Cost – performance curves
to evaluate alternative remedial options before and during projects.

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Abstract.

In engineering projects the criteria safety and quality are paramount and cannot be compromised. These first two project standards are often followed by cost and delivery on time. Conflicting interests in these two important project parameters can make selection and tendering processes difficult for those owning or managing contaminated sites. What to do when there is a choice between projects with a long and often open timeframe at a possibly much lower cost when comparing these with a fast approach offered for a fixed price? When considering a consent application which other criteria are relevant?

This paper discusses the use of cost – performance curves to allow evaluation of several remedial options. They can be used prior to project commencement or during projects when the implemented technique has lost it's effectiveness. Remedial techniques used in cost – performance evaluations have to be robust and a number of pre-requisites have to be met. Criteria are given to ensure all contesting techniques pass required benchmarks relating to safety, quality and certainty of costing, time requirements and delivery of required results. In environmental projects the criteria sustainability and social acceptability gain in importance, so they need to be evaluated for long-term projects.

Four case studies will be presented. The first will focus on hotspot treatment with assisted monitored natural attenuation (MNA). Design parameters will be discussed as well as methods for evaluating the cost-effectiveness of changing to a more active in situ remediation. The next case will focus on a flexible emission control approach. An example of application is given for an on-site capping of Arsenic and POP's contaminated soil with some unexpected problems. In the third case the use of cost-performance curves is discussed to evaluate three remedial solutions for a complex contamination of chlorinated solvents. The last case deals with the evaluation of two active in situ remediation systems against using a low energy input system.

Introduction

In any engineering project safety and quality are the primary criteria. The third factor of importance in environmental engineering in New Zealand is for territorial authorities human health and for regional authorities the health of natural ecosystems. In the practice of site remediation the costs of the proposed solution is a close second to these primary criteria. Surprisingly the total costs for these often quite expensive projects are at times poorly evaluated against the required outcomes. Even the outcome is often poorly defined and side effects during of after the remediation are often ignored. In small projects of minor importance this may lead to substandard completion or trouble for future site owners, however is mostly left un-addressed. For large prestigious projects poor preparation often leads to massive overspending, numerous re-evaluations, re-contracting, finding black sheep and enough evaluation reports to bury the original intentions of the project. This may sound exaggerated, however there are countless examples worldwide.

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Cost-performance curves provide an ideal management tool which can be used prior or during any remediation project. The basis of any remediation is the removal of contaminants. When the site assessment has been carried out properly the total mass of contaminants can be determined. A cost – performance curve describes is the cost to remove each kilogram of contaminants or the change of costs in time. This enables evaluation of alternatives.

Let's look at an example in its simplest form: When a 200 litre container of herbicide is driven over by a tractor the remediation may involve only the immediate mopping up the liquid followed by scooping up of about 1 - 2 ton of soil in which the herbicide is contained. Immediate remediation cost will consist of:

- time of the farmer to load all contaminated materials and soil on a trailer
- time and cost to transport the soil to the landfill / transfer station
- tipping fees

When decision is made to delay the clean-up the hotspot may feature in a future site assessment. The additional costs at that time to clean up the spill consists of:

- further investigation costs of consultant to delineate the hotspot
- laboratory analysis
- more soil may be in need of excavation as the herbicide has migrated outwards
- council(s) get involved (cost of council time (internal, external)
- cost of consent
- cost of contractor to excavate all contaminated soil
- time and cost to transport the soil to the landfill
- tipping fees
- consulting fees for managing the remediation process and
- groundwater may become affected, leading to a required risk assessment or a groundwater remediation followed by a evaluation / verification.

It is important to note that the additional costs also apply when during the first emergency excavation not all contaminants were removed and were subsequently found as a hotspot during a (pre-sale) site assessment. Clearly it would be penny-wise and pound-foolish to excavate too little during the initial emergency response clean-up.

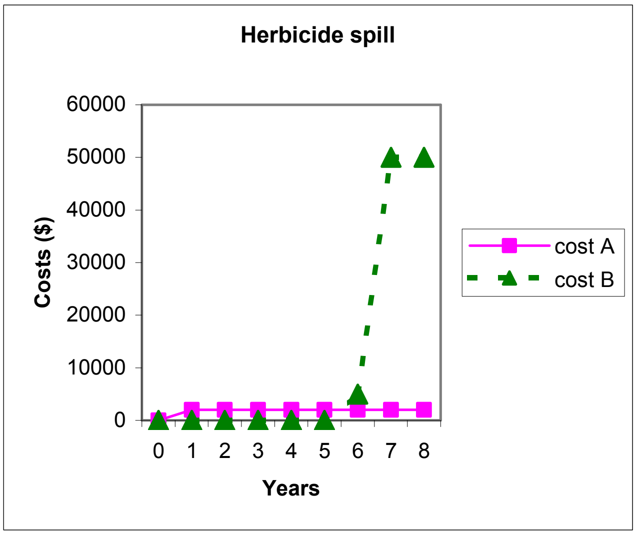

Figure 1
The cost benefit of immediate remediation (cost graph A) is easy to see for everyone. To evaluate several remedial approaches for a historic contamination the costs are often more similar. For these cases the estimation of costs for each part of the work has to be determined accurately.

It is also important to ensure all data on which the cost estimates will be made are accurate. This is hampered by the intrinsic uncertainties present in the base data.

In the next chapter we will look closer at these uncertainties.

The uncertainties

Determining the costs of a site remediation requires insight in the uncertainties in the base data. There are four main categories of uncertainties:

A Uncertainties in the initial conditions:

Often the horizontal delineation is reasonably mapped, even though within the concentration contour lines the illusion is given that the contamination is homogeneous and gradually increasing towards the single source. This assumption appears in practice often untrue: often multiple sources are present. The contours are just the superposition of the contours of all individual plumes. Unfortunately these individual hotspots and associated plumes frequently have different characteristics. This is not only due to different chemicals entering the soil, but more often caused by a different age of the hotspots. Due to natural bioremediation the composition has changed and the older a hotspot is the more its composition will have altered from the initial composition. Even on site with assumed homogeneous, diffuse contamination like orchards many hotspots can be identified, such as: leak point from the pesticide hydrant system, places where the old spray wagons got stuck and were emptied out, high lead from paint off glasshouses / sheds, fill points of spray equipment (often near water wells), old fuel tanks above or below ground, etc. In many reports these hotspot are not only missed, however; it is not even mentioned that undiscovered hotspots may be present. This leads to an unrealistic feeling of certainty.

Much worse is the delineation vertically. Very often there are none or just a few vertical transects and if they are present in the reports the number of sample points at depth is often very limited. In addition often no correlation between specific soil or hydrogeological layers and the type of contamination is made. In addition many samples do not represent the correct concentration at specific depths due to cross contamination during drilling, groundwater samples are more often then not taken from too long screened intervals of monitoring wells and leaky clay plugs above or below the screened sections add to the dilution. Of many layers important information is missing, such as:

a. Vertical permeability of semi- confining layers;
b. Permeability for water and air of aquifers as well as for the aquicludes;
c. The actual retardation coefficient of key-contaminants of interest, their breakdown intermediates and
d. The retardation coefficient the compounds likely to be used during the remedial stage.

