ELSEVIER Journal of Hazardous Materials B97 (2003) 127–143

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Vacuum extraction based response equipment for recovery of fresh fuel spills from soil

Sakari Halmemies[a,*], Siri Gröndahl[b], Mika Arffman[c], Keijo Nenonen[d], Tuula Tuhkanen[e]

[a] *Emergency Services College, P.O. Box 1122, FIN-70821 Kuopio, Finland*
[b] *Finnish Road Enterprise, P.O. Box 101, FIN-65101 Vaasa, Finland*
[c] *Pohjois-Savo Polytechnic, P.O. Box 6, FIN-70201 Kuopio, Finland*
[d] *Geological Survey of Finland, P.O. Box 1237, FIN-70211 Kuopio, Finland*
[e] *Environmental Engineering and Biotechnology, Tampere University of Technology, P.O. Box 541, FIN-33101 Tampere, Finland*

Accepted 21 August 2002

Abstract

Accidental overturns of fuel tankers can have, depending on soil types, severe consequences. This applies, particularly in areas of shallow soils where the groundwater is located 2–4 m below the ground surface. By rapid, vacuum extraction based recovery emergency services, which would normally be the first to arrive on the scene, could minimize consequences of fresh fuel spills and even prevent groundwater contamination, the primary purpose of emergency response. Powerful vacuum extraction-based response (PER), equipment has been developed to recover freshly spilt volatile fuels from the soil, primary by emergency services, but also by other trained responders. The main components of mobile PER-equipment are perforated extraction pipes, a recovery vacuum tank, a vacuum pump and an incinerator. The PER-equipment has been tested in summer and sub-zero winter conditions, and in both cases 50–80% of fresh gasoline spilled into sandy soil was recovered during the first 2 h of operation. Gasoline was recovered in both liquid and vapor form, and hydrocarbon vapors were destroyed by controlled incineration at a safe distance from the spill. Recovery of less volatile diesel oil is not so effective from the sandy soil, but about 30% of it could be pumped from a fresh pool directly after a seepage time of 15 min.

Keywords: Fresh fuel spills on soil; Emergency response methods; Recovery of fuels from soil; Fire departments; Prevention of groundwater pollution

---

[*] Corresponding author. Tel.: +358-17-307317; fax: +358-17-307222.
E-mail addresses: sakari.halmemies@pelastus.intermin.fi (S. Halmemies), keijo.nenonen@gsf.fi (K. Nenonen), tuula.tuhkanen@tut.fi (T. Tuhkanen).

0304-3894/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0304-3894(02)00249-2

1. Introduction

Typical transportation accidents are overturns of a tanker on a road or railway, and the spills caused by such accidents. The most common chemicals spilt are, at least in Finland, petroleum products and the volume of spill can be several tens of cubic meters [1]. Consequences are normally a big fire or an extensive pollution of the soil. Because emergency services normally arrive at the accident site during the first 15–30 min, they could, by rapid response actions recover any contaminants that have not been retained by the soil itself. In this way pollution of groundwater could be prevented, an action whose value cannot be measured in monetary terms. Moreover, the need for lengthy and expensive remediation efforts in the future can be avoided. Permeable sandy and gravely soils are most vulnerable, and severe groundwater contamination could occur within a few hours of spillage. Emergency services normally have at least 2 h to save the groundwater, if they had methods and equipment to do it.

Current response actions by emergency services are generally restricted to pumping from pools and ground pits. Because of the lack of suitable response equipment and experience, emergency services leave fuel recovery from the soil to environmental organizations. These operations tend, from an environmental point of view, to begin recovery too late, may be days or weeks after the accident.

By adapting the conventional techniques of soil vapor and dual-phase extractions to the existing response equipment of the Emergency Services College (ESC) a vacuum extraction-based response system was developed to enable emergency services to recover fuels from soil. The more fuel can be recovered from ground during the first hours of accidental spill, the more savings it will cause during the remediation phase. In addition, it is much easier to recover fresh fuel.

1.1. Background

This study is a part of a broader project, the main purpose of which is to develop a vacuum extraction-based response equipment for recovering accidentally spilled fuels from

Table 1
Results of soil sample analyses

Soil type	Dry bulk density[a]	Hydraulic conductivity (m/s)[a]	NAPL retention capacity as weight fraction[b]	
			Gasoline	Diesel oil
Gravely sand	1.85	2.6×10^{-5}[c] 1.2×10^{-7}[e]	0.03[d]	0.05[d]
Sandy till	1.81	6.4×10^{-7}[c] 8.2×10^{-8}[e]	0.06[d]	0.07[d]

[a] [4].
[b] [3].
[c] Column and tank experiments.
[d] Moisture content = 6%.
[e] Basin experiments.

soils, so as to minimize environmental impact. The PER-technique was first tested in small laboratory scale columns where fresh fuel spills were successfully recovered from different soils with the aid of strong vacuum [2]. Larger column tests involved determinations of seepage velocities of fuels in different soils, and determinations of retention capacities of soils for different fuels. By combining the existing equations of seepage and vaporization a simplified gasoline spill model was developed [3].

