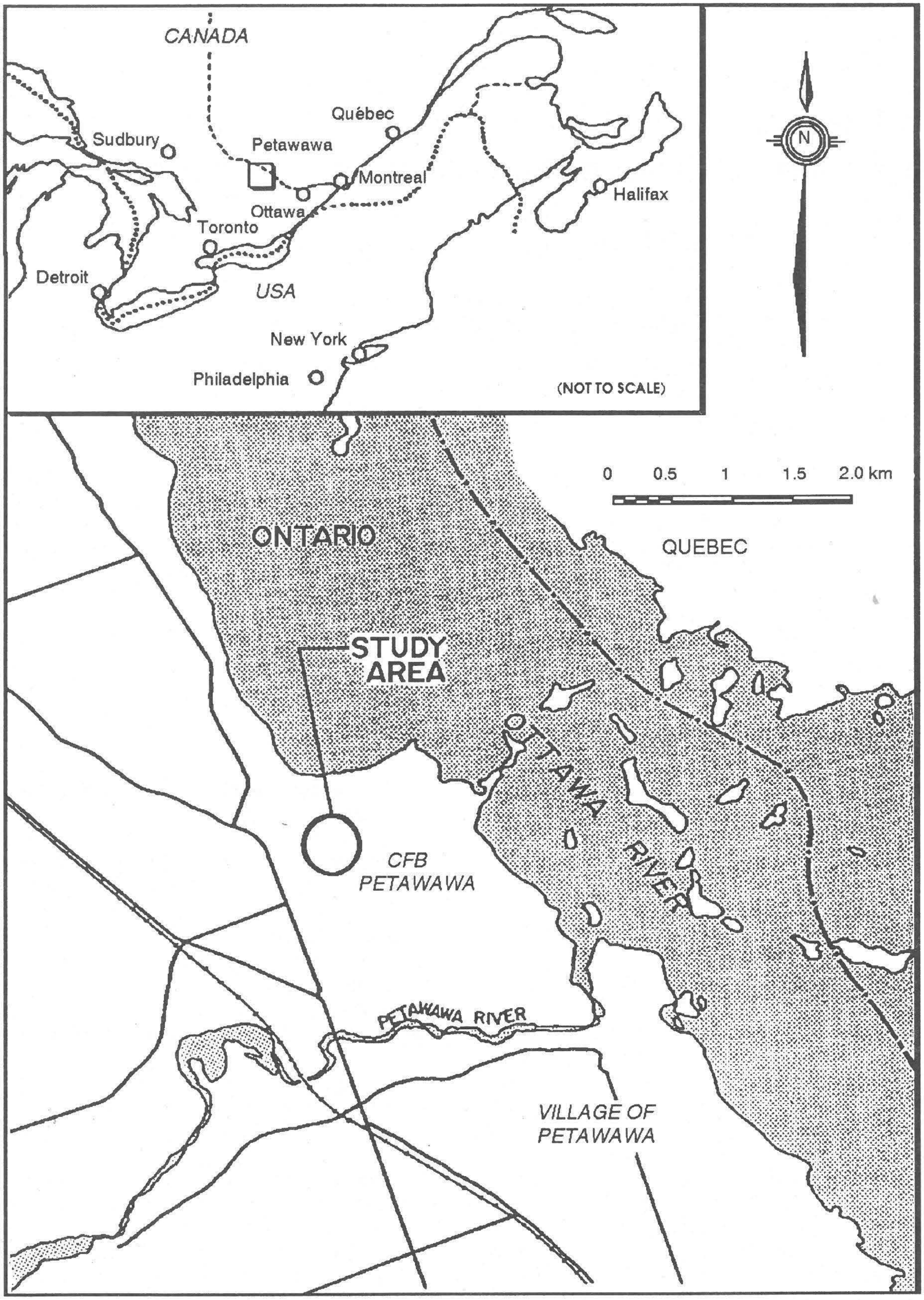

Figure 1. Location of CFB Petawawa, Petawawa, Ontario.

### Soil Leaching/Flushing

Soil leaching/flushing involves flushing the soil contaminant zone with an aqueous solution that mobilizes the adsorbed contaminants by dissolution or emulsification. The contaminated flushing solution is then collected and pumped back to the surface for treatment, amendments, and reinjection.

This technology may be easy or difficult to apply depending upon the permeability of the impacted soils and the local hydrogeologic characteristics of the underlying aquifer that must be manipulated to attain hydraulic containment of the flushing solution.

Treatment costs for this technology range considerably depending on the nature of the soil material; on average, costs range from $50 to $150 per tonne. Average cleanup times can range from 3 to 24 months depending on the nature of the soil materials and climate.

The main advantage of this technology is that it is relatively unobstructive and inexpensive, depending on the soil conditions and depth to groundwater (U.S. EPA 1987).

### Isolation/Containment

Isolation/containment involves isolating the contaminated soils from the surrounding area by means of a barrier wall and an impermeable cap to prevent lateral migration and surface infiltration, respectively. The barrier wall generally extends down to a low permeability horizon (i.e., clay, bedrock, etc.) and can consist of a synthetic membrane, sheet pile wall, and/or a bentonite slurry trench.