Even basic parameters like the organic matter and clay content (important to the leaching of contaminants like Arsenic), redox potential and likely changes, natural electron acceptors or donors, substances competing with the contamination like dissolved / total organic carbon (DOC/TOC) and humic acids (old and young) or aspects such as bound residue, seasonal fluctuations in groundwater flow direction, historical variations of groundwater, etc. are all too often absent in site assessment reports.

B Uncertainties pertaining the effect of the chosen remedial technique:

Technical tests to select the correct remedial techniques are often not carried out. Frequently the selection procedure was limited to a desk study. With the excuse of no time or money lots of assumptions are made instead of the performance of several simple lab or field tests to determine for example:

- Breakdown speed (half-life time),

- The natural or enhanced breakdown potential,
- Leaching / migration potential (current, during and after remedial action)
- Lowest possible attainable concentration by mixing or remediation,
- Radius of influence of injection or extraction wells in their specific layers.

Obviously the application of the chosen remedial technique is purely a gamble (some call it an educated guess) when results of these tests are not available. Still very often one may find tenders for 'turn-key' or 'design and construct' remediation projects where non of these data are made available to the bidding parties. It then becomes a matter of taking risks and trusting on the capacity of ones lawyers when sending or accepting a (low) bid.

C Uncertainty of the quality of implementation of the remediation

The quality of a remedial project is not so much dependent on the choice of technique. Often different techniques can result in similar end results. When aiming for quality the focus should be more on the way the systems are implemented and controlled. The eagerness to apply the newest technology often leads to neglecting some of the more important, however, often less glamorous aspects like the underground configuration that should:

- Take into account the soil characteristics and stratigraphy;
- Take into account the permeability differences both horizontally and vertically;
- Ensure the heterogeneity works in the advantage of the applied technique and not against it.

Combined with the quality of the implementation methods will finally determine the end result. Implementing adequate monitoring procedures can reduce the uncertainty about the quality of the remediation. It also ensures sufficient quality data to base the cost – performance (CP) curves on. This in turn enables quality decision-making.

Quality monitoring will consist of four groups of monitoring. Each is essential to update the CP curves at anytime during the project:

Monitoring not geared to keep eye on cost per kg removed
Generally in well-engineered projects verification is an ongoing effort. Verification is then part of an ongoing monitoring program. In situ remediation needs four types of monitoring:

1. System monitoring This registers if the remedial system is operational. It stores records of pump operating times, the periods the valves are open or closed and can be crosschecked against the energy consumption of the unit. Often this is the minimum requirement of the regulators who like to know: does the system operate? For our CP curves it provides part of the cost input.

2. Process monitoring This is a more involved type of monitoring. Flow rates, concentration of fluids to be injected, pressures, temperatures, etc. may all be recorded. Also environmental factors like emissions, discharge concentrations etc. can be grouped in this type of monitoring. It is important for the contractor to prove later on that his remediation system has operated according to the design specifications.

3. Effect monitoring Monitoring the effect of the remediation system is the core of the monitoring process. For example when lab tests have shown that the contamination will be biodegraded to CO_2 and water as long as the circumstances are aerobic, then monitoring dissolved oxygen (the 'effect' of the remedial system) will tell whether the biodegradation is likely to occur in situ as well. It will also indicate whether the site will be clean in several years. Other parameters in this group are CO_2, in situ pressure differentials, conductivity, redox, temperature, DO, COD, nitrate, Fe, etc. Sensors can determine most of these. Coupling these to the control system of the remediation unit makes it possible to regulate the remediation system automatically. This was first done in Holland in 1996 by the IHRIS™ system. For the CP curves it provides part of the performance data (kg removed / broken down).

4. Verification monitoring In contrast to the former three this type of monitoring has to be carried out by a complete independent party. Preferably directly for the regulator (like in Luxembourg). Definitely not by the contractor nor by the consultant who designed the remedial system.

Verification monitoring is aimed at checking whether the remedial project is reaching its goals or not. It is a convenient way to determine if certain milestones are reached (for example 50 % of contaminant mass removed, or residual concentrations exceed desired concentrations by 20 %. Project payments may be linked to the results of verification monitoring. This also applies to permeable barriers: the payment is depending on the downstream concentrations meeting the required level. Outcomes of this monitoring complete the ‘performance’ input for the CP curves.

At potential MNA sites a verification monitoring system may be in place before remedial systems are added. When in time it becomes clear that natural remediation is effectively controlling migration and / or is reducing the contaminant levels further action may not be required. When many sites need monitoring e-sensors that generate an SMS message on a weekly basis is a way to reduce monitoring costs, while site data are instantly available to multiple parties.

D Other technical uncertainties

Site and soil conditions are often changed during and after remediation. Dewatering before excavation may oxidise sulphites and create acid soils / groundwater. On-site burial of contaminated soil may change the redox conditions increasing mobility of the contaminants. Secondary effects such as soil heating may also create unexpected mobility, vapour or dust problems. As the number of remedial technologies expands so does the list of uncertainties. Quite some remedial techniques leave unwanted residues, wells, cables, chemicals, changed soil conditions etc., which have been poorly considered, before the start of the project. The long term effects are often unknown, however after the main contaminant has been removed often not an immediate concern, until………

E Contractual uncertainties

Most contractual uncertainties arise from poorly defined remediation goals[2], which include not only the verification levels or residual risk levels and final sampling methodology, but also the definitions of the deliverables, in- and exclusions, ownership of any remaining equipment and of intellectual property developed for the client. Often a remediation is considered completed when the site is clean, however on large sites invariably some sections will be completed ahead of schedule and others at much later dates. Remediation contracts should cater for this and include bonus and penalty schedules. Too often project accounting

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[2] Managing Contaminated Sites in Europe from a Dutch Perspective; Moving from Selling Certainties to Managing Uncertainties, Keet, B. (2003), Keynote Paper Contaminated Sites Session, WasteMINZ conference 2003, Nelson New Zealand.

is only carried out in the (historic) recording mode. A case is made here to account pro-actively.

Case 1 Midpoint evaluation

Making decisions based on cost effectiveness of a proposed remediation solution is very difficult in practice. Often lots of data is unavailable and the ones which are, may be of dubious quality. To demonstrate the decision-making process based on cost-performance curves during the second year of a remediation project a simple and small project is chosen. The following case is typical of many small remediation projects: it started with a number of emergency actions after a spill of diesel was noticed in 1997. Oil was being observed oozing from a bank into the nearby creek.

The recent contamination is situated partly below a glasshouse in which robotic cars drive around day and night to deliver flowers from the picking areas to the packing hall. The diesel had leaked from a pipeline running close to the building. The foundation of the building is only 50 cm deep and placed directly on the sandy subsoil. Due to minor subsidence and the proximity of the foundation at the same depth a coupling had broken. The top 3 meters of soil is humus rich medium fine sands. The water table is only 1 meter below the surface.
The contamination had not penetrated deeper then 2 meters.

In an initial attempt to clean up the spilled oil as much as possible, the pipeline was dug up and all contaminated soil outside the building was excavated and disposed of off-site.
As diesel appeared to continue to run back into the excavation it was decided to place a drain in the excavation and to backfill with gravel. A small pump was installed and an oil/water separator placed. The effluent (only 20 ltr/hr) was discharged directly into the sewer.

