



BIODEGRADATION OF JET FUEL (JP-8) IN THE PRESENCE OF VEGETATION

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ABSTRACT

The environmental impact of spills of JP-8, a kerosene-based jet fuel, has been studied very little. For the more volatile JP-4, earlier studies showed that biodegradation was less important than evaporation but for JP-8, evaporative loss from soil is very slow. Disappearance of JP-8 from watered mesocosms was monitored over several months. In two, 10-cm wide x 35-cm deep x 180-cm long channels planted with alfalfa, an initial 1700 ppm level of JP-8 was reduced by more than 90% at most depths of the channels, in less than five months. Growth of the plants was excellent despite the initially high level of contamination introduced near their roots. Both drip irrigation and subsurface watering gave comparable results. In planted (with horseradish) and unplanted cylinders, an initial level of 2500 ppm was reduced by at least two-thirds over the same time interval. By contrast, JP-8 in dry soil at a depth of 20 cm lost just half its weight over 18 months. Bioremediation of JP-8 in the presence of plants is an effective means of cleanup.

Key words: jet fuel, bioremediation, alfalfa, drip irrigation, JP-8

INTRODUCTION

Jet fuels were formerly supplied for turbine engines in grade JP-4 (low vapor pressure) and grade JP-5 (high flashpoint). Less volatile jet fuels such as grade JP-7, JP-8, and JP-T (thermally stable), were supplied for special aircraft. During the 1990's, many units of the U.S. Air Force changed their usage of fuel from JP-4, in use since the 1950's, to JP-8. JP-4 is a wide-cut petroleum distillate exhibiting compounds from the lighter naphtha fraction as well as the kerosene fraction of petroleum. JP-8 typically ranges in composition from 6-carbon hydrocarbons to 18-carbon hydrocarbons (Mayfield, 1996).

The Air Force is now in the process of changing operations at its installations within the continental U.S. to use JP-8 in place of JP-4. This changeover has required the alteration of many environmental impact estimates. There are few studies conducted on fate and environmental effects of JP-4 and JP-8. Results of experiments conducted in aquatic systems indicate that evaporation was the major loss for low molecular weight hydrocarbons in JP-4 and JP-8 (Spain and Somerville, 1985; Dean-Ross et al., 1992). An experimental study on fate of JP-8 in soil showed that higher molecular weight hydrocarbons were removed significantly faster in soils with indigenous microbial populations than in sterile soil (Dean-Ross et al., 1992). Similar study on fate of JP-4 in soil concluded that biodegradation contributed to the removal of the higher molecular weight fraction of JP-4 from soil (Dean-Ross, 1993). The above two studies suggest that for the less volatile hydrocarbons, manipulation of conditions to enhance biodegradation may increase their rate of removal from the terrestrial environment. Results of a study on the biodegradation of JP-4 in a contaminated aquifer indicate that biodegradation was compound specific (Aelion and Bradley, 1991).

Evaporation is undoubtedly a major fate of jet fuels in the terrestrial environment; however, biodegradation has the potential to lessen the environmental impact of less-volatile hydrocarbons. By manipulating the soil physical, chemical, and biological conditions, biodegradation of jet fuels can be enhanced. This may increase their rate of removal from the terrestrial environment. A study was undertaken to assess the biodegradation of jet fuels (JP-8) in soils and the toxic effects of JP-8 on vegetation. This paper presents the results of the experimental study.

EXPERIMENTAL SECTION

Two vegetated systems were used to study the fate of JP-8 in the presence of vegetation: two-channel system and four-column system.

Two-Channel System

For the experimental study, a large chamber with 25-mm thick slate walls used in a previous biodegradation experiment was chosen. The chamber was 40 cm wide, 90 cm long, and 35 cm deep. The chamber was divided axially into two equal halves, each with a width of 20 cm. Each half was further divided by a 78-cm long wall into two halves, each with a width of 10 cm. Thus, the chamber consisted of two U-shaped channels 10 cm in width, 180 cm long, 35 cm deep, with inlet and outlet holes 5 cm from the bottom. The chamber construction and schematic details can be found elsewhere (Narayanan, 1994).