This article describes so called tank and basin experiments, by which power vacuum extraction of fuels were tested both in a pilot study and in the field. Basin experiments were to simulate spills of real accidents; a few parameters were changed to correspond to different weather and geological conditions. The final response equipment was developed on the basis of the results of these experiments.

2. Materials

2.1. Soil types

In tank experiments, mainly conducted for the development of response equipment, only gravely sand was used, but in basin experiments both gravely sand and sandy till were used. The sandy till was chosen since it is the most common soil type on Finnish road-sides. On the other hand, in many places the Finnish roads have preferentially been constructed on sandy and gravely soils. Dry bulk densities were determined by the Proctor method and hydraulic conductivities by a constant pressure method [2]. Short-term (2 h) retention capacities of the soil types for the two fuels were determined in separate column experiments for this project [3]. The results of soil sample analyses are given in Table 1.

2.2. Fuel types

The contaminants used in basin experiments were 98 Octane gasoline containing MTBE and diesel oil (winter type). The densities, dynamic viscosities and vapor pressures of the gasoline and diesel liquids at the temperatures of column experiments are given in Table 2.

2.3. Equipment

2.3.1. Tank experiments

The developing of a vacuum extraction-based response equipment for recovering fuel spills from soils started with tank experiments, where some of the existing response

Table 2
Densities, dynamic viscosities and vapor pressures of gasoline and diesel oil used at different temperatures[a]

Fuel type	Density (kg/cm^3)			Dynamic viscosity (cP)			Vapor pressure (kPa)		
	7 °C	25 °C	50 °C	7 °C	25 °C	50 °C	7 °C	25 °C	50 °C
Gasoline	0.75	0.73	0.71	<1	<1	<1	20	50	115
Diesel oil	0.85	0.83	0.82	8	4.5	2.5	<1	<1	<1

[a] Aimo Rautiola, Fortum Company, Personal communication, 2002.

Fig. 1. Vacuum extraction based equipment for recovering spilt chemicals from liquid pools.

equipment of ESC was utilized. ESC uses vacuum extraction-based equipment for training purposes for recovery of spilt chemicals from liquid pools. The main components of the system were a peristaltic pump ELRO GP20/10 Ex combined with a transport drum, suction pipe and other accessories, forming a waste disposal system as described in Fig. 1. Technical data for this dual speed pump are as follows: flow rates 150/300 l/min, nominal pumping pressure 2 bar, nominal speed 120/240 rev/min, power ratings 2.1/2.75 kW, electrical supply three phase, pump connections DN 50, suction capability up to 9 mwc and dry running ability.

The equipment described in Fig. 1 is designed to extract spilt chemicals from the ground surface into a recovery container (barrel), utilizing a vacuum generated by a peristaltic pump. The tank experiments included the pump and the barrel of Fig. 1, but also a steel tank with a volume of 600 l and an iron pipe (length of 60 cm and i.d. of 25 mm) perforated with 2 mm holes at a distance of 10 cm from the tip.

2.3.2. Basin experiments

The “response equipment” tested in the basin experiments differed from that used in the tank experiments. As a result of the tank experiments both a new vacuum collecting tank and an incinerator were constructed. The collecting tank was an iron cylindrical tank with a volume of 250 l and included a special cyclone application to separate hydrocarbon liquids from vapors. The tank was filled from the top by a perforated spiral pipe to lead liquid to the bottom of the tank. To prevent excess vaporization of recovered liquid, extracted vapors could escape from holes in the spiral before entering the bottom of the tank. The tank included inlets that made it possible, if necessary, to fill and discharge the container simultaneously. During a possible discharge from the container the escape of vacuum was to be prevented by maintaining a certain level of liquid.

The incinerator was constructed by utilizing a barrel containing water. The burner, a metal pipe with i.d. of 10 cm and equipped with a piece of incombustible textile as a flame arrester, was welded at the top of the barrel. Hydrocarbon vapors had to penetrate a layer of water in the barrel and a filter of incombustible material before reaching the atmosphere combustion. The incinerator was equipped with a Bunsen burner and LPG bottle for ignition of hydrocarbon vapors, or if needed to burn weak vapors, outside the explosion limits.

Fig. 2 shows the two key components developed and used in basin experiments.

A concrete basin (9 m × 9 m × 3 m) with a volume of 243 m^3 was constructed on a landfill site in the municipality of Kuopio, to facilitate large scale extraction experiments without disturbing wall effects. The basin was filled with both sandy till and gravely sand. The basin was divided into two equal parts and the first part was filled and packed with sandy till (2.8 m of height). In the second part the lower 1.5 m was filled with sandy till, followed by 1.3 m of gravely sand. Soils were packed with a shaker to correspond to natural conditions. New longer perforated pipes with a length of 1.5 m were sunk into the soil with the aid of a combustion engine driven shaker (Cobra mk).

