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IN-SITU AND ON-SITE TREATMENT OF GROUNDWATER

(Technical Report)

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In-situ and on-site treatment of groundwater (Technical Report)

Synosis This paper reviews the possibilities of in-situ and on-site treatment of groundwater as a feasible alternative method for remediation of subsurface petroleum and other chlorinated hydrocarbons to "Pump and Treat" followed by recharge to the aquifer or offsite disposal. In-situ bioremediation has however its limitations. Not all the contaminants are biodegraded or eliminated. High microbial growth rates can occur in the near-field of the injection well, reducing permeability and well capacity. The efficiency also depends on local hydrogeological conditions and is limited to areas at which hydrogeological data are well established. Lack of reliable information on application, performance and cost are also a major impediment to its use. Recent estimates for the Superfund Program, indicate that the average cost is about $1.7 million per site, very close to the present estimate of $2.5 million for the cleaning of about 400 cu.m. of jet fuel from a contaminated site in Israel. These estimates are significantly lower as compared to the average cost of $12.5 million for a pump and treat system. The total sums are substantial and are indicative to a fast developing technology and a growing market for innovative clean-up processes. Concerted efforts are still required to develop techniques for cleaning of groundwater employing integrated research approach, combining biotechnology with environmental engineering. However, the prospects for feasible combination of below and above ground processes, competitive costs, reduced residuals and positive environmental impacts as reported in this review give reason for optimism.

INTRODUCTION

Contamination of aquifers has become a great concern in many countries where population relies on groundwater resources for drinking water supply. Sources of contamination include: gasworks, coal gasification plants, refineries, abandoned industrial areas, storage tank areas, military areas, bus-stations and airports. Seepage of gasoline and other petroleum-derived fuels from these facilities is one of the major sources of groundwater contamination. In Israel, fuel pipes network extends on 1400 km of which 780 km are laid above active aquifers, in addition there are fuel depots and a large number of underground storage tanks in petrol stations, army camps, industrial plants and residential areas. Within a period of 20 years about 70 incidence of spillage were reported seeping between tens to thousands of cum per case. (ref.1). In the USA a conservative estimate indicates that about 10% of the gasoline tanks have leaked (ref.2) Chlorinated aromatic and aliphatic compounds, such as 1,1,2,2-tetrachloroethane, 1,1,1-trichloroethane 1,1,1- trichloromethane and carbon tetrachloride are the most prevalent and frequently reported constituents (ref. 3). Similarly,70% of the full scale bioremediation projects in the USA involve petroleum, wood preservatives, coal or tar compounds (ref. 4).

These compounds are known to undergo a variety of both chemical and biological transformations, leading to various products, some of which may be more hazardous than the original compounds. Of particular concern are volatile organic compounds (VOCs) some of which are toxic and have been classified as carcinogens. Maximum allowable levels for VOCs in groundwater by the European Union has been defined as 1 ppb. Benzene, toluene, and xylene (BTX) are some of these volatile organic compounds which comprise up to 20 percent of the weight of gasoline.

Following a spill or leak of gasoline, VOCs dissolve in groundwater either by contact with a free product or by leaching from contaminated soil. On release to the land surface or underground, the contaminants are subject to a variety of processes which influence the transport, distribution and fate of the compounds including:

- Immiscible transport, as a separate liquid phase
- Dispersion - mixing and spreading along the flow path
- Advection - solute transport
- Sorption - on the solid phase
- Transformation - abiotic or biotic conversion into products or intermediates.

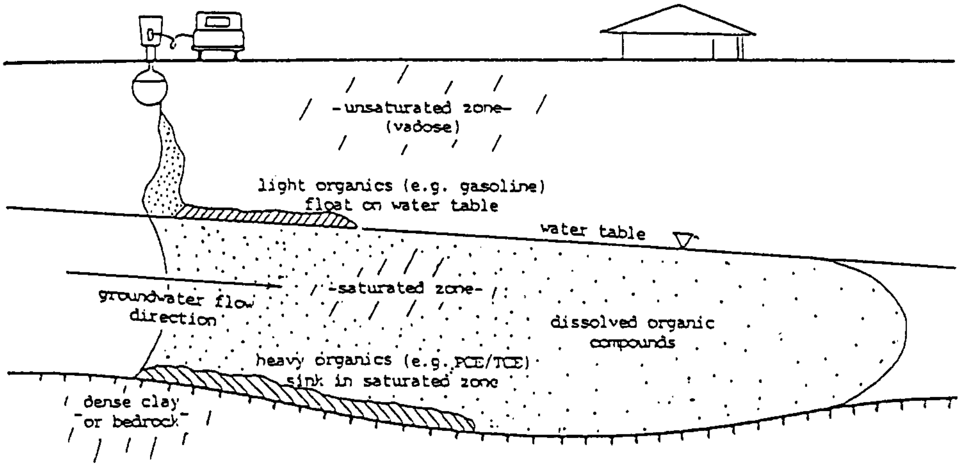


Fig. 1. Illustration of distribution and immiscible transport of contaminants through the soil profile.