The mass of contaminant removed is listed in table 1 below. The values up to May 1998 are actual, the remainder are guestimates. This scenario of possible steps in the remediation project is labelled scenario 0. In this scenario the extraction of groundwater was to continue for 4 years after which the situation would be evaluated and possibly the remainder excavated.

The costs of the various remedial steps is given in table 1 as well as the relative remediation costs in $/kg contaminant removed.

Remedial phase	**Kg oil removed**	**Remedial costs $**	**Kg oil/1000 $**	**$/kg oil**
1. Excavation	1700 - 2200	80.000	21 - 27	37 - 48
2. Remove fee oil layer with drain	488	19.000	26	38
3. Year 98-99	100	12.317	8,1	123
4. Year 99-01	80	9577	8,6	116
5. Year 01-02	60	7152	8,3	120
6. Year 02-03	40	7152	5,5	181
Phases 1 t/m 6	2468 - 2968	135.198	18,3	55
Excavate remainder in future *	1032	20.000	50	20
TOTAL	3500 - 4000	155.198	22,6 - 25,8	39 - 44

Table 1: Summary of remediation costs Scenario 0: (continue current situation)

* excavation during future building expansion: only the extra cost for soil replacement inserted.

After 1 year the free oil production fell dramatically and so did the contaminant mass removal. The regulatory authority demanded the site owner to intensify the remediation to remove the remaining 30 – 50 % of the contaminant mass and to evaluate the risk of any contaminants remaining. In addition several remedial scenario's had to be worked out to evaluate the effectiveness of alternative remedial methods over a period of 4 years. Several proposals were requested from in situ remediation contractors. Three were selected for this evaluation:

Scenario I	Maintain extraction and o/w separator and add biosparging
Scenario II	Biosparging only with passive oil removal in extraction well using oil absorbing materials (manual replacement during site visits)
Scenario III	Maintain extraction and inject mobiliser solution around contaminated zone, add water treatment unit after o/w separator

This resulted in a prognosis of costs and efficiency as is summarized in figures 2, 3 and 4.

It should be noted that no allowance has been made for the cost of money so effectively the interest rate is set at zero. During periods with high interest rates scenario's with low upfront costs can be more favourable compared to multi-year project of equal annual costs.

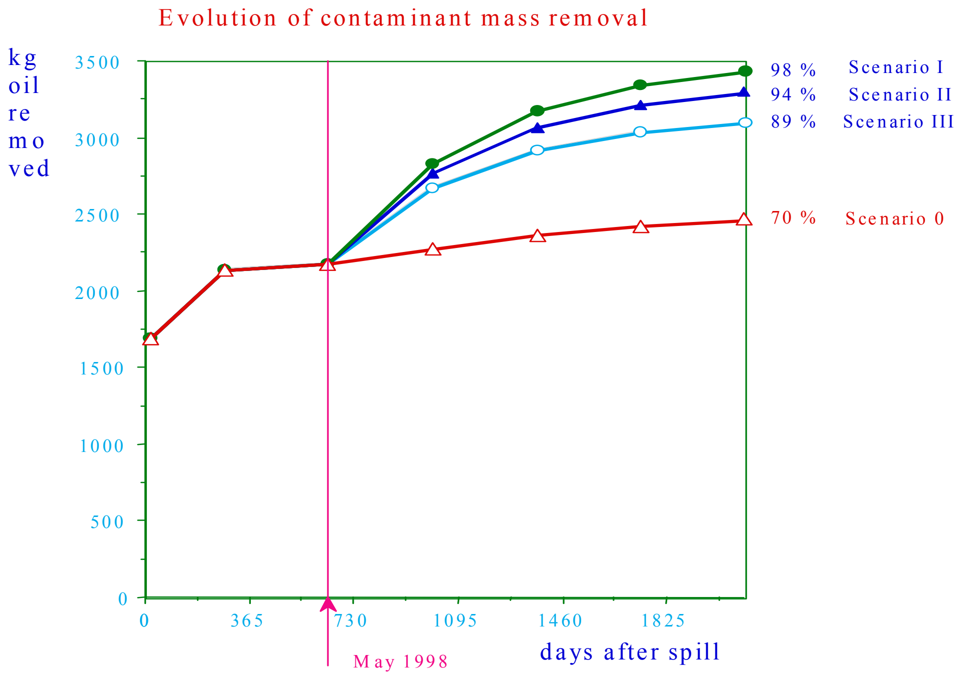

Figure 2[3] shows the forecast of the evolution of contaminant mass removal in time. Clearly the continued extraction with added biosparging will yield the highest contaminant mass removal. Scenario II and III are also far more effective in removing the oil compared to the Scenario 0, the continuation of the extraction system and the o/w separator.

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[3] Acknowledgement: Cost – performance curves of Case 1 were developed for project 'Bleiswijk' in The Netherlands, in which was carried out collaboration with Ir. K. Verschueren.

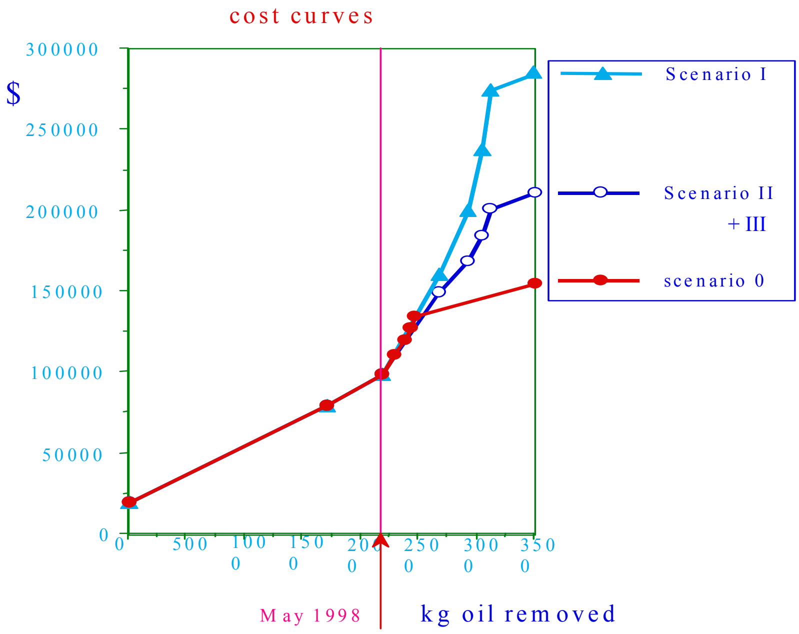

Figure 3 displays the evolution of remedial costs in time. Clearly adding extra systems dramatically increases the costs in the first year due to systems installation cost. For the expected short duration of the project the lower costs over the following years does not make up for this initial outlay.