In order to recover large amounts of fuel from the soil the complete vacuum extraction-based response system is needed, as shown in Fig. 3. Items 9–12 were not used during these basin experiments. The total response equipment was grounded to prevent ignition due to static electricity.

2.4. Procedures

2.4.1. Tank experiments

The stainless steel tank was filled and packed with 500 l of gravely sand. There was a stopcock at the bottom of the tank by which any penetration of fuel through the soil could be checked. Fuel (10 l) was poured on the soil and allowed to seep into it for 5–15 min, before starting vacuum based extraction. Tank experiments were designed to provide information on how parameters such as soil moisture, fuel type, use of compensation air, immersion depth and covering of soil will effect on recovery of water or fuels from the soil. The system was first tested with water, after which four experiments were conducted with fuels, gasoline and diesel oil. Table 3 shows the parameters for the fuel experiments.

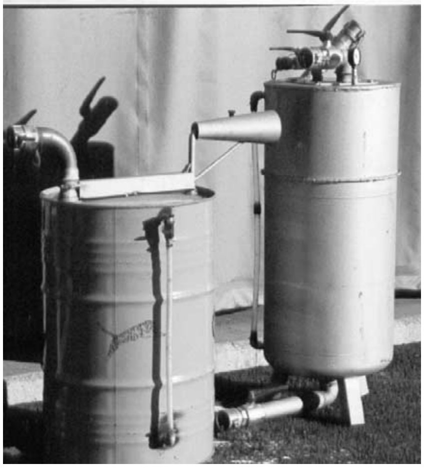

Fig. 2. Incinerator and collecting vacuum tank.

Table 3
Parameters of tank experiments with fuels

Experiment number	Poured fuel (10 l)	Interval of pressure shocks	Soil moisture (%)	Compensation air[a]	Sink depth (cm)	Ambient temperature (°C)	Soil density (kg/dm^3)[b]
1	Gasoline	5	6.0	Passive	42	21	1.8
2	Diesel oil	2	3.5	Passive	42	26	1.8
3	Gasoline	2	5.1	Passive	35	15	1.7
4	Diesel oil	2	9.4	No	42	12	1.7

[a] Compensation air was added to the soil to help extraction.

[b] Soil was gravely sand.

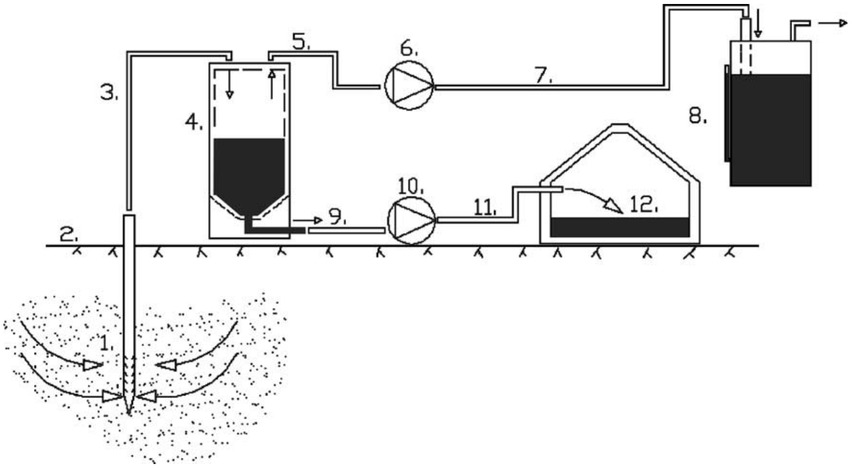

Fig. 3. Operating principle of the power extraction equipment: (1) perforated extraction pipe; (2) plastic sheeting; (3) extraction hose; (4) recovery vacuum tank; (5) suction hose for vapors; (6) peristaltic pump; (7) pressure hose for vapors; (8) burner; (9) discharge hose for liquid; (10) transfer pump for recovered liquid; (11) transfer hose for liquid; (12) temporary container for recovered liquid.

At the end of the fuel extractions (duration 50–120 min, see Table 3) soil samples of 100 g were taken from different depths (10, 25 and 40 cm) and different distances to be analyzed by a gas chromatograph (Shimadzu GC-17A, FID detector). Concentrations of gasoline vapors were measured by an explosimeter (combustible gas indicator, Auer Ex-Ox-Meter II).

The main purpose of the tank experiments was to both maximize efficiencies of vacuum based extraction and to develop a burner suitable for controlled burning of the extracted flammable vapors.