The released contaminants percolate downward through the vadose zone to groundwater where immiscible compounds will either float or sink depending upon their specific gravity. Most hydrocarbons float, while halogenated compounds sink forming a pool or dense non-aqueous phase liquid (DNAPL) above the bottom of the aquifer (Fig. 1).

The magnitude of the hazardous contamination problem of soil, subsoil and the active aquifers below has created enormous pressure for soil and groundwater remediation. In the USA hazardous waste sites being considered for remediation under the Superfund Sites now number more than 32000 and at least 37000 sites under the Resource Conservation and Recovery Act (Ref. 5). In the reunified Germany there are more than 250,000 contaminated sites. In the UK there may be at least 50,000-100,000 contaminated sites with an estimated cleaning cost of 10-30 billion Pounds and in the Netherlands more than 6,000 sites have been cleaned off since 1982 and more than 1.5 billion Dollars spent over the past decade in cleaning up contaminated sites (ref. 6). Other countries have initiated efforts to identify contaminants and contaminated sites but have yet to define contamination measures and plan large bioremediation projects.

Soil and aquifer remediation is implemented in order to achieve the following objectives:

- Statutory requirements.
- Resource management considerations based on local use of aquifers.
- Achievement of acceptable levels for the protection of health and environment.
- Restoration of background levels of off-site contaminants.
- Action for remediation attenuation through induced or natural processes, such as biodegradation, volatilization, adsorption and dispersion.

The various methods of restoration and remediation of soil and groundwater with emphasis on in-situ treatment technologies are reviewed in the following.

IN-SITU REMEDIATION OF SOIL AND GROUNDWATER

Evolution of the in-situ process

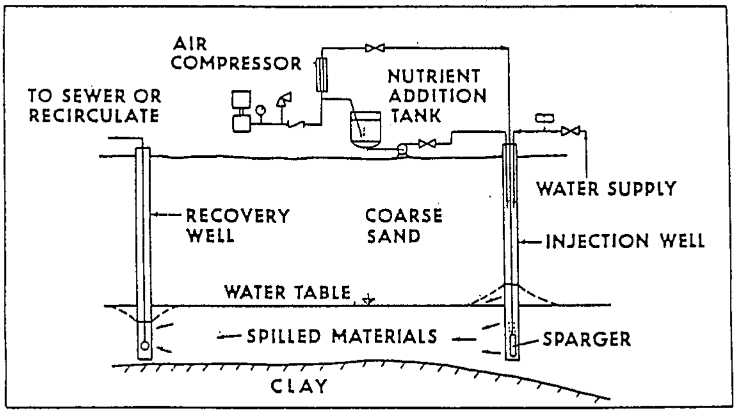
The most practical method for remediation of groundwater contaminated aquifers is a combination of pumping and treatment followed by recharge to the aquifer or offsite disposal. The first step is to pump out any floating oil that can be recovered and then begin groundwater extraction and surface treatment (Pump and Treat). Pump and treat involves flushing clean water through contaminated zones, recovering the contaminated water, treating it in above ground reactors and re-infiltrating the treated water to enhance the removal of the more soluble contaminants.

Recently, in situ remediation has become an attractive alternative treatment technology to Pump and Treat due to its relative cost-effectiveness and in keeping with new trends which recognize the advantage of in situ and on-site treatment technology. In-situ remediation is often the method of choice as it destroys contaminants in place, rather than merely transferring them to another environmental medium, as occurs with Pump and Treat solution. In-situ treatment may involve the use of living organisms to degrade, detoxify or transform hazardous compounds in the environment, as practiced for in-situ hazardous waste remediation and oil spill cleanup of beaches and the open ocean.