The channels were filled with sandy soil collected near the Riley County landfill located south of Manhattan, Kansas. The soil physical and chemical properties are given in Table 1. The soil had been contaminated with toluene, phenol, trichloroethylene (TCE), and trichloroethane (TCA) in previous studies. After a long period of drying down to volatilize TCE, the most recent contaminant, gas and soil TCE measurements were made. The gas and soil monitoring indicated that 99% of TCE was gone by December 1998. A total of 36 alfalfa plants (9 plants in each row) were grown at 10-cm spacing.

Channel one was subirrigated using a graduated 5-L reservoir that supplied water to the inlet located near the bottom. The water level in the reservoir was raised to allow natural flow of water through a nylon tube. Occasional plugging at the inlet was observed and rectified daily. Leachate, if any, was collected from the outlet and measured. Channel two was irrigated by four subsurface drip tubes along with one each at inlet and outlet ports. Each consisted of two 50-mL syringes connected with a Y tube and tubing to a glass tube inserted into the soil at 20 cm.

Four-column System

Four glass cylinders, 40-cm deep and 15-cm in diameter, were used in the study. The cylinders were filled with sandy soil collected near the Riley County landfill. The soil's physical and chemical properties are given in Table 2. The soil was previously contaminated with TNT and then watered with toluene, and most recently two of the cylinders had been exposed to the water soluble

portion of jet fuel for several months. A graduated reservoir with a capacity of 5 L was used to supply water from the bottom to subirrigate columns one and two; columns three and four were surface irrigated. Columns one and four were kept unvegetated and columns two and three were planted with four horseradish plants in each.

One-Column System

A 250-mL glass measuring cylinder cut off at 210 mL was used to conduct a separate study on the fate of JP-8 in air-dried soil. A known amount of JP-8 (10 mL) was added at the bottom of the cylinder and soil from the same location as that used in the two-channel and four-column systems was packed uniformly to fill the cylinder to the 200 mL mark. This column was kept in the laboratory for about 18 months and the weight loss was recorded periodically.

Soil Contamination

The soil systems were contaminated with jet fuel (JP-8). The physical properties of JP-8 used in the study are presented in Table 3. For the two-channel system, 3 mL of JP-8 was added at 20 locations in each channel on December 3, 1998, and again on January 1, 1999. Approximate locations were near plants. Holes were pre-drilled in channels with a screwdriver. An 18-gage cannula was used to inject JP-8 starting at about a 35-cm depth and gradually withdrawing to 15 cm. The holes were filled with the same soil to avoid volatilization. The overall average contaminant concentration* in the two-channel system was about 1700 mg of jet fuel/kg of soil. After injection, both channels were surface irrigated with 2 L distilled water to assure a moist surface that would limit volatilization of JP-8. For channel one, a siphon was set up from the 5-L reservoir such that there was a small head (approx. 3 cm) from inlet to outlet. This was at a level of 5 L on the reservoir and ought to give a water table at 27 cm below ground surface. After a day, the level had decreased to 3 L which was the static point of the outlet (no outflow). Water was regularly added, initially at 1 L/d, then at 2 L/d to get some outflow and moisten the entire soil system. Then water was added according to the water consumption rate by alfalfa plants with little or no saturated zone. The wells in the channel were monitored to maintain this condition.

Columns one and four each received approximately 10 mL of JP-8 on December 3, 1998. Holes were pre-drilled with a screwdriver and then an 18-gage cannula was used to inject 5 mL of JP-8 at two different locations starting at about a 35-cm depth and gradually withdrawing to 10 cm. The holes were filled with the same soil to avoid any volatilization. Another 10 mL of JP-8 was injected into column one and four on January 1, 1999. Following the fuel injection, each cylinder received about 330 mL distilled water, equivalent to a 2-cm depth over the entire surface. Columns 2 and 3 each received about 20 mL of JP-8 on January 1, 1999. An 18-gage cannula was used to inject 5 mL of JP-8 at four different locations. The overall contamination concentration in each

* The units are mg/kg of dry soil for the JP-8 and TPH data throughout the manuscript.

column was about 2500 mg of jet fuel/kg of soil. Four horseradish tubers (about 30 g wet weight each) were planted in columns two and three on the same day. Each cylinder subsequently received about 330 mL distilled water.