2.4.2. Basin experiments

Fuels were extracted into the recovery tank with the aid of a vacuum and vapors continued until released to the atmosphere or the incinerator. Incinerator burning was used only for gasoline.

After the components 1–8 in the Fig. 3 were connected and the system grounded, the experiment commenced. The first 100 l of fuel (98 octane gasoline or diesel oil) was poured onto the soil over an area of about 1 m^2, where it formed a pool. The pool was allowed to seep and vaporize for 15 min, after which recovery was started. If there was any liquid left in the pool, it was first recovered by pumping before commencing the vacuum based extraction from the soil. Before starting extraction of fuel, the spill area was covered with foam to prevent the risk of ignition. Next, the perforated extraction pipe was sunk into the soil. Two compensation air pipes used in experiments 5 and 8 had previously been sunk diagonally to a depth of 0.8 m, at a distance of 1.3 m from the extraction pipe. To intensify the extraction effect the spill area was covered with plastic sheeting of polyethylene.

Concentration and volume of gasoline vapors were measured during extraction. In addition, the dispersal of gasoline through the soil was monitored by taking soil vapor samples. Soil samples were taken after all experiments and analyzed to determine yields and

Table 4
Parameters of basin experiments with fuels

Experiment number	Poured fuel (100 l)	Soil	Duration (min)	Compensation air	Soil moisture (%)	Ambient temperature (°C)	Depth of extraction pipe (cm)	Interval of pressure shocks (min)
5	Gasoline	Gravely sand	120	2 pipes, distribution 1.3 m	3.5	15	130	5
6	Gasoline	Sandy till	50	No	4.8	15	50	2
7	Diesel oil	Gravely sand	60	No	3.5	15	50/80	2
8	Gasoline	Gravely sand	120	2 pipes, distribution 1.3 m	Frozen	−1	120	2

efficiencies of response actions. Volumes of gasoline vapors were determined by Pitot-tube, which indicates local velocity by measuring the difference between impact pressure and static pressure [5]. The Pitot-tube was connected to a micro manometer (SwemaMan 2000), which indicated a pressure difference in the range of ±2000 Pa and flow velocity on the scale 2–60 m/s. Accuracy of the meter was ±3%.

Concentrations of benzene, ethyl benzene, toluene, xylenes (BTEX), methyl tertiary butyl ether (MTBE), tertiary amyl methyl ether (TAME) and total volatile organic compounds (TVOC) of gasoline were analyzed from captured vapors and the soil samples taken after extractions by Golder Associates Oy. When analyzing soil vapor samples EPA instructions and standards were followed [6]. The gas chromatograph used was an HNU-311 model with PID detector. For analysis of soil samples the standards used were EPA-5021, EPA-8015B, EPA-8021B and ISO-11423-1. The analysis was based on gas chromatography with double columns and head space technology (HSGC-FID).

Four different extraction experiments were conducted; three in summer and one in sub-zero winter conditions. Table 4 shows parameters of basin experiments.

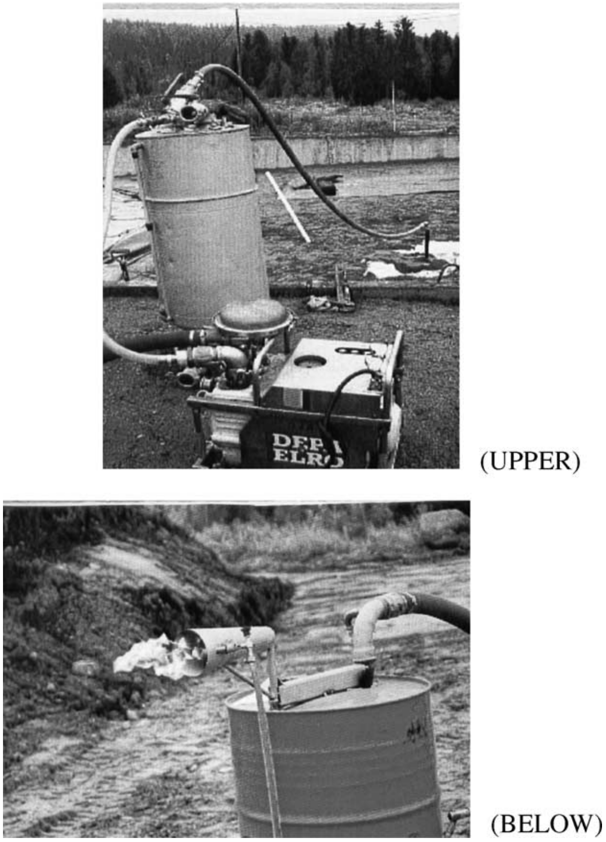

Fig. 4. Power extraction of gasoline from gravely sand during basin experiments. The vacuum pump, the collecting tank and an extraction pipe (upper). Controlled burning of gasoline vapors by the incinerator (below).