In-situ groundwater treatment has been reported for removing particular contaminants from groundwater. Werner (ref. 7) utilized the subsoil as a reactor for removal of mineral oil pollution from groundwater. Kruithof et al. (ref. 8) carried out in-situ denitrification experiments at the J.H. Van Heek water treatment plant in the Netherlands and Chalupa (ref. 9) reported the performance of a pilot plant for in-situ nitrate removal in Czechoslovakia. Alternative in-situ denitrification schemes were also defined by Mercado et al. (ref. 10). However, these experiments and many other bioremediation projects completed to date have been either a laboratory or a demonstration scale work.

In-situ Treatment Technologies

Most enhanced in-situ bioremediation techniques practiced today are variations of the aerobic process pioneered in the early seventy (ref. 3). The basic process includes the injection of nutrients (polyphosphates, nitrogen and trace salts) and oxygen (sparged air or hydrogen peroxide) into the aquifer and circulation through the contaminated zone by pumping from extraction wells. Oxygen can be added by sparging the gas directly, achieving a concentration of 40 mg/l as compared to 8 to 10 mg/l if air is used for sparging (ref. 11). However, because of oxygen limited solubility, it is difficult to get sufficient amounts into the groundwater to produce significant degradation. Oxygen may also cause biofouling and or the precipitation of dissolved metals (ref. 12). Vertical and/or horizontal injection and extraction wells strategically placed within the contaminated zone to control flow and direction in the vadose zone, are typically used to introduce the required electron acceptors, electron donors, and essential nutrients into the groundwater to enhance biodegradation (fig. 2).



Tursman and Cork, 1992.

Fig. 2. Illustration of in-situ bioremediation process of the vadose zone and groundwater (injection well).

The process involves biostimulation i.e. stimulating the indigenous bacteria with appropriate nutrients or Bioaugmentation and introducing non-indigenous bacteria to degrade the organic contaminants in place. Bioaugmentation is a difficult process to put into practice because of competition from the natural bacterial population and the inability of the cultured organisms to handle the stress of the natural environment.

Conditions required for microbial in-situ remediation include:

- biodegradability of the contaminants
- bioavailability of the contaminants
- optimum concentration
- absence of toxic substances
- homogenicity of the contaminants
- homogenicity of the flushing water (ref. 7).

High microbial growth rates can occur in the near-field of the injection well, reducing permeability and well capacity. Ultimately biofouling may decrease the injection capacity to the point where the well is no longer usable. The ability to perfuse the subsurface with nutrients and oxygen is in many cases limited by the specific site lithology - Clay type soils are poor candidates due to low hydraulic conductivity while sandy-type soils are better suited. Water chemistry also may limit its application as delivery of oxygen via H_2O_2 is precluded if levels of iron and or manganese are excessive due to the catalytic nature of these chemicals.

Improved engineered microorganisms that can be tailored to degrade specific waste are essential for further development of bioaugmentation. The supplemental bacteria must be able to survive and compete for nutrients with indigenous microorganisms; to be mobile from the point of injection to the location of contaminant and to retain selectivity for metabolizing the compounds for which they were selected.

The addition of surfuctants has been suggested in order to release absorbed petroleum by increasing solubility, bio-degradation and reduced interfacial tension between the water phase and the soil phase (Ref. 13). Various geophysical methods including a vertical electrical sounding methods, buried electrode method and ground penetrating radar system have also been suggested for mapping contaminated zones of aquifer (ref. 14). These methods if successful can substitute expensive drilling and soil/water chemical analysis.

Groundwater Remediation Engineering

Soils and the vadose zone layers can be treated through a combination of various engineering structures including liquid and vapor extraction wells, with or without downhill pumps and infiltration galleries, with or without injection of nutrients, micro-organisms or oxygen. Infiltration galleries can be used to percolate water, nutrients and oxygen through the contaminated unsaturated zone. Aquifer injection and infiltration galleries can be used in conjunction to effect remediation of the saturated and unsaturated zones.

The clean-up concept includes in-situ bioremediation with the support of on-site water treatment (flushing circuit) to remove HC, Fe, Mn and ito increase temperature. The on-site treatment consists of stripping, flocculation, sedimentation and sand-filtration. The stripped HC are absorbed on GAC which is steam regenerated. A large scale remediation system of - 400 m/h^{-1} would require an average residence time in the subsurface of 50 days (ref. 7).

Technical Remediation systems include:

- Dual Vacuum Extraction (DVE) wells - liquid and vapor extraction with or without downhole pumps.
- Air stripping.
- In situ vapor stripping method.
- Air sparging wells (in-situ).
- Dual vacuum stripers (DVS) wells (with nutrients, oxygen and or microbial injection).
- Infiltration galleries and trenches.