This technology does not destroy or reduce the amount of contaminant in the soil, but simply ensures that it does not migrate via the groundwater regime or escape into the environment via soil vapours. As a result, the future land development potential of the site is severely restricted. Another important consideration is establishing the long-term integrity of the materials used for the barrier wall and/or cover.

Costs associated with this technology depend largely on the distribution of the contaminants and on average range between $80 and $200 per tonne (U.S. EPA 1987). Construction time can vary from 2 to 6 months, excluding monitoring, which may go on indefinitely.

## Ex Situ Technologies

### Low Temperature Thermal Desorption

Low temperature thermal desorption (LTTD) involves excavating the contaminated soil and passing it through a rotary kiln that heats the soil to approximately 250°C in order to volatilize the contaminants. The contaminated vapours are filtered of fine particulate matter and then directed towards a high temperature thermal oxidizer for treatment. The treated soil is amended with water and is generally suitable for reuse on site.

Average treatment costs are typically in the range of $40–$90 per tonne, depending on the nature of the soil material, moisture content, volume of soil requiring remediation, and the overall petroleum concentration (OMEE 1992). LTTD units can treat between 25 and 50 tonnes per hour; taking into account mobilization and demobilization, average cleanup periods range approximately from 1 to 6 months.

The advantages of this technology are that it is relatively fast and cost effective, and treated soil can often be returned to the site for reuse. The primary disadvantages are that it is relatively disruptive, noisy, dusty, labour intensive, and consumes a lot of fuel.

### Land Farming

Land farming involves excavating contaminated soil and placing it on an impermeable surface where it is spread out in relatively thin lifts of approximately 0.3–0.6 m in thickness. The soil is then periodically tilled using conventional farm equipment (e.g., disc harrow) in order to aerate the soil and promote volatilization. Typically the soil is left uncovered and is periodically doused with liquid nutrients.

Although very few, if any, studies have tried to quantify the amount of volatilization and biological degradation that occurs when using this technique, it is widely considered that volatilization plays a significant role in the degradation process. Very few land farming projects involve capturing and treating the volatilized contaminants.

The primary advantage of this technology is that it is one of the least expensive methods to remediate petroleum-contaminated soils, with the average cost in the range of $20–$60 per tonne (OMEE 1992; U.S. EPA 1987). Furthermore, land farming is simple to design and operate. Typical cleanup times range from

6 to 36 months depending on the nature of the soil, the contaminant, and the climatic conditions (i.e., temperature, precipitation, wind velocity, etc.). The use of this technology does, however, require considerable land area and no time constraints.

### Bioreactor

Bioremediation of petroleum-contaminated soils using a bioreactor involves placing contaminated soil within one or more engineered bioreactor cells to heights ranging from 1 to 3 m. Aeration pipes and a spray system are typically erected over the pile to apply liquid nutrients as required. The bioreactor cells are then covered with a vapour barrier or contained within a structure whereby any off-gases can be captured and treated before being released into the atmosphere. Excess moisture is contained in a subdrain system and recirculated into the bioreactor making each bioreactor totally self-contained.

Average treatment costs are typically in the range of \$20–\$60 per tonne, and average cleanup time ranges from 2 to 24 months (OMEE 1992; U.S. EPA 1987).

The primary advantage of this method is that it is inexpensive, requires less space than land farming, provides the user with maximum control of the treatment process, and does not result in the volatilization of the contaminants into the atmosphere. The main disadvantage is that it requires a moderate amount of space and an unknown amount of time to attain an acceptable level of remediation.

### Landfill Disposal

Landfill disposal, although not a treatment technology, is a conventional technique of remediating contaminated sites. This option involves the excavation and transportation of all contaminated soil to the nearest approved landfill facility for disposal. The contaminated soil at the landfill site is generally used as cover material for the refuse.

Landfilling of petroleum-contaminated soil has typically been an expensive endeavour because of relatively high tipping fees. The relative expense is often outweighed by the extremely rapid rate at which the site can be rendered acceptable (on average from 1 to 3 weeks). Landfill tipping fees a few years ago exceeded \$100 per tonne in major metropolitan areas. Although tipping fees in this range still exist, there are private landfill sites that have reduced their tipping fees in order to compete with the introduction of alternate treatment technologies such as low temperature thermal desorption and bioremediation. Currently landfill disposal of petroleum-contaminated soil costs on average in the range of \$40 to \$150 per tonne.

The main disadvantage of this technique is that it simply transfers contaminated soil from one site to another, providing very little, if any, treatment.

### Solidification/Stabilization

Solidification/stabilization involves excavating the contaminated soil and immobilizing the contaminant in the soil by adding material that either combines physically (solidification) or chemically (stabilization) with the contaminant to decrease its mobility. With decreased mobility, the likelihood of the contaminant migrating off site via the groundwater regime or by volatilizing to the atmosphere is greatly minimized. The resulting mixture is either safely disposed of or reused on site.

The main disadvantage of this technology is that very little information is available on the long-term integrity of the solidified material and, as a result, if it is reused on site, restrictions may be imposed on future land use (U.S. EPA 1987; OMEE 1992).