Sampling and Analysis

For the two-channel system, plants were harvested every month and dry biomass was determined; soil samples were collected on March 8 and May 5, 1999, and analyzed by gas chromatography (GC) on May 15, 1999. During the March sampling, a 0.9-cm diameter, 9-cm long brass cylinder with a wooden plunger was used. Soil cores were taken at eight different locations in each row of each channel at three depths (from top): 0-10, 10-20, and 20-30 cm. A composite sample of the eight locations was made for each of three depths and two rows of the two channels. Samples were kept frozen until analysis. Three g of subsample (in triplicates) was taken from each composite and used for total petroleum hydrocarbon (TPH) extraction. For the May sampling, a different sampling procedure was used. A 10 x 10-cm box was used to take soil cores at one location in only one row per channel at three depths: 0-10, 10-20, and 20-30 cm. Box samples were taken from the front row of each channel because of convenience of taking samples. Composite samples were made for each depth and each channel and frozen until analysis. A subsample (in triplicate) of 3g was taken from the composite and used for TPH extraction. The analysis was replicated.

For the four-column system, a destructive sampling was done on May 30, 1999. Each column was divided into three segments (from top): 0-10, 10-20, and 20-30 cm. Soil from each segment was thoroughly mixed and a composite sample of about 500 g was taken and stored in a freezer until analysis. Approximately 200 g of soil out of 500 g was sent to the soil testing lab for physical and chemical analysis. A subsample of 3g for each of three replicates was taken from each composite and used in the TPH extraction.

For the one-column air dried system, a destructive sampling was done. The column in the graduated cylinder was divided into four equal segments (from bottom): 0-50, 50-100, 100-150, 150-200 mL. Soil from each segment was thoroughly mixed and a 3 g subsample was taken from each segment and used in the TPH extraction.

Extraction of petroleum hydrocarbons from soil was done by mechanical shaking procedure, developed by Schwab et al. (1999). The procedure involved weighing 3 g of soil in a foil-lined 20-mL scintillation vial, adding 10 mL of Optima[®]-grade acetone and a matrix recovery standard, shaking for 30 min in a reciprocating platform shaker at 120 cycles/min, centrifuging for 10 min at 2100 rpm, and collecting supernatant in a 60 mL-foil-lined bottle. This was repeated three times. The combined extract was weighed and 1 mL of extract was transferred to a 2-mL GC vial along with an internal standard. A set of JP-8 standards was prepared with the same matrix and all GC vials were stored in the freezer until analysis.

Analysis of the sample was performed on a 5890A Gas Chromatograph (Hewlett-Packard, Avondale, PA) with Chemstation© integration software and HP7673A auto sampler. The GC utilized a DB-TPH column (J & W Scientific, Folsom, CA). The 5890 GC was equipped with a flame-ionization detector. The column specifically designed for TPH analysis had dimensions of 0.32-mm inside diameter, 30-m length, and 0.25-mm film thickness. The fuel and carrier gas was H₂ (99.999%). The carrier gas was delivered at 4.0 mL/min and the fuel gas at 40 mL/min. The make-up gas was N₂ (99.999%) at a flow rate of 32 mL/min. A support gas of zero-grade air was delivered at 420 mL/min. The temperature program began at 40°C for two minutes and rose at 12°C/min to 320°C, and was held at 320°C for one minute. The injection port and detector temperatures were 250°C and 350°C, respectively. The injection volume was 2 mL splitless.

RESULTS AND DISCUSSION

Alfalfa Production in the Contaminated Soil

In general, alfalfa growth in the chamber was good. The above-ground dry biomass production varied from 70-110 g/m²/30 days which corresponds to 7-11 metric ton/ha/yr. In Kansas, alfalfa production of 20 metric ton/ha/yr is considered to be a good yield under field conditions. The plants were grown under growth-chamber conditions, lighted by artificial lights with relatively lower intensities than sunlight, which resulted in lower yield under those conditions. The dry matter production was reasonable and alfalfa plant growth was not affected by JP-8 in soil.