The general technical specifications of these systems are given in the following:

Dual vacuum extraction (DVE) techniques

Vapor Extraction. Vacuum enhanced soil venting is one of the most efficient and frequently used tools to address fuel hydrocarbons in the subsurface. The technique takes advantage of the generally highly volatile nature of hydrocarbons. The system produces a vacuum which is transmitted to the subsurface soils through manifold piping and extraction wells. Vapors flow through the piping to an air liquid separation and collection vessel which contains the extracted groundwater.

As the contaminated laden vapors are removed, other phases of the VOCs will vaporize in place which in turn will continually be driven out by the vacuum extraction process. Extracted vapor can be treated using catalytic oxidation, or dispersed into the air at a rate in which air quality is maintained at a safe level.

The chief components of a vacuum extraction system include:

- Vacuum extraction wells (VEW).
- Vacuum manifold piping.
- Vacuum extraction unit.
- Air/liquid separation vessel.
- Vapor treatment system (steam regenerated activated vapor phase or a catalytic oxidation Unit).

Extraction of the Liquid Phase (free oil). Liquid phase hydrocarbons penetrate the soil layers to the more permeable sandy clay layers. Consequently, dissolved phase hydrocarbons are prevailing in the groundwater. The free oil can be extracted by the application of vacuum which enhances the hydraulic yield and is essential in low yielding clay layers. Alternatively, downhole pumps and free product pumps can also be employed. These pumps work best for removal of liquid phase hydrocarbon in the sands.

DVE utilizes the same well for recovery of vaporous VOCs and contaminated groundwater, thereby increasing the rate of contaminant removal several fold. This system reduces the number of wells and consequently, reduces the costs while improving the performance of both the groundwater and vapor recovery.

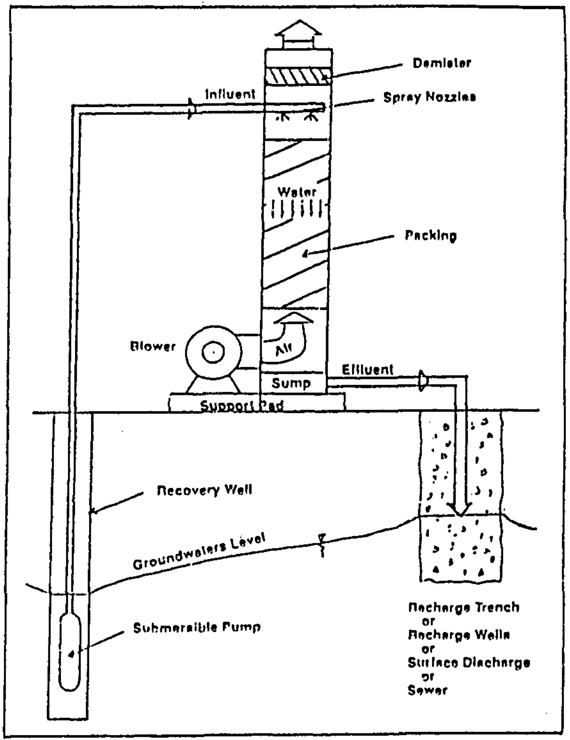
Recovery of the Dissolved hydrocarbons. Dissolved hydrocarbons are recovered as part of the liquid hydrocarbon recovery operation when a dual vacuum pump system is used. The bulk of the groundwater containing dissolved hydrocarbon can however be treated with a variety of engineered systems depending on the flow rate, the contaminant concentration and groundwater chemistry. Alternative treatment and disposal solutions include:

- Discharge to a water treatment system.
- Discharge to a surface water outfall, if permitted.
- Treatment and recharge to the aquifer.
- Establishment of a recirculation cell followed by treatment and reuse.

Air Strippers

Air stripping has proven to be one of the most practical alternatives for removing petroleum contamination from groundwater. By pumping petroleum contaminated groundwater through an air stripping tower most VOCs can be removed, including chloroform, trichloroethylene, methylene chloride and carbon tetrachloride contained in solvents, degreasers and other chemicals.

A typical air stripper is a counter current design where water flows in the opposite direction to air flow (fig. 3). Contaminated water is introduced to the top of the tower



McFarland 1989.

Fig. 3.
Illustration of an air stripping system.

by nozzles or distribution trays. Water flows by gravity around and through a packing material in the tower which is designed to spread out the water into thin films maximizing both the surface area and water to air transfer. A blower forces air upward through the packing where it picks up the volatile chemicals and is exhausted through the top of the tower. Water leaves the stripper through a sump at the bottom of the tower. Depending on temperature and treatment efficiencies, removals to fewer than 1 ppb are possible in a single pass system. When effluent quality is critical multiple air strippers in series or activated carbon filtration can be used to remove VOCs to below detectable levels (ref. 15).