Average cost estimates are in the range of \$75–\$200 per tonne, with cleanup times ranging from 1 to 6 months (OMEE 1992).

## FACTORS AFFECTING BIOREACTOR SELECTION

Upon careful review of the available conventional soil remediation technologies, DND, in collaboration with Environment Canada, decided that bioremediation technology in the form of an above-ground bioreactor was the most appropriate treatment techno-logy to remediate their petroleum-contaminated soils.

Some of the factors affecting DND's decision were as follows: their predetermined decision to down-size the capacity of their petroleum storage facility, the relatively shallow depth of contaminant penetration (approximately 6 m), the relatively deep groundwater table (approximately 23 m), the absence of groundwater contamination, the lack of time and space constraints, and the nature of the soil and contaminants themselves.

Environment Canada, for its part, agreed to participate in this project and fund a detailed

**Table 1. Conventional Soil Remediation Technologies**

| Remediation technology and description | Average cost (per tonne) | Average cleanup time | Advantages | Disadvantages |
|---|---|---|---|---|
| IN SITU | | | | |
| **Soil Vapour Extraction (SVE)**<br>Screened wells are installed through zone of soil contamination and connected to a vacuum pump. Air is withdrawn from these wells promoting volatilization and biodegradation of the contaminants adsorbed to the soil. The contaminated vapours are treated on site and discharged to atmosphere. | \$35–\$80 | 6–36 months | • relatively low cost<br>• unobstructive, inconspicuous<br>• relatively low maintenance<br>• relatively fast<br>• can remediate soils under buildings, roads, etc.<br>• low labour requirements | • no guarantee of final remediation level<br>• requires constant monitoring<br>• limited effectiveness in heterogeneous soils and soils with high silt/clay content |
| **Soil Leaching/Flushing**<br>Large exfiltration gallery is constructed over zone of soil contamination, and nutrient solution and surfactants are injected to wash soil and promote natural bioremediation. All contaminated water needs to be recovered by extraction wells and pumped to surface where it is treated, amended, and reinjected into subsurface. | \$50–\$150 | 3–24 months | • relatively unobstructive<br>• can be undertaken cost effectively in certain situations. | • dependent on soil composition and distribution<br>• difficult to ensure complete hydraulic control<br>• difficult to monitor remediation progress<br>• no guarantee of final remediation levels |
| **Isolation/Containment**<br>Contaminated soils are isolated by installing a barrier wall and cover or cap. Contaminants are not actively destroyed, but rather contained indefinitely. | \$80–\$200 | 2–6 months | • relatively low cost<br>• controls contaminant migration | • does not destroy or reduce contaminants, but merely prevents their migration to the groundwater or atmosphere<br>• long-term monitoring required<br>• difficult for large areas<br>• affects future of site development |
| EX SITU | | | | |
| **Low Temperature Thermal Desorption (LTTD)**<br>Contaminated soil is excavated and passed through the LTTD unit. The unit heats the soil, volatizes the petroleum contaminants, and treats the air emissions with a thermal oxidizer. | \$40–\$90 | 1–6 months | • treated soil can be reused<br>• fast<br>• relatively inexpensive<br>• no long-term liability | • may not be suitable for soils with high clay and moisture content<br>• disruptive, noisy<br>• consumes a lot of fuel<br>• labour intensive<br>• disruptive |
| **Land Farming**<br>Contaminated soil is excavated and placed in thin layers over a lined treatment cell. Liquid nutrients are applied and a tractor is used to till the soil periodically to facilitate volatilization. | \$20–\$60 | 6–36 months | • inexpensive<br>• simple to design and operate<br>• effective on various soil types and conditions | • transfers contaminants from soil to air<br>• requires a lot of space<br>• no guarantee of treatment levels<br>• disruptive<br>• subject to climatic conditions |

**Table 1. Continued.**

| Remediation technology and description | Average cost (per tonne) | Average cleanup time | Advantages | Disadvantages |
|---|---|---|---|---|
| **Bioreactor**<br>Contaminated soil is excavated and placed in an engineered cell and treated using indigenous bacteria. Nutrients and oxygen are supplied to the soil and contaminated off-gases are captured and treated on site. Self-contained system makes it easier to manipulate and control thereby ensuring a higher level of treatment. | $20–$60 | 2–24 months | • inexpensive<br>• requires less space than land farming<br>• maximum control of treatment process<br>• closed system<br>• no containment discharge to atmosphere<br>• easy to monitor remediation progress | • no guarantee of treatment levels<br>• disruptive |
| **Landfill Disposal**<br>Contaminated soil is excavated and transported to an approved landfill site for disposal. | $40–$150 | 1–3 weeks | • fast<br>• eliminates contamination on site<br>• no long-term responsibility | • disruptive<br>• expensive<br>• does not treat the soil, but merely transfers the problem from one site to another |
| **Solidification/Stabilization**<br>Contaminants in the soil are immobilized by adding materials that either combine physically (solidification) or chemically (stabilization) with the contaminants to decrease their mobility. | $75–$200 | 1–6 months | • raw materials are inexpensive<br>• high degree of control | • relatively expensive<br>• affects future development of site<br>• long-term integrity of solidified material not well established |

monitoring program in order to capitalize on the opportunity to assess whether this technology was a cost-effective, environmentally benign method of remediating petroleum-contaminated soils; to assess the monitoring requirements needed to optimize natural biological degradation processes within the bioreactor; to validate the new federal guidelines on sampling, analysis, and data management (CCME 1993); to assess whether bioremediation can be successfully undertaken within a typical Canadian summer and to determine whether soil remediation is predominantly due to volatilization or biological degradation and whether temperature or nutrients are more important in the biological degradation process.