Gravimetric Water Content: Two-Channel System

The gravimetric water content for channel one, front row, increased with depth (Table 4); this may be due to feeding water from bottom. However, for channel one back row, the water content was more uniform with depth (Table 4). The water inlet was into the back row, which might have resulted in more uniform wetting of the back-row soil profile. In channel two, the soil profile had the lowest water content at the top 0-10 cm and highest at the bottom 20-30 cm (Table 4). The subsurface drips emitted water 20 cm below the soil surface, which might cause higher water content in the middle and bottom 10 cm of channel two. In general, the water content at 10-20 cm and 20-30 cm of channel one was much higher than that of channel two even though the amount of water supplied was similar. The water content in top 10 cm was almost identical in both channels except for the back row of channel one. Most of the alfalfa roots were concentrated in the top 10 cm and some of the water in the top 10 cm was transpired. Due to transpiration and evaporative losses, the top 10 cm of the channels had the lowest moisture content. The values reported are for one point in time; one would expect transient variations due to periodic harvesting and ambient conditions. The average values of water supplied in Table 4 are for the entire channel.

Gravimetric Water Content: Four-Column System

For column one, the water content increased with depth (Table 5); this is primarily due to

feeding water from bottom. Column two had the highest water content at 10-20 cm (Table 5). This column had horseradish plants with roots extending down to 30 cm. The roots appear to affect the water distribution significantly. Columns one and two are both subirrigated from the bottom. Column three was surface irrigated, and had its highest water content at 0-10 cm and its lowest at 10-20 cm (Table 5). This column had horseradish plants with roots concentrated between 0 and 15 cm of the soil profile. Column four which was unvegetated, had its highest water content at 10-20 cm and its lowest at 20-30 cm (Table 5). Between column one and column two that were fed from bottom, column two had higher water content than that of column one; however, significantly more water was evapotranspired as well. Between columns three and four that were fed from top, column four had a higher water content than that of column three in the top 20 cm. It should be noted that column three had a free outlet and column four had a closed bottom. However, there were only a few occasions when leachate appeared in column three and the amount of leachate was not significant.

Total Petroleum Hydrocarbons: Two-Channel System

Table 6 shows the TPH levels in a two-channel system on March 8, and Table 7 shows the TPH levels in the front row of a two-channel system on March 8 and May 5. The TPH levels varied with depth and position of the row (Table 6). Initially the overall average contamination level was about 1700 mg of jet fuel/kg of soil. After three months, the mean concentration had decreased to 215 mg of jet fuel/kg of soil in the top 10 cm of the front row of channel one (Table 6). The mean concentration in the middle layer was 1249 ppm, and in the bottom layer it was 405 ppm. For the back row of channel one, the concentration of jet fuel was below detectable limits (GC detection limit was 100 ppm*) in the top and bottom layers (Table 6). The concentration in the middle 10 cm was 242 ppm (Table 6). On March 8, the water content was higher in the back row of the channel one than that of the front row of the channel (Table 4). This higher moisture content might have facilitated microbial degradation of jet fuel compounds. If one assumes the initial distribution is uniform, the reduction in jet fuel concentration in the front row of channel one varied from 87% (0-10 cm) to 27% (10-20 cm) (Table 6). For the back row of channel one, the reduction of JP-8 varied from almost 96% (0-10 cm and 20-30 cm) to 88% (10-20 cm) (Table 6). The standard deviation of JP-8 concentration was higher than 25% of mean concentration in several cases (Table 6). However, this much spatial variability is rather usual in similar systems (Schwab et al., 1999). This might be due to the extraction procedure itself (Schwab et al., 1999), sampling and sub sampling processes, and overall soil heterogeneity.