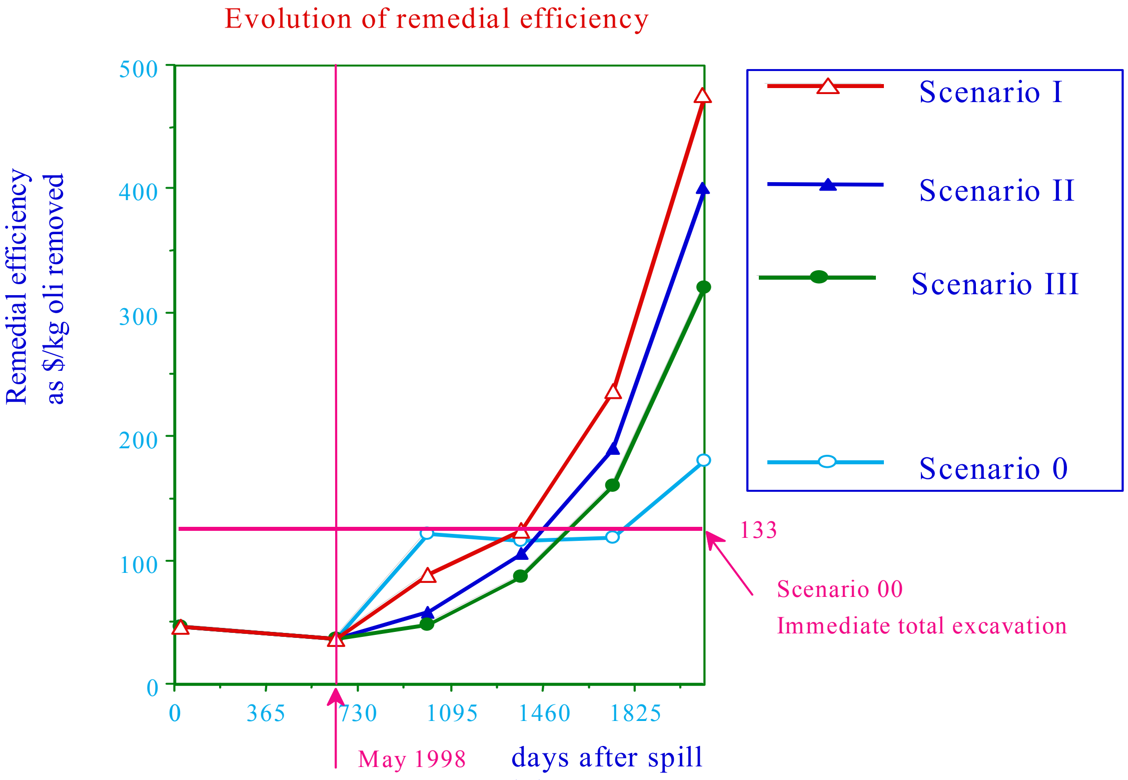

Figure 4 shows the evolution of the remedial efficiency of several alternative in situ options. For each the remedial efficiency is expressed in $/kg oil removed. Added in this figure is the remedial efficiency of immediate excavation. The regulators did not require this as the risk of exposure or migration was very limited.

On the basis of this remedial efficiency graph the authorities agreed to continue with scenario 0 until the curve would bend too much upward (i.e. when the amount of oil removed becomes negligible.

Conclusion

This case is typical in that the least expected solution was chosen. With hindsight it is clear that immediate excavation would have been the cheapest and therefore have the highest efficiency.

The in situ techniques are all too expensive, which is mostly caused by the high monitoring costs which bear heavy on such a small project. Environmentally they would have delivered a better product. The extensive monitoring requirement was mainly due to uncertainty about the methods at the regulatory authorities at the time.

The efficiency of the immediate excavation is compromised by the serious disruption of the site, extra costs and loss of resources as the building had to be partly demolished and re-build. So even in hindsight not the best solution.

The winner was the most basic technique available: dig what is easy and pump a little to control migration and take some oil out. As there is not a lot to monitor these costs are also relative low. It is however good to realize that by ending the remediation ‘when the efficiency-curve becomes too steep the remaining 30 % of contamination is left behind.
The authorities agreed in this case as the fairly non-toxic contamination is situated below an industrial building. The remaining risk is therefore low.

Post project note

A number of years after this project was completed it was revisited. For reasons unknown the pump was never turned off, however virtually no oil was present in the oil / water separator. A few water samples taken from the pump outlet and 1 monitoring well just outside the spill area showed full depletion of nitrates, increased iron levels and reduced concentration of sulphates in the extracted water, a clear indication of natural degradation at work. So effectively the slow extraction rate had caused the inflow of natural electron acceptors into the spill area, effectively cleaning it up at possibly a similar speed as an assisted in situ bioremediation method would have done.

Case 2 Evaluating side effect treatment: Old orchard / sheep-dip soil

Orchard and sheep-dip soil is often contaminated with heavy metals and persistent organic pollutants (POP’s). Often Arsenic is the most wide spread and commonly the main element of concern. Fortunately rapid field screening methods for Arsenic are available allowing site assessment work to be done with greater precision, less change on missing hotspots and lower costs.

At an 8 ha subdivision in Hawkes Bay the soil is contaminated with Arsenic, Lead, Copper and DDT[4]. The soil sample most contaminated with DDT reported in the three site assessment reports had a concentration of about 8 mg/kg d.m or only 1/3rd the guideline

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[4] This case has been modified from the ‘real’ project for educational purposes.

value[5] for residential development. DDT was therefore considered not a contaminant of concern. Similarly none of the Copper concentrations was over 1/10th of the guideline value of 2.300 mg/kg d.m..
Lead was found over this guideline value of 400 mg/kg d.m. only at the positions of an old implement shed and the old glasshouse and was likely paint related. Arsenic was higher then the guideline value of 30 mg/kg d.m. at 48 of the proposed 60 lots.

Given the low natural background levels for Arsenic of 6 – 8 mg/kg d.m., lots with As levels up to 45 mg/kg d.m. in the top 300 mm could be mixed with soil from lots with low levels of Arsenic (up to 15 mg/kg d.m.). The lots with concentrations up to 30 mg/kg d.m. were left untouched. This left 14 lots of a total of 15.000 square meters where the top 400 mm had concentrations over 45 mg/kg d.m., which was considered not mixable with other topsoil only. Some of this soil with As concentrations lower the 90 mg/kg d.m. could be used in road berms, however; for most of this 6000 m3 of soil the following options were evaluated:

1. off site burial (landfill)
2. on-site burial in small reserve as part of residential development
3. deep mixing

ad. 1 The local landfill is able to accept the contaminated soil, however will charge $ 66.-/ton of soil. Combined with transport and buying replacement soil the cost comes close to $ 100.-/ ton.

ad. 2 Discussion with the Territorial Authority resulted in a decision from the council that soil having Arsenic levels up to 180 mg/kg d.m. could be disposed in deep pits dug on a section of the site, which was designated reserve. This highly contaminated soil needs to be capped with at least 500 mm of soil having Arsenic concentrations less then 90 mg/kg d.m. The on-site soil burial required some off-site disposal of sub-soil however this could be sold as fill. The resulting on-site disposal cost was calculated to be $ 28.-/ ton.

ad. 3 Deep mixing of the soil to a depth of approximately 1 m is only viable in the garden areas of a site. The mixing can be done on a heap using scrapers and rotary hoes and the resulting soil backfilled. The areas available were strips of back sections where lots were side by side. At 1 meter depth there was sufficient area to accommodate the soil volume. Mixing topsoil with subsoil to lower concentration down to below 30 mg/kg d.m. required creating a mixing pile of over 1.5 meter high twice, each time with 16 passes of the road works-sized rotary how. Including deposition and mild compaction in the designated garden areas the cost came to $ 45.-/ ton.