## BIOREACTOR DESIGN

### Bioreactor Construction

The bioremediation facility consisted of four rectangular bioreactor cells, each approximately 27 m long and 14 m wide. A longitudinal cross section through one of the bioreactors is shown in Figure 2.

Each bioreactor cell was 2 m high and contained approximately 450 $m^3$ of contaminated soil. The base of each cell sloped towards one end and was lined with an impermeable membrane. Rounded peastone material was placed on top of the liner to form a highly permeable subdrain. The peastone material was subsequently covered with a synthetic fabric.

Petroleum-contaminated soil was placed on top of the fabric in layers or lifts of approximately 0.3 m in thickness. After each lift, a nutrient solution was applied to the soil surface. The lift was lightly compacted to promote uniform density. After two successive lifts were in place, the lower tier of a unique two-tiered nutrient delivery system, which consisted of perforated tubing with pressure-compensating valves behind each perforation, was installed. The nutrient delivery system was designed to promote uniform moisture/nutrient application over the entire lift area.

After the third lift, or approximately mid-height, two active 100-mm diameter soil vapour extraction pipes and one passive 100-mm diameter air intake pipe were installed. The two soil vapour extraction pipes were connected to a central vacuum pump, while the passive intake pipe was left unconnected and temporarily capped.

Three more lifts of petroleum-contaminated soil were placed in each cell, attaining a total cell height of approximately 2 m. At the top of each cell, an upper nutrient delivery system, similar to the lower one, was added. Each cell was then covered with approximately 100 mm of straw and then draped with a black polyethylene vapour barrier. One of the four bioreactor cells was covered with a white membrane in an attempt to reduce solar heating in order to assess the effect of soil temperature on the rate of biological degradation.

### Design Objectives

The various components of the bioreactors were designed specifically to attain certain objectives. Some of the more significant components and their operating objectives are discussed below.

The nutrient delivery system permits the controlled application of inorganic nutrients and provides a means of maintaining optimum soil moisture content and pH for the hydrocarbon-degrading bacteria within the bioreactor cells.

The soil vapour extraction system provides a continuous source of oxygen to the bacteria by continuously replacing soil vapour with fresh oxygenated air. The contaminated soil vapours are directed to a central treatment facility, which consists of a moisture separator, a sand filter, and a series of granular activated carbon units. The volatile organic contaminants present within the vapours are adsorbed onto the carbon, and the treated vapours are discharged to the atmosphere.

The subdrain/leachate collection system at the base of each cell permits excess moisture to pass through the cell and collect in the frontal sump area. The water is then amended with nutrients and lime and recirculated through the cell from which it originated.

The layer of straw over the cell serves as insulation and allows air flow over the entire surface area of the pile, while the black vapour barrier minimizes volatile emissions and attracts solar radiation to promote soil heating.

### Construction Events

The design of the bioremediation facility was undertaken during the winter (January–February) of 1992. The original intent was to have the facility constructed during April or May 1992 and to operate it from May to October of the same year. Due to