During the process some VOCs are transferred to the atmosphere by the stripper and air quality limitations may require the exhaust stream to be treated, typically by activated carbon adsorption. The effluent air stream is passed through a bed of activated carbon to "adsorb" the VOCs (fig. 4), Periodic carbon replacement or regeneration is necessary to maintain effective removal of airborne contaminants. Spent carbon must be handled and disposed of as hazardous waste, since it will contain significant concentrations of toxic organic chemicals. On-site carbon regeneration by incineration or stream stripping may be cost effective for use with large treatment systems. Catalytic incineration is now being used to treat contaminated airstreams without generating hazardous waste materials and is cost effective for larger clean-up projects.

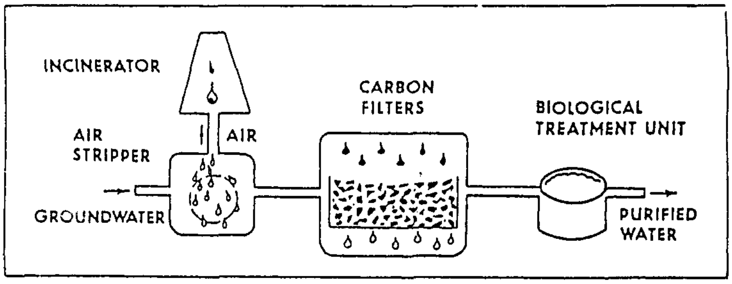
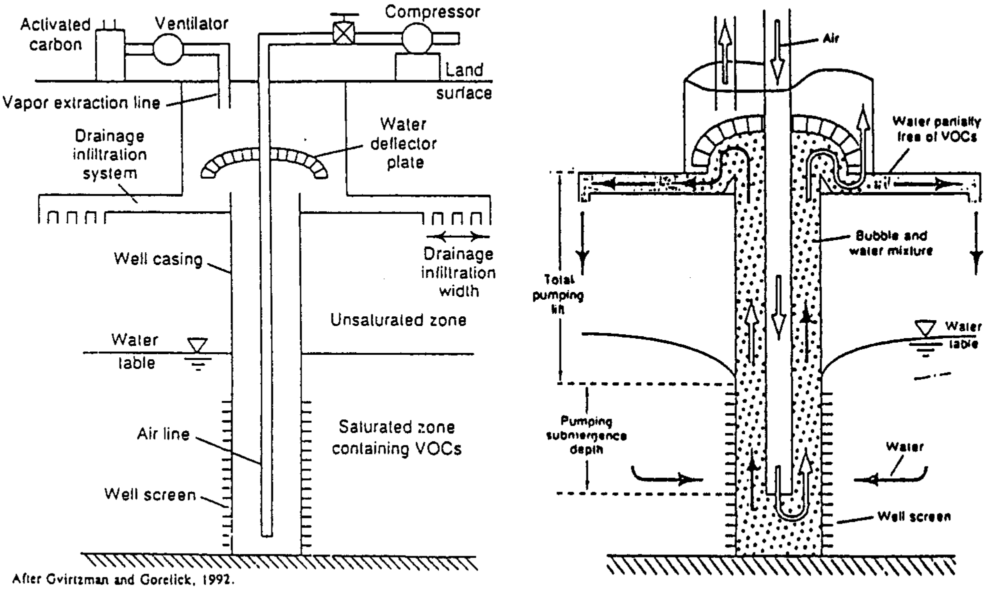


Fig. 4.
Above ground treatment of groundwater and vapour.

In-situ vapor stripping method

This method is a combined air-lift pumping technique and in situ vapor stripping technique (ref. 16). The idea is to inject air into wells which lifts the contaminated water in the well. During the process VOCs are transferred from the water to the air bubbles. The VOCs are then collected at the top of the well by vapor extraction. The partially treated water is forced into the unsaturated zone where it reinfiltrates without being brought to the surface (fig. 5). No above ground installations are required as remediation occurs while water is circulated within the well.



After Gvirtzman and Gorelick, 1992.

Fig. 5. Schematic design of in-situ vapour stripping well.

The rate of air injection creates groundwater circulation towards the well and in situ volatilization of VOCs, gradually reducing the concentrations of the VOCs. The lifted water bubble mixture is diverted through a series of drains installed within the sub-surface back by infiltration to the aquifer. The organic rich bubbles are collected using vapor extraction techniques and treated by sorption into activated carbon.