There was a significant reduction in TPH concentrations in the front row of channel one from March to May (Table 7). The reduction in TPH concentration varied from almost 74% (20-30 cm) to 41% (10-20 cm) (from March to May). The TPH levels in the top and bottom layers for May

* Values below the detection limit were assigned a value of 50 mg/kg of soil in finding the mean value.

were near or below detection limits and the TPH concentration in 10-20 cm was 732 ppm (Table 7). After five months, the mean jet fuel concentration in the front row of channel one ranged from 732 ppm (10-20 cm) to non-detectable limits. This clearly shows a significant reduction in the TPH concentrations. The overall reduction (from January to May) of TPH concentration varied from 57% (10-20 cm) to 96% (0-10 cm).

After three months, the mean TPH concentration in the front row of channel two was decreased to below detection limits in the top 10 cm (Table 6). The mean concentration in the middle layer was 198 ppm and in the bottom layer was 148 ppm with standard deviation of 99 ppm (Table 6). For the back row of channel two, the concentration of jet fuel was below detectable limits in all layers (Table 6). The reduction in jet fuel concentration in the front row of channel two varied from almost 95% (0-10 cm) to 88% (10-20 cm) (Table 6). For the back row of channel two, the reduction of JP-8 was about 96% throughout the soil profile (Table 6). The standard deviation of JP-8 concentration was higher than 25% of mean concentration in several cases but was less than 100 for all cases in channel two.

There was a significant reduction in TPH concentrations in the front row of channel two from March to May (Table 7). The TPH levels in the top and bottom layers for May were below detection limits and the TPH concentration in 10-20 cm was only 128 ppm (Table 7). After five months, the mean jet fuel concentration in channel two ranged from 128 ppm (10-20 cm in the front row) to below detection limits elsewhere. This clearly shows a significant reduction in the TPH concentrations. Channel two with distributed drip irrigation had lower water content and lower residual TPH values. Superior results with drip irrigation were also reported by Lewis who compared TPH degradation using surface irrigation and drip irrigation for grasses (Lewis, 1998).

Total Petroleum Hydrocarbons: Four-Column System

Table 8 shows the TPH levels at different depths in a four-column system. For column one, the mean TPH concentration was 101 ppm in the top 0-10 cm, 177 ppm at 10-20 cm, and 517 ppm at 20-30 cm (Table 8). The overall initial concentration was about 2500 ppm which decreased to the above mentioned concentration levels after five months. The reduction in jet fuel concentration in column one varied from 96% (0-10 cm) to 79% (20-30 cm) (Table 8).

In column two, the TPH concentration was below detection limits in the top layer, 769 ppm in the middle layer, and 237 ppm with a standard deviation of 91 ppm in the bottom layer (Table 8). The reduction in jet fuel concentration in column two varied from almost 96% (0-10 cm) to 69% (10-20 cm).

For column three, the mean TPH concentration was below detectable limits in the top layer, 901 ppm in the middle layer, and 822 ppm in the bottom layer. Based on the overall initial concentration of 2500 ppm, the reduction in jet fuel concentration in column three varied from almost 96% (0-10 cm) to 64% (20-30 cm) (Table 8).

In column four, the TPH concentration was below detection limits in the top 0-10 cm, 137 ppm in the middle layer, and 777 ppm in the bottom layer (Table 8). The reduction in jet fuel concentration varied from almost 96% (0-10 cm) to 69%(10-20 cm).

In general, the standard deviations were more than 25% of the mean for all the columns (Table 8). This shows the heterogeneity of samples. Since 3-g subsamples were taken from 300-g bulk samples, some error is associated with sample size and representative sampling.

In general, the TPH concentrations in the top 10 cm were below detection limits (Table 8). The TPH concentration increased with depth for unvegetated columns one and four (Table 8). Columns two and three had the highest TPH concentrations in the middle 10 cm (Table 8). It is evident that the TPH concentrations at the deeper soil profile were higher than those in the top 10 cm (Table 8). This might be due to unfavorable conditions, such as low oxygen concentration prevailing at deeper soil profiles that may not facilitate biodegradation of jet fuel from the soil system. Unfortunately, most of the leaking of jet fuel and other petroleum hydrocarbons finds its way to deeper soil profiles which makes cleaning up of those soils very difficult. Plants can provide conducive environment through roots to those unfavorable zones by transpiring water, and supplying oxygen and other nutrients for microorganisms that could degrade jet fuel.