Option 3 had additional hidden cost as the ‘no-build’ designated garden area focussed attention of prospective buyers to the former contamination status of the property, thereby lowering the property prices.

Option 2, being the most economic was chosen and implemented. At the time of digging the burial pits some rain seemed to fill the pits so this water was pumped out prior to disposal of the contaminated soil that was compacted using a vibrating plate on the excavator arm.

About a year after the development was completed routine monitoring of groundwater revealed high Arsenic levels next to the road close to the reserve area of the development. The Regional Council further investigated this and subsequently the source of the high

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[5] The guideline value for DDT in Plan Change 28 of the Hastings District Council is set at 25 mg/kg d.m. ref.: http://www.hastingsdc.govt.nz/planchanges/28/index.htm and http://www.hastingsdc.govt.nz/environment/pesticides/index.htm and TRIM reference: STR-7-03-04-17

Arsenic levels was traced back to the on-site burial pits. Natural groundwater level fluctuated between 1 and 1.5 m, leaving well over 3 meters of contaminated soil below the groundwater table. Being old topsoil the organic matter contents was quite high so the conditions below groundwater quickly turned anaerobic. Under these conditions the Arsenic was mobilised and was migrating off-site.

The reserve was now owned by the Territorial Authority who became owner of this section together with the road reserve. Being locked in by residential properties the re-excavation and disposal on the landfill was going to cost well over the original cost for this option of $ 100.- /ton. With 6000 tonnes of actively leaching contaminated soil the search for a solution became urgent. There were three options available:

1. Install a groundwater extraction system with an iron based treatment plant[6]. After the initial outlay of $ 90.000.- the annual monitoring and maintenance bill was estimated to be $ 8000.-.
2. Install a groundwater extraction system and dispose of water to sewer. Initial outlay reduced to $ 30.000.- with annual maintenance and disposal costs of $ 2000.-
3. It seemed possible the dissolved Arsenic compounds would re-adsorb downstream where the strictly anaerobic water leaching from the fill would mix with the natural slightly aerobic groundwater. To limit the outflow from the pit area the area could be capped at a cost of $ 10.000.- and to observe the effect 3 pairs of monitoring wells were installed downstream for an additional $ 6000.- with annual monitoring costs of $ 3000.-

In figure 5 below it is clear the option which allows some controlled emission of Arsenic is the most economic in the short term. When adding the cost of money (interest rates not zero) it may remain the cheapest. However given the current assumptions the option extraction and disposal to sewer is the most economic in the long term.

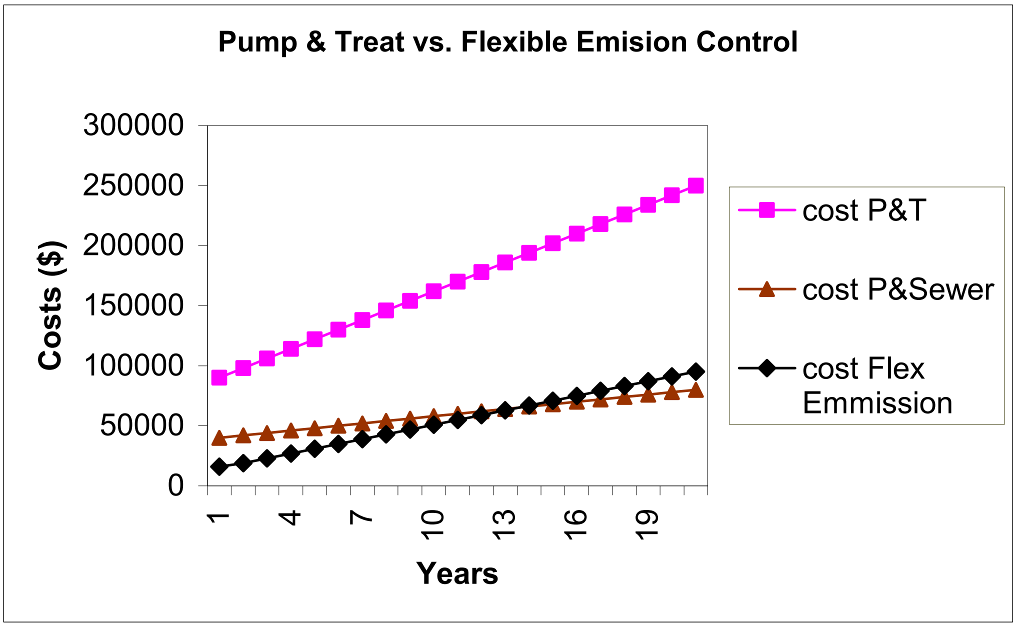

Figure 5 Additional costs for future owner of the small reserve with buried As – POP's soil

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[6] An alternative is a treatment system based on SAMMS, or Self-Assembled Monolayers on Mesoporous Supports, is a technology that can be tailored to selectively remove metal contaminants without creating hazardous waste or by-products, ref.: Battelle / PNNL in Technology : May 23, 2006 (www.archive.physics.com/23/05/2006, alert via: http://tech.groups.yahoo.com/group/tracenz/)

Discussion

When flexible emission monitoring has been carried out for some years the frequency of monitoring can be reduced, which greatly influences the costs. The loading up of the sewer system with a constant base-flow is not a sustainable engineering solution. Neither was the Zero-scenario of re-excavating all the soil and disposal at a landfill, as the total cost would have been close to $ 750.000.-.

It should be noted that the assumption has been made that the Arsenic will re-adsorb, that no downstream use of the groundwater is being made and that no leakage of Arsenic contaminated groundwater to a deeper (and more anaerobic) aquifer will take place.

Case 3 Using cost performance curves before project start.

The small building of a former dry-cleaning business has been sold recently and will be refurbished to house a trendy café. During the sewer works an odd smell is noticed. A soil sample send off for urgent analysis reveals high levels of chlorinated solvents. Apparently the solvent had dissolved the rubber seals of the concrete sewer-line and leaked out into the soil. An environmental assessment was started. The initial findings were contradictory; the concentrations reduced with increasing distance from the building and in depth, however at a certain point they increased. The deeper samples taken at several meters below the water table even became almost saturated with the solvent. The samples taken further down the street indicated several other leak-points from the sewer line. After the third round of investigation the contaminated area, originating at a small shop with a frontage of only 7 m wide, had grown to 80 m along the street, following the sewer line, and reaching the underlying clay layer at 14 meter depth at many points along the way. When the groundwater investigation was complete the plume appeared to pass under the buildings of 4 streets running parallel to the street of the former dry cleaning shop, or approx. 350 m.

The chlorinated solvent used at the dry cleaning shop had been mainly tetrachloroethylene that has a specific gravity of 1.6 kg/ltr and a solubility of 150 mg/ltr. In soil under anaerobic conditions the Tetra will slowly dechlorinate to trichloroethylene (Tri), and further to cis-dichloroethylene (Cis) to vinylchloride (VC) and loosing it's last chlorine atom to become ethylene.