This concept together with enforced ventilation and bio-stimulation are being tested in a room size model in which VOCs are degraded due to air lift pumping of the contaminated water and the recharging of the treated water.

Air Sparging

Air sparging is in-situ injection of pressurized air into the aquifer to enhance the recovery of the VOCs from the groundwater. As the air moves through the saturated zone, dissolved, adsorbed and liquid phase VOCs are partitioned to the vapor phase and rise to the unsaturated zone where they are recovered by the vacuum extraction process. In some cases compressed nitrogen is used if the iron content in groundwater indicates that precipitation could occur.

Air sparging used in conjunction with soil vapor extraction is now the primary treatment technology of choice for soils and groundwater contaminated with VOCs. Air sparging creates a crude air stripper in the subsurface, although a misapplied sparge system could actually push the contamination away from the remediated site (ref. 17). A clay barrier above the injection zone could cause this to happen. Therefore restrictive geological conditions and optimal operating pressures must be determined prior to implementation.

Vertical Groundwater Circulation Wells

Vertical circulation flow around wells with two screen sections in one aquifer, so called "Vertical Groundwater Circulation Well," has become increasingly important for aquifer remediation in Germany (ref. 18). In this system, the contaminated water entering the well through the lower screen is pumped through an activated carbon filter which is installed within the well casing. Adaptable bacteria absorbed on the activated carbon particles can be used to decontaminate groundwater from various contaminants such as atrazine and nitrates.

ESTIMATED COSTS OF GROUNDWATER REMEDIATION

Costs of remediation were assessed based on a remediation plan for a jet fuel polluted site in Israel - as described below:

The contaminated site - OR AKIVA

The jet fuel spill of about 400 m^3 originated from a 10-inch pipeline on October 29th, 1990. About 70,000 m^3 of soil have been affected extending on an area of 100 x 30m. Twelve pumping wells which collectively extract 5 million m^3 per year of groundwater are located within the area of concern. Soil and groundwater samples taken from the site indicated that the soil and bedrock at the site consist of three identifiable layers; an uppermost layer of sand dunes three m thick, followed by a black heavy clay layer six m thick and finally a sandy clay (hamra) layer 6 to 12 m thick. The watertable level is seven to eight m below the surface.

VOCs were found to be partitioned between four phases including: vapor, liquid, dissolved in pore water and adsorbed to solid particles. The investigation revealed that a lens with a maximum thickness of 90 cm covers an area of 1000 m^2, amounting to about 235 m^3 of liquid phase hydrocarbon and approximately 90 m^3 of dissolved phase hydrocarbon in concentrations of 0.5 to 100 ppm over an area of about 3600 m^2. Approximately 54 m^3 are estimated to remain adsorbed in the unsaturated zone.

The proposed remediation system.

The remediation of the Or-Akiva Site will involve:

a. Containment - prevention of further migration of mobile hydrocarbon phases by controlling hydrocarbon plume movement (liquid and dissolved phases).

b. Cleanup - removal of as much liquid hydrocarbons as possible to minimize spreading of the residual hydrocarbon in the saturated and unsaturated zones.

A combination of technological processes which represent a combination of various technologies as discussed above was proposed including:

- Vacuum Extraction (VE) for the unsaturated sand.
- Dual Vacuum Extraction (DVE) for the saturated clay and sandy clays and
- Pump and Treat (P&T) for the dissolved-phase plume.

The DVE will treat the soils as well as the contaminated groundwater in the area of spill. Air sparging was not considered because the presence of the clay layer would cause the air bubbles to move laterally outside of the active zone. Groundwater will be treated by an oil/water separator, an air stripper and a liquid phase carbon adsorption system for polishing. The treated water will be reinjected into the aquifer (Fig. 6).