Fig. 4 shows the power extraction equipment in use during basin experiments.

3. Results and discussion

3.1. Tank experiments

Tank experiments were started with water to determine, among other things, suitable combination of equipment and the effect of compensation air to liquid recovery. Water yields were between 7 and 10% as liquid, but because of the vacuum (40 kPa) about 10% of water should be released as vapor (not measured). The best yield (10%) corresponded to the case, when compressed air was used as compensation air. The low yield percentage can also be attributed to the retention of all of the water in the sand, corresponding to a moisture content of 10%. As a result of water experiments it became clear that there needs to be a sufficient number of holes on an extraction pipe, and that they have to be located at a depth where liquid has seeped. To intensify recovery and vacuum efficiency, the surface of the soil could be covered by plastic.

Tank experiments were continued with fuels (gasoline and diesel oil) to determine recovery from sandy soil. Table 5 shows the results of the fuel experiments, using parameters shown in Table 3.

There were at least two reasons why the recovery of liquid fuel was much better in experiment 1 compared to experiment 3. First, the extraction pipe was 7 cm closer to the soil surface during experiment 3, so that there was insufficient vacuum for drawing liquid gasoline that had seeped to the bottom of the tank. Secondly, because the moisture content of the sand was higher during experiment 1 higher than in experiment 3, gasoline was more effectively released from the more moist sand. On the other hand, concentrations of gasoline vapors were much higher in experiment 3 (up to 9%) compared to those of the experiment 1 (maximum of 4%), which shows that during experiment 3 gasoline was recovered mainly as vapors. Vaporization of gasoline during experiment 3 must have been improved by pressure shocks given by shorter intervals (2 min) than in experiment 1 (5 min). Even though volumes of gasoline vapors were not measured, on the basis of remaining fuel concentrations of the sand (0.2–1.5 wt.%), the total fuel recovery is about 70%, since vapors correspond to 5–6 l of gasoline as liquid.

Gasoline will very easily vaporize, especially in a vacuum. Fig. 5 shows a typical vapor pressure curve for the gasoline used. According to this curve, at a temperature of 15 °C, 30%

Table 5
Fuel yields of tank experiments

Experiment number	Fuel	Poured fuel	Extracted liquid (kg)	Total liquid recovery (%)	Amount of water (%)[a]	Fuel recovery as liquid (%)
1	Gasoline	10	3.6	49	ca. 50	24
2	Diesel oil	10	0.6	7	0	7
3	Gasoline	10	0.5	7	0	7
4	Diesel oil	10	15	186	ca. 90	19

[a] Estimation.

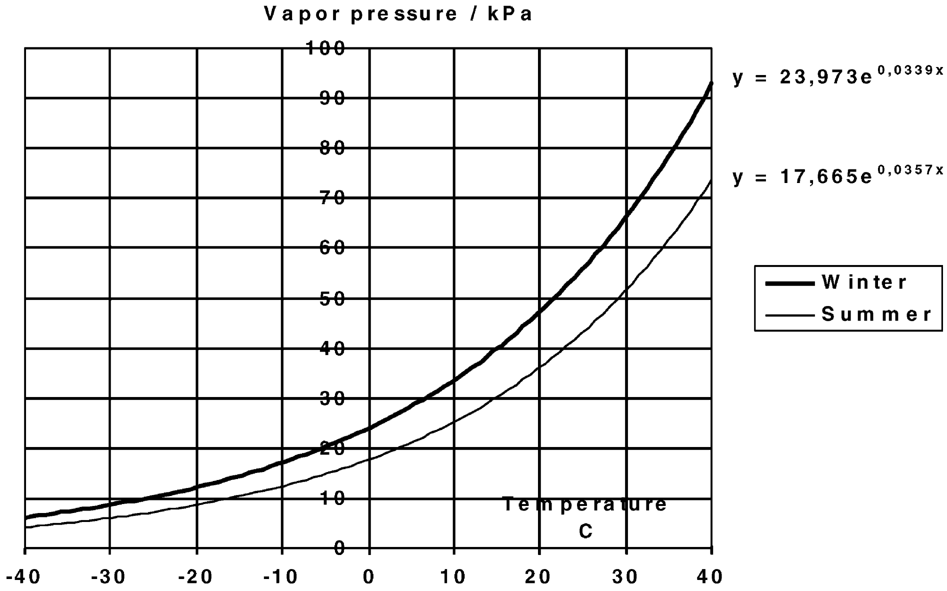

Fig. 5. Vapor pressure curve of gasoline used. Temperature range over 0 °C: (Aimo Rautiola, Fortum Company, Personal communication, 16 February 2000). Temperature range below 0 °C, calculated by S. Halmemies and by simulating gasoline with so called Pseudo component composition [7] and by using the equation of Clausis–Clapeyron [8].

of summer type gasoline is already vaporized. At a vacuum of 40 kPa (absolute pressure of 60 kPa) gasoline boils at 33 °C (corresponding to a vapor pressure of 100 kPa). Vapor pressure at 15 °C (30 kPa) is 50% of the value of 60 kPa, which means that 50% of gasoline is vapor at 60 kPa. According to this in our case at least 50% of the gasoline was in vaporized form.