The environmental hazard arises from this natural breakdown. With the loss of each chlorine atom the chlorinated compound becomes more toxic. This culminates in VC, which is a known carcinogen. To make things worse: VC is a gas and although very soluble (1100 mg/ltr at 25 ^{o}C) it accumulates as each dechlorination step under similar conditions takes longer, with the last step, degradation to ethylene / ethene taking much longer then the other steps.

To remediate such a large plume in a build up inner city area is a complex task, however even the basic decision of selecting the correct remedial technique is far from straightforward. Due to the high coefficient of Henry for Tetra ($H = 0.3$ at 10 ^{o}C) which means about 30% of the Tetra will partition into the air phase at the air – water interface, air-stripping would be quite efficient as remedial technology. The Henry coefficient of Tri is in the same order of magnitude (0.2 at 10 ^{o}C), however Cis will strip less easy from water at an H of 0.07 at 10 ^{o}C. VC however being a gas strips quite easy with an H of about 0.4 at 10 ^{o}C. So dependent on the progression of the natural degradation and the formation of Cis, the air-stripping / airsparging option could be viable (see figure 5, the 10% option).

However stripping brings the contaminants to the unsaturated zone, and thus within reach of basements and sub-floor spaces of the buildings. From there it will migrate into the buildings through the chimney effect. Stripping the contaminants using an airsparging method can only be safely carried out when a negative air pressure can be created in the soil just below the buildings, using a soil vapour extraction (SVE) installation. An advantage of using the airsparging (AS) – SVE technique is the accountability of the process as the mass of extracted chlorinated compounds can measured. The AS – SVE technique can be accelerated when the soil is heated, either with steam or some form of electrical heating (electrokinetics, six-phase heating, etc.). These are not taken into account in

An alternative is to avoid the natural step-wise degradation by introducing bacteria which undertake the dechlorination as one process. The Dehalococcoides ethenoges strain 195 bacteria[7] achieves this, however is seldom encountered in natural soil. One way to introduce the bacteria is to multiply them in an above ground bioreactor. To actually modify the indigenous bacterium consortium with the new introduced species requires a significant and for some time continuous infiltration of bacteria rich water. For this purpose the above ground bioreactor is designed to 'leak' bacteria into the outflow, which is infiltrated into the ground. The system needs careful tuning to avoid clogging of the soil and the whole system needs to be kept strictly anaerobic. The advantage is that once the bacteria are fully introduced into the subsoil system sub-soil system simple addition of an organic carbon source will maintain the introduced bacterial population and they will eventually eat most of the chlorinated compounds away. During the introduction phase the breakdown intermediaries are flushed out of the soil and degraded in the aboveground bioreactor. As the biological system will handle future dissolution of possible free phase DNAPL's in the soil profile it can be expected to leave the least residue (option 5% in figure 5). It is however a very expensive operation, and the introduction phase may take many years to complete, with decennia of further remedial efforts. When a lot of free phase DNAPL's are present a pre-treatment using a thermal technology or a multi phase recovery technique may precede the biological treatment.

The simplest, most conventional and least effective, however also least expensive remedial technique is pump and treat (P&T). When natural degradation has converted the majority of the chlorinated solvents to VC, P&T may be very effective due to the high solubility of VC. Above ground VC can be removed using a stripping tower and collected on Activated Carbon or polymerised into PVC using UV light. Any pockets of free phase DNAPL's will be left behind and will cause the tail of the project to become very drawn out. In figure 5 the P&T option has been given a removal efficiency of 70% (30% remaining) at the lowest costs.

Making a choice between these remediation techniques requires far more knowledge then only a full site assessment report and extensive insight in to the remedial technology. For each it is important to go through lab- and pilot testing to determine the effectiveness. With this information cost – performance or efficiency curves can be made. One outcome of lab- and pilot tests can be the removal efficiency of the applied technique. This can be plotted against expected costs. An argument can then be made to favour one of the remedial solutions. In this example all techniques lead to site remediation and cheaper techniques can have the same removal efficiencies. Which technique to apply will be very site specific? However there is another use for plotting the efficiency against the costs. The use of the efficiency curve is a good tool in to build arguments to aim for a certain removal percentage. Looking at this before the project has started, and before the technique is chosen, clarifies the need for accurate information. Using a cost – performance curve can indicate the need for further pilot testing or even make clear the remediation, as proposed in not viable (in simple

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[7] MaymoGatell, X., Chien, Y.T., Gossett, J.M., and Zinder, S.H., 1997. Isolation of a bacterium that reductively dechlorinates tetrachloroethene to ethene. Science, 276(5318): 1568-1571.

terms: a waste of money as the remaining contaminant concentrations will be significant). The contractual use of cost – performance curves is to introduce milestones in a remedial contract that are clear to all involved.

In figure 5 all curves start with the initial site costs, mobilisation of the installation etc. After this follows a period of very effective remediation, as all selected methods will work best when concentrations are high. There are no economic reasons to end a remediation when it progresses nearly horizontally along the curve (between points 0 and 1) as relative small incremental costs lead to large results.

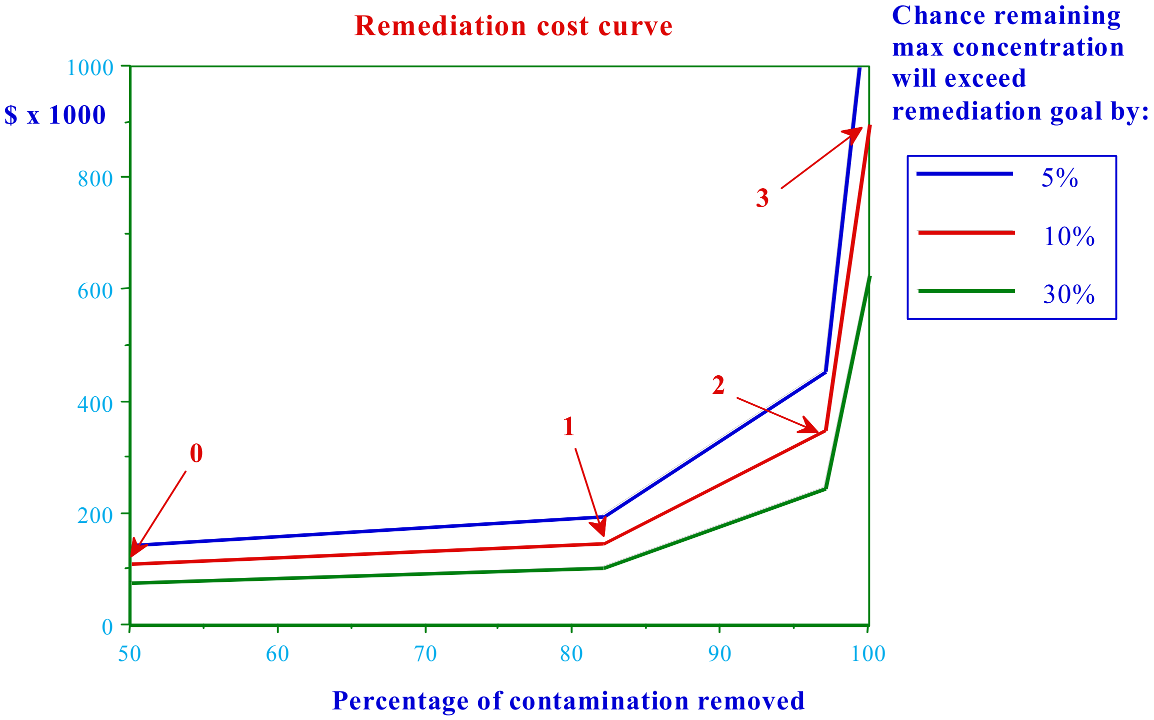

Figure 5

Clearly when the project enters the third phase and follows the vertical curve (between points 2 and 3) there have to be pretty strong arguments (like very high human or environmental health risks) to continue. The environmental gains are very small compared to the economic input. It may be likely that even the environmental effects of producing the electrical power to operate the remediation unit is larger (negative) then the positive environmental effect of the remediation itself. The remaining risks may be outweighed by the results of a Total Life Cycle analysis.