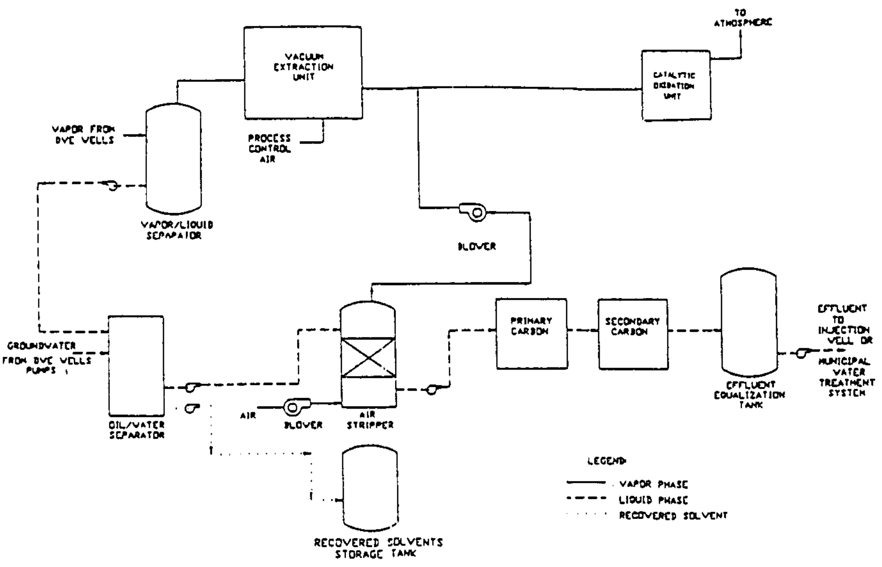


Fig. 6. Flow diagram for proposed groundwater and vapour treatment process for Or Akiva site.

The reinjection of treated groundwater could include the injection of heated air to enhance volatilization and/or the addition of oxygen, nutrients or microbes to enhance biodegradation. Reinjection may be carried out through horizontal wells placed at the water table perpendicular to the hydraulic gradient, on the entire upgradient side of the contaminated area or through infiltration trenches.

A staged plan starting with a pilot plant upscaling to a full stage design was proposed including:

- A pilot experiment of bio-venting/dual extraction.
- Extraction of the liquid phase hydrocarbon.
- Full scale implementation.

Modelling is to be performed to generate a preliminary capture zone as a starting point for the design and placement of DVE, VE and P&T wells.

Cost Estimates

For estimation of costs, the plan assumes that for full scale treatment, about 20 VE and DVE wells and 7 pump & treat wells (50 m^3/hr^{-1}) will be required, amounting to about US$ 2.5 million as detailed in Table 1.

The proposed combination of investigative tasks with interim remedial measures would make the project more cost effective and the time scale for cleanup shorter.

DISCUSSION AND CONCLUSIONS

This presentation indicates that contamination of groundwater resources will remain a problem for many years and effective measures will be required to confine and alleviate the pollution hazard. Groundwater supplies contaminated by traces of oil products are likely to be difficult and expensive to treat. Laboratory tests indicate that a concentration of approx. 0.02 mg/1 of the fuel would be sufficient to cause an objectional odour in the potable water supply. Chlorine has been used to remove minor taste and odour problems resulting from oil spills (ref. 19) but probably the most effective treatment is to press the

TABLE 1. Estimated costs of in-situ and on-site groundwater remediation

		US$000
1.	Site assessment and preparation of a remedial action plan, including drilling of wells and laboratory costs	150
2.	Procurement and installation of equipment: - Pumping units - Vacuum Extraction Equipment - Soil venting/air sparging system - Air stripper - Oil/water separator - Liquid phase Activated Carbon - Vapor Treatment Equipment - Electrical equipment	1,200
3.	Remedial system startup and pilot testing - Soil venting/air sparging tests - Laboratory cost	250
4.	Operation and M&E of the remedial system/year	350
5.	Bioremediation of soil and groundwater	150
6.	Contingencies 20%	420
Total Cost Estimates		2,520
Remediation per m^3. (based on 235 m^3 of free oil, 90 m^3 of dissolved oil and 54 m^3 absorbed oil)		$ 6.650/cu.m

groundwater through a bed of activated carbon. As a realistic alternative, in-situ and on-site treatment processes are increasingly being considered. A review of operating systems has shown that properly designed extraction systems can significantly reduce the concentration of dissolved contaminants in groundwater, although complete clean up is often not possible using the available techniques.

Results of field experience using in-situ bioremediation are positive in the case of aromatic, aliphatic and phenolic compounds, although in-situ bioremediation of TCE containing water is apparently limited to fluids containing less than about 100 ppm of TCE, as higher concentrations seem to be toxic. Contaminant concentrations usually decrease rapidly after initiation of pumping and then tend to level off at some asymptotic concentration (ref. 4).

Bioremediation also has other limitations as not all of the contaminants are biodegraded or eliminated, the desired target that the area treated should be reduced to a level that the area can be used again and the groundwater leaving the area is free of contaminants is not easily achievable. For mixed contaminants, different requirements and a combination of different methods are necessary to overcome mass balance limiting factors including: bioavailability of the contaminants (spatial separation, solubility), lack of electronacceptors and decrease of the clean-up target values followed by risk assessment of metabolites and dead-end products.