The biodegradation of hydrocarbons can be related to the soil-water content. Values of both TPH and water in the soil tend to be low near the soil surface where oxygen is available. Lewis (1998) also reported that the greatest disappearance of petroleum hydrocarbons was in the top portion of soil where oxygen is available and plant roots are numerous.

Total Petroleum Hydrocarbons: One-Column System

The TPH concentration for each segment of the air-dried column was converted to total mg of JP-8 for the whole column, about 3896 mg (data not shown). This corresponds to about 4.8 mL of JP-8. The periodic weight loss was attributed to loss of hydrocarbon. There was about 52% reduction in JP-8 over the period of 18 months. While there may have been some biodegradation, if we assume the air-dried soil did not facilitate microbial growth, we can consider this dry-soil system as a sterile control. This data implies that the maximum value of any abiotic loss due to volatilization and diffusion is 52%. We can conclude that if the reduction is more than 52%, that might be due to some other losses than abiotic. In our two-channel system and four-column system, the lowest overall reduction after five months was 57% (in two-channel system, 10-20 cm in channel one) (Table 6). But, for many of the cases the reduction was more than 90% (Table 6, 7, and 8). This clearly shows losses other than abiotic are also a major fate of JP-8 in vegetated soils. This agrees with a previous study which was conducted with soils (Dean-Ross et al., 1992). Our study shows promise in bioremediation of JP-8 contaminated soils with or without vegetation.

SUMMARY

There was a significant decrease in JP-8 concentrations in the two-channel and four-column systems. The losses were not just due to volatilization but also due to biodegradation. In both the channel systems and columns, the final TPH concentrations were close to the detection limit in the top 10 cm where oxygen is expected to be most available. This is a promising result that shows manipulating the JP-8 contaminated soils, either by adding water to maintain sufficient moisture for microbial growth or by growing plants, could result in faster restoration of those soils. Bioremediation or plant-assisted bioremediation may be a feasible and inexpensive method to clean up JP-8 contaminated soils. Further studies should be conducted to assess the influences of plant-induced upward water movement on JP-8 biodegradation in soils.

ACKNOWLEDGMENT

This work was partially supported by the U. S. EPA and the U. S. Air Force through the Great Plains/Rocky Mountain Hazardous Substance Research Center under assistance agreements R-819653, R-825549, and R-825550. It has not been submitted to the EPA for peer review and, therefore, may not necessarily reflect the views of the agency and no official endorsement should be inferred. The center for Hazardous Substance Research provided partial support. We acknowledge Dr. K. Xia for use of and assistance with the instrumentation in Throckmorton Plant Sciences Center, Kansas State University.

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Table 1. Physical and chemical properties of soil in two-channel system*.

Soil Property	Top Layer (0-10 cm)		Middle Layer (10-20 cm)		Bottom Layer (20-30 cm)	
	Channel 1	Channel 2	Channel 1	Channel 2	Channel 1	Channel 2
pH	7.4	6.6	6.7	5.9	6.6	6
Sand (%)	82	90	88	90	90	90
Silt (%)	16	8	10	8	8	8
Clay (%)	2	2	2	2	2	2
Extractable NO ₃ ⁻ -N (mg/kg)	4.3	1.4	0.4	0.4	0.3	0.4
Extractable NH ₄ ⁺ -N (mg/kg)	8.1	4.9	1.8	2.1	1.0	5.3
Bray P (mg/kg)	35	26	51	33	37	27
Organic Matter (%)	1.1	1.0	0.6	0.7	0.6	0.6

* Data from samples taken on March 8, 1999.

Table 2. Physical and chemical properties of soil in four-column system* .