So in practice the negotiating room is limited to between points 1 and 2 on the curve. When the risk of residual contamination is low the remediation might be ended close to point 1, when the risk is estimated higher the site closure will occur near point 2. Clearly this will not only depend on technical facts but also by the negotiation skills of the project manager / consultant acting for the site owner. In all cases the negotiation can only be effective when all aspects, costs, risks and uncertainties are made clear to all involved and discussed openly, if not a long litigation procedure might commence.

For this case the project has been simplified. Often several techniques are applied to deal with specific compartments of the contamination. The immediate risk of VC can be pumped away using a P&T process. Using the mobility of the groundwater some form of chemical oxidant can be added to oxidise the remaining highly chlorinated compounds in the saturated zone, especially when natural organic matter contents is low and when a fast result is required. For chlorinated solvent tenth of remedial techniques are now available. However on each site only a few will be economical and environmentally viable.

CASE 4 Influence of project duration on design and costs

On a sandy location, with many pipelines running over the surface and with groundwater at 8 m b.g.l, light aliphatic hydrocarbons are found up to 4 meters into the saturated zone. The first consultant assumes the remediation has to be completed quickly as migration may move the contamination off site in a few years. He considers the contaminant, looks up the coefficient of Henry for the heaviest compound (octane Log H = 2) so decides to apply in situ stripping as process. Due to all the infrastructure he selects horizontally installed air injection screens combined with a shallow soil vapour extraction system (drains in hand dug trenches). Due to the high concentrations (but no free LNAPL) and the perceived urgency as migration was 'imminent' this Airsparging – SVE system was initially chosen even though it appeared quite costly due to:

- High cost of horizontal drilling
- High cost of large compressor and vapour extraction equipment (all explosion proof)
- High cost of activated carbon or catalytic vapour treatment unit, required due to emission controls on the property

During the installation of some additional monitoring wells the sand from the saturated zone appeared dark brown to black. Due to uniform grain size installing the horizontal filters without drilling mud became doubtful. Which alternative remedial design would be possible?

When the site investigation reports would have included an assessment of the organic matter contents it would have revealed a high percentage of organic matter (4 %). This means the retardation of the strictly a-polar aliphatic hydrocarbons has to be quite high (high adsorption to the organic matter). This migration rate, which was crucial factor in the decision-making, was the main reason for choosing a rapid remedial technique. However, using the organic matter contents of the soil to calculate the retardation rapid migration appeared not very likely at all.

Straight chain light aliphatics are easy to biodegrade under aerobic and to some extent anaerobic conditions. In the first case injection of oxygen in some form is needed. For the second nitrate is a suitable alternative remedial process.

Oxygen can be derived from many sources. Initially it was only available as a gas or in a fluid. With the discovery of oxygen release compounds in 1989 by the University of Cincinnati, oxygen can now be delivered by introducing solids as well. The following figure shows the relative costs of oxygen expressed in kilograms of pure oxygen delivered to the point of injection.

Source	Approx. costs in $(NZ) per 100 kg pure oxygen*
Oil free compressed air	90.-
Pure compressed air in steel bottles	280.-
Hydrogen peroxide (as 30%)	640.-
Ozone from an on site generator	700.-
Sodium per sulfate	900.-
Potassium per manganate	1900.-
Calcium peroxide	2400.-
Magnesium peroxide (commercial ORC)	3000.-

* cost very dependent on supplier and purity of chemicals

Fig. 6 Cost of pure oxygen derived from different sources

Even though the oxygen-methods work fast, access to the site to use solid oxygen products is expensive due to the elaborate pipe work. The rapid reaction speed works against any solution involving injection of gaseous or liquid forms of oxygen from the side of the contaminated area, as the oxygen would be reacting with the natural organic matter, rather then with the contaminant of concern.

A nitrate / sulphate – based remedial process was therefore considered. Both nitrate and sulphate are very soluble in water and can be injected in several vertical wells upstream to create a nitrate plume running through the hydrocarbon-contaminated area. As the retardation factor of nitrate and sulphate salts is 1 (no retardation) it moves with the velocity of the groundwater. Assuming the retardation of the most mobile compound to be around 20 (moves 20 times slower then groundwater) the salts will rapidly overtake the hydrocarbons.

Before field-testing the anaerobic degradation using nitrate as electron acceptor was tested in the lab. For this purpose soil samples of the soil around the groundwater table were taken under strict anaerobic conditions. Using a nitrogen box the samples were transferred to bio-test bottles to which nitrate and some additional supplements like phosphorus were added. The bottles were incubated at 20 ^{o}C for 12 weeks. Assuming full mineralisation of the hydrocarbons using nitrate as electron acceptor the reaction and mass balance looks as follows:

$$1.0 \text{ gram HC} + \text{approx. } 3 \text{ gram } NO_3 / SO_4 \rightarrow 3.1 \text{ gram } CO_2 + 1.3 \text{ gram } H_2O$$

In practice quite a lot of intermediates (organic acids etc.) are formed (see figure 7 below). In the full scale design the injection water is pumped from some wells downstream on the contaminated area. Slightly more of the recovered water is discharged then flows into the remedial zone naturally to ensure a closed system.

After a successful lab test a field trial using a ‘huff and puff’ technique[8] or a small re-circulation loop can be used to investigate for breakdown evidence at field scale. If also the field trial has given positive evidence a prudent project manager may install a pilot system

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[8] The term “huff and puff” is taken from the oil industry to indicate a technique to extract heavy oils by intermittently injecting steam and then recovering the heated oil. For remediation of the saturated zone this is simulated by extracting contaminated groundwater, keep strictly anaerobic, inject into soil through same well while dosing some additives, wait (not too long otherwise the volume of water has migrated out of reach of the well), and recover to observe effects of additive.

along a narrow corridor (parallel to the groundwater flow lines) and trial the system for some time (6 – 18 months). If this is successful, implement the full-scale system.