High microbial growth rates can occur in the near-field of the injection well, reducing permeability and well capacity. Ultimately, bio-fouling may decrease the injection capacity to the point where the well is no longer usable. The efficiency also depends on local hydrogeological conditions and is limited to areas at which hydrogeological data are well established. Biological processes though capable of destroying more than 99% of the waste are not sufficient to meet the regulations. Also biological processes are temperature dependent and cannot be used effectively in cold climate. Therefore, it is doubtful whether the maximum concentration level of 5 ppb mandated by the EPA could ever be achieved with the current technology (ref. 5).

Bioremediation is considered as potentially advantageous in treating hazardous wastes, but the limited experience and the lack of reliable information on application and performance and cost is a major impediment to its use. Most of the remediation work which was reported to date, is still at the laboratory and field demonstration level although a real progress can be observed since the early work of Werner (ref. 7) in the early 1980 and the current results of the EPA work at the demonstration site in Traverse City MI.

The current limited experience results in a lack of data on performance and costs of bioremediation technology (ref 20). The dearth of cost data is particularly evident for biology-based waste treatment methodologies which were applied on a recycling and disposal of chemical wastes site in South Carolina. Based on a remediation of 45,000 cubic yards of soil, cost estimates for various remedial technologies were given as follows (ref 21):

-	In-situ Soil Vacuum Extraction	\$ 1.1 M
-	On-site Incineration with Stabilization of Treated Soils	\$ 28.3 M
-	On-site Thermal Desorption with Stabilization of Treated Soils	\$ 18.3 M
-	Off-site Disposal of Contaminated Soils	\$ 20.7 M
-	Off-site Thermal Treatment of Contaminated Soils	\$ 100 M

According to recent estimates for the Superfund Program (Dept of Energy, 1988), the average per site cost of characterization, assessment and remedial action design is about \$1.7 million, very close to the cost estimate of \$2.5 million made for the cleaning of about 400 cu.m of jet fuel from the Or-Akiva site (Table 1). These estimates are significantly lower as compared to the average cost of the conventional remedial action, usually a Pump and Treat System, which is about \$12.5 million.

Based on these cost estimates, the total cost of managing and remediating contaminated sites could be enormous. Current estimates for the cleaning of USA Department of Energy waste sites are estimated at about \$ 350 billion, as reflected by the new 1993 DOE budgeted expenditure of \$ 5.3 billion on waste remediation, an increase of 24% over 1992. (ref. 5). In the EEC, soil rehabilitation efforts are expected to reach \$ 10 billion by the year 2000 and expected to grow to \$ 30 billion in the next decade (Ref. 22). These figures are indicative of a fast developing technology and a growing market for innovative clean-up processes. The magnitude of the polluted sites and the huge amounts of expenditure that will be required justifies the wide interest of the various concerns in groundwater remediation technology.

In accordance, the extensive remediation activity which is still relatively limited to USA and Europe must expand to other regions. A growing number of EC countries are already involved in bioremediation work. The Netherlands, Denmark and Germany, especially, have high level of public awareness that will continue to influence environmental legislation. Thus, site remediation activity in Europe is expected to grow at the accelerated rhythm of the USA. About 20 European companies are actively developing and applying in-situ technologies at a field demonstration level. Consequently, the need for a regional, interdisciplinary approach to pollution in Europe and elsewhere is obvious and imperative (ref. 19).

Concerted efforts would be required to develop techniques for cleaning of groundwater by a collaborative research approach, combining scientists and engineers working together on integrated molecular genetics and physiology with environmental needs. Technologies related to the application of micro-organisms to the soil, to the release of nutrients into the soil, to the enhancement of microbial decontamination through various additives and restoration of enzymatic activity to xenobiotic decontamination have yet to be defined.

The promise of a feasible combination of below and above ground treatment technologies, favorable economics, reduced residuals and little environmental impacts give reason for optimism. Yet, additional basic research, field demonstrations and track records of bioremediation success remain to be done before groundwater treatment is to reach its potential. Specifically, to build confidence in bioremediation among decision makers and the general public, more credible field experience is needed. It is to be noted however, that attempts to recapture, isolate and treat eventual pollution is costly and prevention of pollution by strict control of pollutants is more desirable. A vigorous development control policy on land close to groundwater sources is imperative to prevent the pollution of public supplies derived from aquifers.

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