In the experiments made with diesel oil, the effect of soil moisture could be seen more clearly. In experiment 2 diesel recovery was 0.6 kg (soil moisture 4.5%) compared to 1.5 kg of the experiment 4 (soil moisture 9.4%). Because of the large amount of water recovered during experiment 4 (90% of liquid), the amount of diesel recovered is only an estimate. However, the higher the soil moisture content the more easily fuel can be recovered, since soil pores filled with water. On the basis of the remaining concentrations of diesel oil in the soil, total diesel recovery can be estimated to be between 25 and 40%, where an amount of vapors corresponding to 1–2 l of liquid in a vacuum was used. It is clearly much more difficult to remove diesel oil from the soil than gasoline; diesel oil is not only heavier, but especially many times more viscous than gasoline. Moreover diesel oil has a much lower vapor pressure than gasoline.

3.2. *Basin experiments*

Experiments in the research basin were made to give a better view of real scale accidents. Table 6 shows the results of the four different experiments made under the conditions described in Table 4.

Table 6
Fuel yields of the experiments done in the research basin

Experiment number	Fuel type	Poured fuel (l)	Pumped as liquid from pool (l)	Removed as liquid from soil (l)	Removed as vapors from soil (l)[a]	Total recovery liquid + vapour (%)	Residual in soil (l)[b]
5	Gasoline	100	0	8	74	82	16
6	Gasoline	100	16	1	23	40	30
7	Diesel oil	100	27	1	2	30	70
8	Gasoline	100	0	0	55	55	33

[a] Calculated on the basis of the average vapor concentrations (see Table 7) and air flow rates measured, and converted to correspond gasoline as liquid. For diesel oil an estimate.

[b] Estimated on the basis of the maximal residual fuel concentrations of the soil analyzed by a gas chromatograph (see Table 7).

Table 6 shows that the PER-method is effective in both summer and sub-zero conditions. In experiments 5 and 8 it was possible to recover up to 70–80% of gasoline from the gravely sand as a fresh product, most of it as vapors. The small amount of liquid recovered does not reflect any inherent weakness in the PER-method, but can be attributed to the fact that in the vacuum in the recovery container (maximum 0.4 bar), at least 50% of gasoline is present as vapors. In addition, vaporization has been increased by the use of compensation air pipes (experiments 5 and 8) and an airflow caused by the vacuum pump. It has been estimated that vaporization of gasoline increases by a factor of about six when wind or in this case airflow speed increases from 1 to 10 m/s [3]. Even in winter conditions, when the soil was frozen to a depth of 70–80 cm below the ground surface, it was possible to recover a large volume of gasoline vapors with a maximal concentration of 9 vol.%. Because of vaporization, even in experiment 6 only 30% of the initial amount of gasoline left in the soil. Experiment 7 shows that it is much more difficult to recover heavy and viscous diesel oil than gasoline. The four experiments are not totally comparable, because compensation air pipes were used only in experiments 5 and 8; they seem to increase the extraction effect to a remarkable extent. In addition experiments 6 and 7 lasted only 50–60 min, compared to the 2 h duration of experiments 5 and 8.

Table 7 shows the maximal residual fuel concentrations in soil after the extraction, gasoline concentrations measured during the extraction, the retention capacities of the soils and the estimated amount of fuels vaporized from pools. Soil vapor concentrations were measured to ascertain dispersal of fuels in the soil. The highest concentrations (900–2200 mg/m^3) were obtained after experiments 6 and 8, which show that gasoline spread a little laterally both in sandy till and in the frozen gravely sand, but otherwise flow was mainly downward.

Table 7 shows that in case of gasoline experiments soil concentrations could be lowered below the short-term retention capacities of the soil. In other words, it is possible to slow spreading of gasoline during the first 2 h to such an extent that pollution of groundwater is prevented, the purpose of an response. This kind of first response provides extra time for further remediation of polluted soil, which can be continued with the aid of the same equipment or a similar technology, to reach acceptable levels for contaminated soils, namely 0.08 wt.% for gasoline and 0.5 wt.% for oils, [10]. In the case of diesel oil the results are not so good and were adversely affected still further because the extraction pipe was first sunk too low (50 cm). However, gasoline is a much greater risk for groundwater, because it penetrates at a rate 3 (sandy till) to 5 (gravely sand) times faster than diesel oil [3].