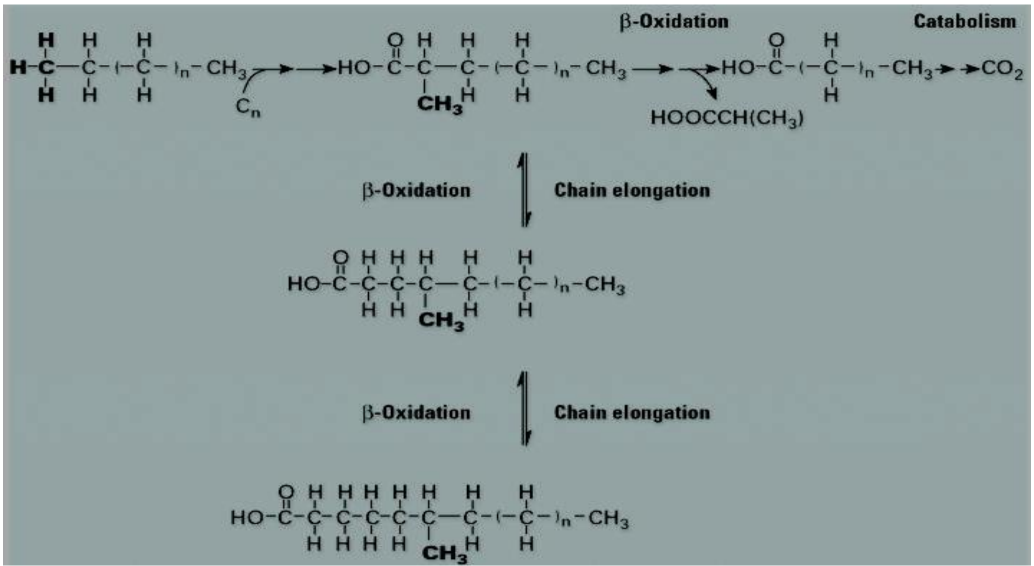

Figure 7 example of breakdown pathway for anaerobic alkane metabolism[9]

Based on the results of the lab and field tests the cost – performance for an anaerobic re-circulation system was compared to the aerobic system using horizontal injection filters.

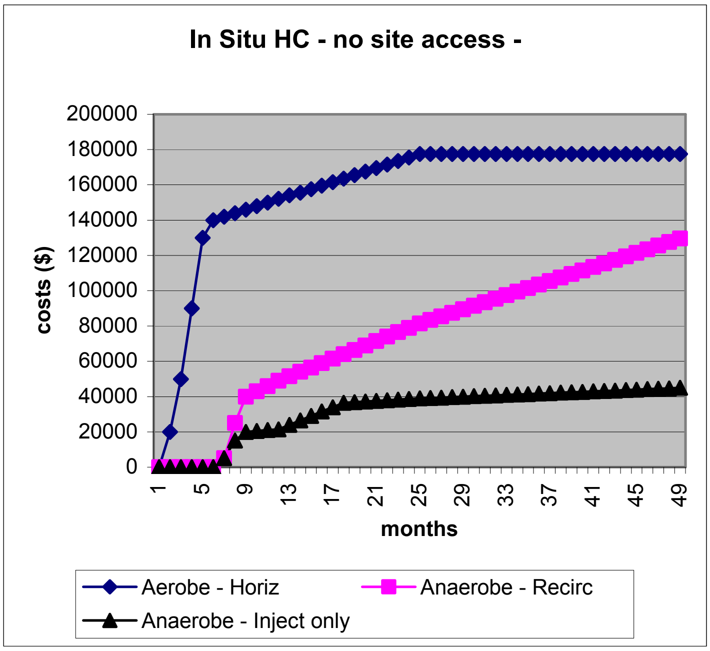

Figure 8
Cost – performance Aerobic vs. Anaerobic degradation HC

The Horizontal drilling costs clearly make the aerobic bioremediation project unviable, unless the shorter timeframe (estimated to be 2 years) is important.

The Anaerobic nitrate – sulphate system using re-circulation is more economic based on project duration of 4 years. Note the importance of accurate lab and pilot testing, as a project duration increase of 50% will make the anaerobic solution the most expensive option. The third option is nitrate – sulphate injection only. This removes the costly re-circulation system, however the duration of the project does not pose a significant financial risk. Such a low energy input system can very useful when time is not of the essence.

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[9] So CM, Young LY. Initial reactions in anaerobic alkane degradation by a sulfate-reducer, strain AK-01. Appl Environ Microbiol. 1999a;65:5532–5540.

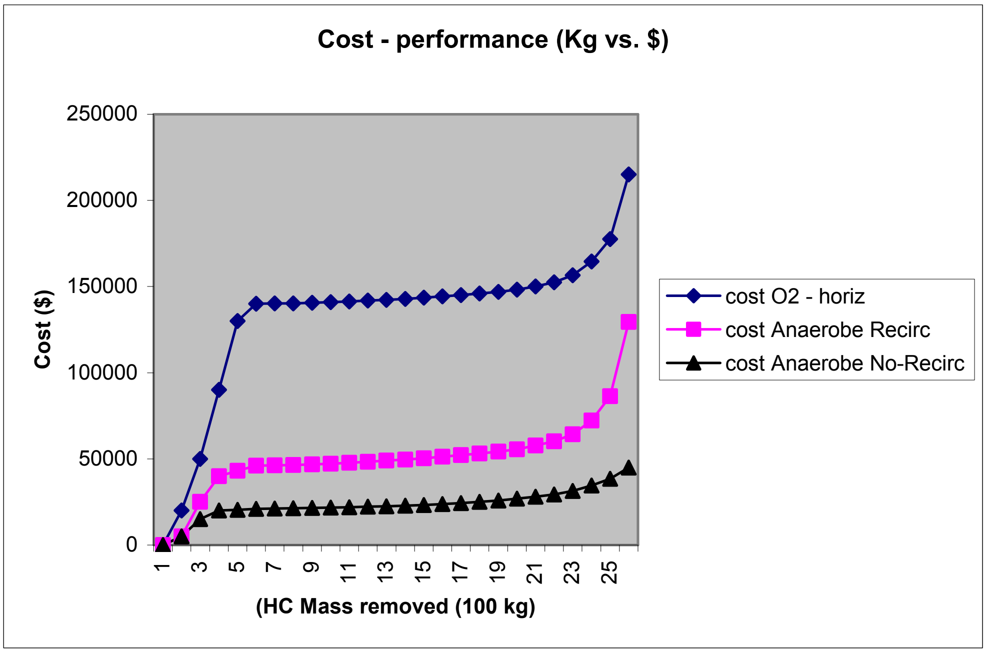

Figure 9 Cost – performance aerobe vs. anaerobe treatment Case 4

When converting the graph to cost per kilogram contaminant removed it instantly becomes clear the two faster techniques (Aerobe, 2 years; Anaerobe with circulation, 4 years) both reach the more uneconomic stage at about 2300 kg mass removed (phase 3 in figure 5). The slower technique appears not too much affected yet by the diminishing mass. There could be many reasons, however, the most likely is that the contaminants need diffusion to become available for breakdown and a slower technique allows more time for diffusion to take place. This could be investigated by carrying out a 'stop-test' at some points in time for each technique to measure the rebound of concentrations. Usually the slower techniques have less rebound compared to the faster ones.

Conclusions

- When remediation is required and safety and quality criteria are met, determine the parameters which will affect the cost of the project during the several phases of its live
- Pay specific attention to the uncertainties, when needed carry out specific studies to eliminate or quantify them
- Always consider all alternative remedial options; besides technical solutions sometimes a site management solution can be more economic, even temporary
- Try to implement only environmentally sound systems, they often are the most economic as well
- Implement in stages: take small steps and only proceed if proven successful.
- Use the different forms of cost – performance curves to assist in decision making