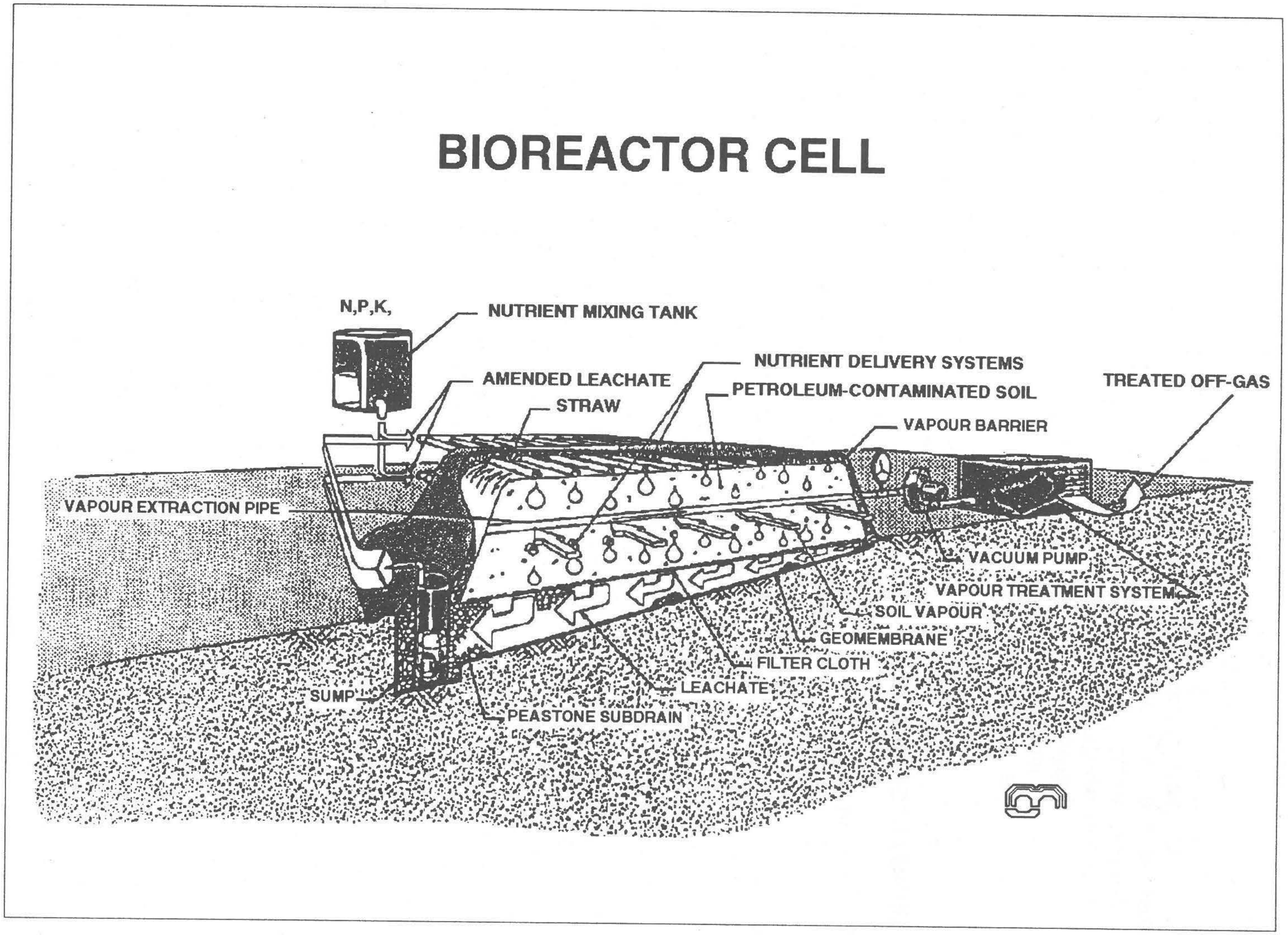

Figure 2. Longitudinal cross section through one of the four above-ground bioreactors.

construction delays, however, excavation and removal of the contaminated soil did not commence until July/August of 1992. The excavated soil material was transported approximately 2–3 km to an abandoned air field, where the bioremediation facility was to be constructed, and stockpiled with a covering of plastic membrane to minimize volatilization and surface water infiltration. It was placed in the prepared bioreactor cells in October, with completion at the end of November 1992 (Photo 1).

Because of the delay in completing the facility and the inefficiency of operating such a system during the cold winter months, it was decided to leave the system dormant over the winter months and to operate it from May to November 1993. An initial soil sampling event was, however, undertaken on November 27, 1992, to determine initial conditions.

## MONITORING PROGRAM

### Control/Treatment Cells

One of the objectives of this project was to assess whether temperature or nutrient amendments have the greater effect on the rate of petroleum biodegradation. The effect of oxygen on the rate of petroleum degradation was not explored as it has been well documented in the literature that oxygen is often a rate-limiting factor in biological degradation (Dupont et al. 1991; Floodgate 1973; Moulna and Grubbs 1990; Zoebel 1973). In order to assess the relative importance of temperature and/or nutrients, two of the four cells were randomly selected to serve as control/treatment cells.

Cell B was randomly selected as the control cell for nutrients. Aside from the initial application of nutrients during cell construction, no nutrient amendments were supplied to the cell throughout the six-month monitoring program. Lake water, however, was applied to cells at the same rate as the remaining three cells to maintain soil moisture levels.

Cell D was randomly selected as the low-temperature cell. In order to save costs, it was decided to proceed with a passive method of creating a temperature difference between cell D and the remaining three cells. For this purpose, a white 5-mm filter cloth material was placed over the cell in an attempt to reflect some solar radiation and hence reduce soil heating. Since the temperature was not controlled directly, the experimental design actually tested the hypothesis that a white covering would have an effect (through temperature) on biodegradation. All factors being equal, any differences in the rate of petroleum degradation between cells B and D and the remaining two cells could then be attributed to the effect of cell cover colour (temperature) and/or nutrient supplementation.

### Sampling Program

Due to the complex nature of biodegradation processes, an extensive monitoring program involving the collection and analysis of soil, water, and air samples was implemented. In addition, field measurements of soil conditions were also obtained.

Two composite soil samples from each bioreactor were collected weekly for the first four months of the monitoring program and every two weeks for the last two months. Water and air samples were collected every two weeks and analyzed for petrochemical constituents such as total petroleum hydrocarbons (TPH) and benzene, toluene, ethyl-benzene, and xylene (BTEX). In addition, nutrient concentrations were measured in all soil and water samples.