In gasoline experiments (5, 6 and 8) concentration of BTEX-compounds, MTBE and TAME both TVOC were analyzed from samples taken from soil and gasoline vapors. They indicated that MTBE vaporizes very easily (highest concentration measured, 45 000 mg/m^3). On the other hand, MTBE has the greatest water solubility of the compounds analyzed (ca. 4 wt.% as pure chemical and ca. 0.4 wt.% as a part of gasoline at 20 °C). Water solubility increases when temperature decreases, as is case in the groundwater; so at 0 °C it is ca. 8 wt.% [11]. The highest soil concentration of MTBE (1200 mg/kg) was measured after experiment 6 from sandy till (moisture content 4.8%); in gravely sand (experiments 5 and 8) concentration of MTBE varied between 0 and 470 mg/kg after the extraction. In experiments 5 and 6 the soil was rather dry (3.5–4.8%), but in wetter conditions MTBE contamination of groundwater is a greater risk. This is particularly so in Finnish shallow soil conditions,

Table 7
Residual fuel concentrations, vapor concentrations of gasoline, vaporization and the retention capacities of the soils

Experiment number	Fuel type	Soil type	Maximum residual fuel concentration in soil (wt.%)	Average vapor concentration of extra air (g/m^3)[a]	Amount of vaporization from pool (l)[b]	Retention capacity, 2 h (wt.%)[c]	Retention capacity, (wt.%)[d]
5	Gasoline	Gravely sand	0.7 (0.7 m)	170	2	3	0.4
6	Gasoline	Sandy till	1.5 (0.5 m)	60	30	6	>0.8
7	Diesel oil	Gravely sand	5.8 (0.7 m)	Not measured	0	5	3
8	Gasoline	Gravely sand	0.6 (0.7 m)	120	12	3	0.4

[a] Measured by a gas chromatograph (experiments 5 and 6) and an explosimeter (experiment 8, average value of 4 vol.%).

[b] Estimated on the basis of Gasoline Spill model Saku [3].

[c] Short time (2 h) retention was determined in column experiments [3].

[d] Indicative values determined for coarse sand (experiments 5, 7 and 8) both for silty sand (experiment 6). Given as vol.% and converted to wt.%. [9].

where the water table is typically located 2–4 m below the surface [12]. In general, the highest soil concentrations were measured from sandy till.

3.3. Critical evaluation of the results

On the basis of the column experiments made earlier, our main interest concerned recovery of gasoline from sandy soil. Accordingly, experiments 6 and 7 were conducted to give information on effects of soil and fuel types to recovery. Even if the results of experiments 6 and 7 are not as good as in the case of experiments 5 and 8, the PER-method turned out to be effective.

Because of expenditure constraints it was not possible to change soils after each experiment, so we divided the basin into four equal squares (4.5 m × 4.5 m), where 100 l of fuel was allowed to seep into the soil over an average area of 1 m^2. This corresponds to a situation in which, as a result of a real transportation accident, about 30 m^3 of fuel would be spilled on the ground, forming a pool with a diameter of 10 m (e.g. 100 l of fuel per 1 m^2). This volume of fuel can be retained within a few cubic meters of soil, but this does not prevent migration of, for example, MTBE below the water table.

In gasoline experiments (5, 6 and 8) the percentages of total gasoline recovery were calculated in two ways: firstly on the basis of liquid and vapor recovery, and secondly, on the basis of the residual gasoline concentrations of the soil measured; the remainder of the original volume of gasoline is assumed to be vaporized. The amount of gasoline recovered as vapors in experiments 5–6, and 8 were obtained by multiplying about 50% of the air flow rates, 300–500 m^3/h (air flow velocities, 9–14 m/s, measured by a Pitot-tube) with gasoline concentration, 2–6 vol.% (measured by an exposimeter and a gas chromatograph). The greatest uncertainty concerns recovery of gasoline vapors, their concentrations and especially their flow rates. There were differences in concentrations measured by different instruments, but both values were used (Table 7). Only a few soil samples from different depths could be taken for analysis, but on the basis of these, the residual gasoline concentrations were estimated. Despite the potential uncertainty in the results, this does not alter the conclusion that the PER-equipment is useful and suitable for development and commercial production.

3.4. Improvement to be made for PER-equipment

Modifications have already been made to overcome deficiencies in the PER-equipment used in the basin experiments. For example, the results of experiments 7 and 8 could have been improved, if the extraction pipes had been sunk immediately to the right depth. Because it is impossible to know this depth exactly, two different extraction pipes sunk to different depths will be used at the same point, to ensure optimal recovery. In a large spill more extraction pipes need to be used. In addition, during experiment 8, which was conducted in sub-zero winter conditions, gasoline vapors remained wet and could not burn after being passed through a layer of water-glycol mixture in the burner. The final incinerator will not include water and is still much smaller than the barrel used in the experiments. The PER-response will be available in its final form during autumn 2002.