Soil Property	Top Layer (0-10 cm)				Middle Layer (10-20 cm)				Bottom Layer (20-30 cm)			
	Column				Column				Column			
	1	2	3	4	1	2	3	4	1	2	3	4
pH	5.7	5.8	5.3	6.3	6.1	5.9	5.6	6.5	5.9	5.7	5.8	6.7
Sand (%)	90	88	88	88	90	92	92	90	94	94	94	96
Silt (%)	8	10	10	10	8	6	6	8	4	4	4	2
Clay (%)	2	2	2	2	2	2	2	2	2	2	2	2
Extractable NO ₃ ⁻ -N (mg/kg)	24.3	0.8	0.6	1.3	0.0	0.4	0.5	0.4	0.4	0.0	0.6	0.4
Extractable NH ₄ ⁺ -N (mg/kg)	5.5	4.5	7.1	7.0	2.5	4.6	3.5	4.9	1.6	3.5	2.4	3.0
Bray P (mg/kg)	23	14	19	25	23	13	15	19	12	12	12	7
Organic Matter (%)	0.7	0.9	0.7	1.1	0.4	0.6	0.4	0.7	0.2	0.2	0.1	0.2

* Samples were taken on May 30, at the end of the study.

Table 3. Properties of jet fuel (JP-8) used in the study.

Property	
Specific Gravity	0.8
Color	Light Yellow
Distillation Boiling Point (°C)	
Initial	159.5
Final	263.5
Average	215.2
Freezing Point (°C)	-48
Flash Point (°C)	56

Table 4. Gravimetric water content in the two-channel system on March 8, 1999.

Channel	Gravimetric Water Content (g of water/g of dry soil)			Water Supplied g/day
	0-10 cm	10-20 cm	20-30 cm	
Channel 1 (Front Row)	0.116	0.166	0.187	1000
Channel 1 (Back Row)	0.183	0.199	0.187	
Channel 2 (Front Row)	0.121	0.149	0.151	1036
Channel 2 (Back Row)	0.114	0.138	0.140	

Table 5. Gravimetric water content in the four-column system on May 30, 1999.

Column	Gravimetric Water Content (g of water/g of dry soil)			Water Supplied (g/day)
	0-10 cm	10-20 cm	20-30 cm	
Column 1	0.115	0.121	0.169	30
Column 2	0.173	0.197	0.161	75
Column 3	0.165	0.142	0.154	76
Column 4	0.178	0.190	0.143	70

Table 6. Total petroleum hydrocarbon concentration (mean and standard deviation) in two-channel system on March 8, 1999. Initial contamination was 1700 mg/kg.

Location	Channel 1	Channel 2
Front Row		
0-10 cm	215 ± 59	89 (2ND) ± 68
10-20 cm	1249 ± 355	198 ± 22
20-30 cm	405 ± 118	148 ± 99
Back Row		
0-10 cm	75 (2ND) ± 43	50 (3ND) ± 0
10-20 cm	242 ± 96	68 (2ND) ± 32
20-30 cm	50 (3ND) ± 0	70 (2ND) ± 35

[ND = non detectable; detection limit of the GC was 100 mg/kg of soil; values below the detection limit were assigned a value of 50 mg/kg of soil]

Table 7. Total petroleum hydrocarbon concentration in the front row of two-channel system on March 8, 1999 and May 5, 1999. Initial contamination was 1700 mg/kg.

Date/Location	Channel 1	Channel 2
March		
0-10 cm	215 ± 59	89 (2ND) ± 68
10-20 cm	1249 ± 355	198 ± 22
20-30 cm	405 ± 118	148 ± 99
May		
0-10 cm	76 (2ND) ± 45	50 (3ND) ± 0
10-20 cm	733 ± 109	128 (ND) ± 70
20-30 cm	107 ± 59	76 (2ND) ± 46

[ND = non detectable; detection limit of the GC was 100 mg/kg of soil; values below the detection limit were assigned a value of 50 mg/kg of soil]

Table 8. Total petroleum hydrocarbon concentration (mean and standard deviation) in the four-column system on May 30, 1999. Initial contamination was 2500 mg/kg.

Location	Column			
	1	2	3	4
0-10 cm	101 (2ND) ± 88	71 (2ND) ± 36	69 (2ND) ± 33	50 (3ND) ± 0
10-20 cm	177 ± 114	769 ± 98	901 ± 330	137 ± 97
20-30 cm	517 ± 269	237 ± 91	822 ± 210	777 ± 175

[ND = non detectable; detection limit of the GC was 100 mg/kg of soil; values below the detection limit were assigned a value of 50 mg/kg of soil]