Field measurements were obtained more frequently by DND personnel and by representatives of Oliver, Mangione, McCalla & Associates Limited. Soil temperature, soil moisture, nutrient injection rate, air withdrawal rate, and soil vapour $O_2$/CO2 measurements were obtained twice weekly. A summary of the sampling and monitoring program is presented in Table 2.

## RESULTS

All of the field and analytical results obtained throughout the six-month monitoring program were compiled into tables and graphs. A few of the more significant trends are discussed below.

### Soil Temperatures

Four soil temperature measurements were obtained from each of the four cells frequently throughout the monitoring program. A graph of the mean soil temperature for each cell and the mean daily air temperature at CFB Petawawa is presented in Figure 3.

The soil temperature measurements show that the white covering placed over cell D to inhibit solar heating was not effective, as soil temperatures in cell D were not significantly different from the remaining three cells (Figure 3).

Photo 1. Bioremediation facility, CFB Petawawa.

Table 2. Summary of Sampling and Monitoring Program

A. Laboratory Samples

| Sample matrix | Sample location | Sample frequency | Analyses performed |
|---|---|---|---|
| Soil | · 6 random locations in each bioreactor (2 composite samples) | · weekly (May–Aug.)<br>· biweekly (Sept.–Nov.) | · TPH, N, P, K, pH, moisture content, total bacteria (May–Nov.)<br>· BTEX (May)<br>· Detailed microbiology (monthly, May–Nov.) |
| Water | · bioreactor sumps | · weekly (June–Aug.)<br>· biweekly (Sept.–Nov.) | · TPH, N, P, K, pH (May–Nov.) |
| Air | · at each bioreactor<br>· at central vapour treatment facility | · biweekly | · TPH (May–Nov.)<br>· BTEX (May–June) |

B. Field Measurements

| Sample matrix | Type of measurement | Measurement location | Measurement frequency |
|---|---|---|---|
| Soil | · soil temperature<br>· soil moisture (TDR) | · four random locations per bioreactor<br>· bioreactor cells A and C only | · twice weekly (May–Sept.)<br>· biweekly (June–Nov.) |
| Water | · flow rate - volume added to each bioreactor | · sump of each bioreactor<br>· upper and lower nutrient delivery system | · twice weekly (May-Sept.) |
| Air | · flow rate - volume extracted from each bioreactor<br>· soil vapour - $O_2/CO_2$ concentrations | · front and back of each bioreactor<br>· two repeated sampling locations per bioreactor | · twice weekly (May–Sept.)<br>· biweekly (June–Nov.) |

A strong positive correlation was found between mean daily air temperature and mean daily soil temperature. The strong correlation and the absence of any lag time suggest that the operation of the soil vapour extraction system, which promoted ambient air to circulate through the soil piles, had a controlling effect on soil temperatures.

No significant differences were observed between the soil temperature in cell B, which received no nutrient amendments, and the remaining three cells.

## Soil TPH Concentrations

The soil TPH concentrations obtained from each sampling event are shown in Figure 4 for all four cells. Each point on the graph is the mean of all measurements for a given cell and sampling session. It is apparent from the graph that a substantial degradation occurred in all four cells.

As can be observed in Figure 4, the variability and concentration levels in TPH measurements decreased drastically over time. The homogenization of the contaminant distribution is believed to be a combination of leaching effects from the moisture system and biological activity.

The amount of petroleum degradation observed in each of the four cells was calculated using the initial and final mean soil TPH concentrations for each cell. Based on these results, total petroleum hydrocarbons were reduced approximately 97% in the four cells.

The soil in all four cells was found to have final TPH concentrations well below the most stringent federal and/or provincial criteria of 40 mg/kg as demonstrated by the mean soil TPH concentration obtained during the final month of monitoring (November 1993). At the final measured concentrations (<10 mg/kg), the soil was considered decontaminated.