4. Conclusions

The tank and basin experiments showed that the PER-method, in its simplicity, is an effective technique for recovering fresh fuel spills from the soil. It is best suited for extraction of gasoline-like volatile compounds from permeable sandy soils. PER-equipment used immediately after the spill will efficiently collect a significant amount of fuel spill, prevent spreading of fuels, and give extra time for further remediation. Residual fuel concentrations of soil (<1 wt.%) reached by the 2 h response are enough to stop spreading of fuel, but the vacuum extraction can be continued with the same equipment or the corresponding technologies to attain the acceptable residual concentrations. PER-equipment is primary intended as a practical initial response system, but it can be used for further remediation as well. Additional tests also showed that even many weeks after the basin experiments, it was still possible to extract gasoline vapors (0.5–3 vol.%) from the sandy soil by PER-equipment.

If gasoline spills on sandy till, a pool will remain for a relatively long time before it penetrates into the soil. This provides first responders with the opportunity of recovering a large proportion of gasoline directly from the pool by transfer pumping. On the other hand, the longer gasoline remains as a pool, the more of it vaporizes into the atmosphere. Vacuum extraction from till soil is not so effective, but neither does fuel seep so quickly into it. In the case of diesel oil spills, a lot of liquid can be recovered from a pool even in sandy soil. Vaporization of diesel oil is very slow, but so is extraction from the soil.

Acknowledgements

The main development work for the PER-equipment has been made with the aid of Emergency Services College and Pohjois-Savo PolyTechnic. In addition we thank Mr. Erkki Karttunen, Lic. Eng. for managing the development project, Mr. Ilari Seppä, Ph.D. for providing advice concerning response equipment, and Mr. Mikko Parviainen for participating in the column experiments. Mr. Risto Lautkaski, Lic. Phil., from Technical Research Center of Finland, is to be thanked for clarifying equations of vaporization. Golder Associates Ltd., and their Managing Director, Mr. Yrjö Lintu and Mrs. Anniina Määttänen, M.Sc., deserve thanks for taking care of chemical analyses for the basin experiments. Mr. Arto Hyvönen, geologist, Geological Survey of Finland, took soil samples and arranged geological analyses of the soils.

References

[1] S. Halmemies, K. Nenonen, T. Tuhkanen, Development of chemical response methods for fire and rescue services, in: S. Autio (Ed.), Current Research 1999–2000, vol. 31 (special paper), Geological Survey of Finland, 2001, pp. 123–131.

[2] S. Halmemies, M. Vuorinen, A. Mayer, T. Tuhkanen, Vacuum based recovery of fresh fuel components in laboratory scale column experiments, Ground Water Monitoring and Remediation, 2002, submitted for publication.

[3] S. Halmemies, S. Gröndahl, K. Nenonen, T. Tuhkanen, Estimation of the time periods and processes for penetration for selected spilled oils and fuels in different soils in the laboratory, Spill Sci. Technol. Bull. 8 (2002).

[4] Working Instructions of Soil Laboratory, Geological Survey of Finland, Finnish, 2000.
[5] R.H. Perry, C.H. Chilton, Chemical Engineers' Handbook, 5th ed., McGraw-Hill, New York, 1973.
[6] How to evaluate alternative cleanup technologies for underground storage tank sites: a guide for corrective action plan reviewers, EPA 510-B-95-003 and EPA 510-B-95-007, 1995, Last updated on Wednesday, 16 January 2002, URL: http://www.epa.gov/swerust1/pubs/tums.htm.
[7] Engulf, Computer programme, Version 1.5, AEA Technology, Culcheth, Warrington, UK, 1991.
[8] P.C. Johnson, M.W. Kemblowski, J.D. Colthart, Quantitative analysis for the cleanup of hydrocarbon-contaminated soils by in situ soil venting, Ground Water 28 (1990) 413–429.
[9] M. Nikkarinen, (Ed.), Geological data for community planning. Theme maps of Iisalmi community. Geological Survey of Finland, Guide 39, Espoo, Finnish, Finland, 1995, p. 49.
[10] J.E.T. Moen, J.P. Cornet, C.W.A. Evers, Soil protection and remedial actions: criteria for decision making and standardization of requirements, 1986, in: Proceedings of the First TNO Conference on Contaminated Soil, 11–15 November 1985, Utrecht. Ministry of Housing, Physical Planning and the Environment 1983. Implementation of the Soil Clean-up (Interim) Act—assessing the severity of a case of soil contamination in The Netherlands.
[11] OVA-instructions, Instructions for Emergencies Involving Certain Hazardous Materials, Methyl tertiary butyl ether, Chemas Oy, Finnish, Last updated 17 December 1999, URL: http://www.occuphealth.fi/ttl/osasto/tt/OVA/fmtbe.html.
[12] J. Airaksinen, Hydrology of Soil and the Groundwater, Oulu, Oy Pohjoinen, Finnish, 1978, p. 248.