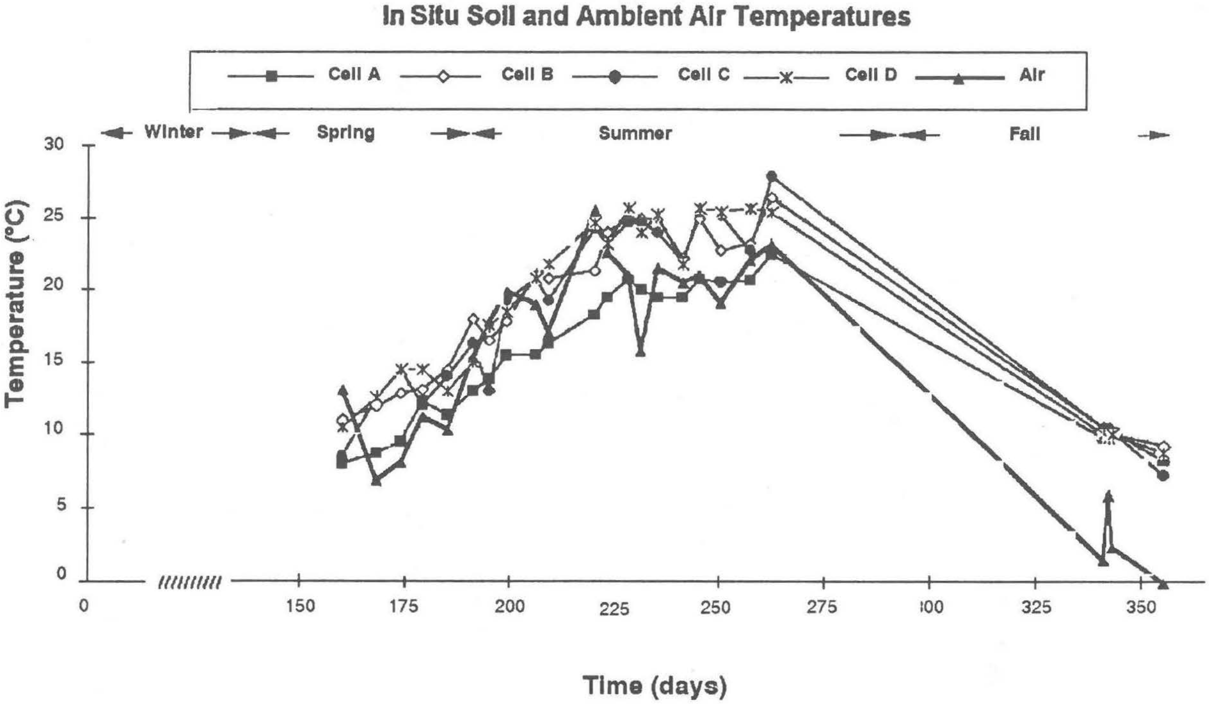

Figure 3. Comparison of in situ soil temperatures for cells A, B, C and D and ambient air temperatures.

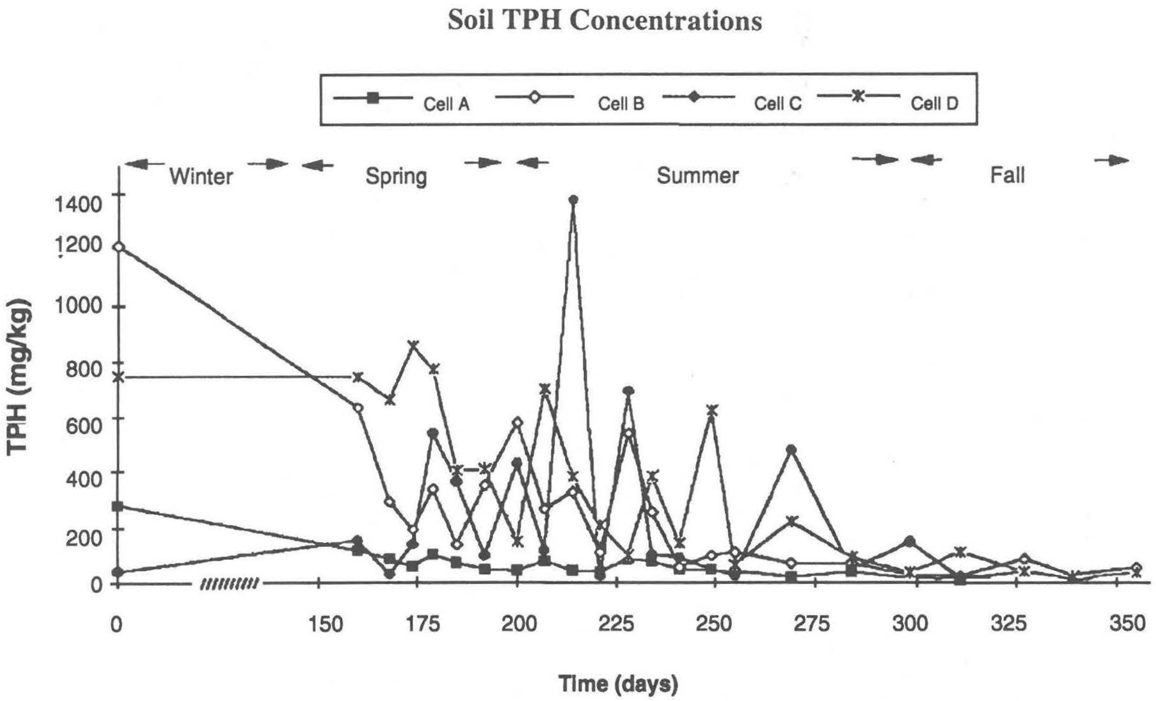

Figure 4. Mean soil TPH (total petroleum hydrocarbon) concentrations in cells A, B. C and D.

No significant differences in the rate of TPH degradation were observed between cell B (no nutrient amendments) and the remaining three cells.

### Microbiological Results

A detailed microbiological program was undertaken to monitor biological activity within the cells. The program involved enumerating total viable and probe-positive bacteria monthly and monitoring the mineralization activity of bacteria using radiolabelled petroleum products.

In general, the probe-positive bacteria counts (i.e., the portion of bacteria with the genetic potential to degrade hydrocarbons) were found to increase significantly with temperature for soil temperatures up to approximately 10°C and were not affected significantly by temperatures ranging between 10° and 26°C.

The effect of temperature on biological activity is not unusual. From a bioavailability point of view, as temperatures decrease, hydrocarbons—particularly the heavier aliphatic compounds—become more viscous and, as a result, are not as easily mobilized and hence mineralized by the bacteria (Greer and Beaumier 1994; Sims et al. 1989).

Based on the probe-positive trends observed in each of the four cells, no significant differences could be detected between the nutrient control cell (cell B) and the remaining three cells (i.e., cell B values were always within the range of the other cells).

### Biodegradation versus Volatilization

One of the objectives of this project was to attempt to quantify how much of the degradation could be attributed to biological processes (biodegradation) and how much was due to volatilization. In order to quantify the different processes, TPH mass balance calculations were performed.

The total initial mass of TPH in the contaminated soil was calculated to be approximately 1096 kg, while the remaining mass at the end of the six-month operating period was calculated to be approximately 30 kg. The resulting TPH reduction was 1066 kg or 97.4%.

Due to the self-contained nature of the bioreactor system, the reduction in TPH mass within the soil could have resulted from one of the following three processes:

(a) leaching of the hydrocarbons from possible biosolublization reactions;
(b) volatilization of the hydrocarbon components with relatively high vapour pressures; and/or
(c) biomineralization of the hydrocarbons into carbon dioxide and water (biodegradation).

The mass of TPH leached from the soil was calculated by analyzing the wastewater collected at the base of the bioreactor cells. The resulting mass of TPH that was leached from the soil was calculated to be approximately 0.008 kg.

The TPH mass loss due to volatilization was calculated using two different methods. The first method was based on calculating the TPH mass detected in the soil vapours extracted from each of the four cells. The second method was to simply measure the TPH mass adsorbed onto the activated carbon of the central soil vapour treatment facility. The resulting TPH mass that was lost due to volatilization was calculated to be approximately 5 kg or 0.5% of the total TPH mass (previously determined to be 1096 kg).

The reduction in TPH mass that can be attributed to biological degradation processes was calculated by subtracting the sum of TPH mass lost due to leaching and volatilization from the total reduction in TPH mass. The reduction in TPH mass attributable to biodegradation processes was calculated to be approximately 99% or 5.6 kg per day over the operating period of the bioreactors.

### Temperature versus Nutrients

Another objective of the project was to assess the effects of temperature and nutrients on the rate of biodegradation. The attempt to generate a temperature difference between the temperature control cell (cell D) and the remaining three cells was not successful due the relatively highair exchange rate (3–5 air-filled pore volumes/day). Nevertheless, the measured probe-positive bacteria counts were found to have a significant positive correlation with soil temperature for temperatures up to approximately 10°C.

Conversely, no significant differences in the rate of TPH degradation, mineralization activity, and/or population of probe-positive hydrocarbon-degrading bacteria were noted between the nutrient control cell (cell B) and the remaining three cells.

Based on the observed results, temperature appears to have been the more important of the two factors in the biodegradation process. These findings are consistent with recent work in similar bioremediation projects (Miller and Hinchee 1990; Miller et al. 1990).

## COST EFFECTIVENESS

The cost effectiveness of using an aboveground bioreactor technique to remediate petroleum-contaminated soils was examined and compared to other conventional soil remediation technologies (Table 1). Although the cost to design, construct, and monitor this particular bioremediation facility was in the range of \$70–\$90 per tonne of treated soil, this cost could be reduced to the range of \$20–\$40 per tonne with continued reuse of the facility and a less stringent monitoring/sampling program.

The extensive monitoring/sampling program that was performed throughout this project was purposely undertaken to assess the rate at which soil and bacteriological conditions changed within the bioreactors during operation. Based on the results obtained, it is recommended that future monitoring programs for similar bioremediation projects incorporate a much less stringent program, such as weekly site visits in the first month of operation, visits every two weeks for the next one or two months, and monthly visits thereafter. This sampling frequency would permit adequate monitoring of the biological degradation process occurring within the cells and would provide sufficient information with respect to soil conditions and the need for adjustments. With the implementation of such a monitoring/sampling program, coupled with the capability of reusing the bioreactors, the treatment cost for similar soils and contaminants could be reduced to the range of \$20–\$40 per tonne . At these costs, bioremediation in the form of aboveground bioreactors becomes one of the least expensive methods of remediating petroleum-contaminated soils.

## CONCLUSIONS

The favourable results obtained from this project clearly indicate that bioremediation of petroleum-contaminated soils can successfully be undertaken within a relatively short time frame (6 months or less). A review of available conventional soil remediation technologies suggests that aboveground bioremediation is the most, or one of the most, cost-effective technologies for treating petroleum-contaminated soils. This project has proven that bioremediation in the form of aboveground bioreactors can efficiently and effectively treat petroleum-contaminated soil to meet the most stringent federal and/or provincial criteria in a cost-effective manner within a typical Canadian summer. Furthermore, the end products of the biological degradation of petroleum hydrocarbons are carbon dioxide and water, both of which are innocuous. As a result, this technology can be considered as an environmentally friendly method of dealing with a potentially hazardous situation. The favourable results obtained on this project should encourage the widespread use of this technology. The general applicability of this technology includes military bases, large commercial complexes, and/or any other sites across Canada where time and space constraints are not a prime concern.

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