

Movement of fuel spills in the Ross Ice Shelf

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Williams Field provides logistical support to McMurdo Station in Antarctica and manages large amounts of fuel for their cargo planes. Numerous spills have occurred at this site with little recovery or remediation of the spilled fuel. From 1980 to 1989, approximately 380,000 liters (L) leaked during documented fuel spills—197,600 L of that total came from one spill alone, in October of 1989, when fuel leaked onto the ice at Williams Field. An additional 20 spills of unknown quantities have also occurred at McMurdo Station and Williams Field. Although recent improvements in equipment and procedures in Antarctica have significantly reduced the accidental release of fuel and all but eliminated the risk of a large fuel spill, the potential for small releases still exists.

The open literature contains virtually no publications on the movement and fate of spilled fuel on ice shelves. To track the movement of fuel spills in ice more accurately and to establish the basis for remediation methods should a small release occur, the National Science Foundation funded a 3-year study by researchers at the Environmental Technology Laboratory/University of Alaska at Fairbanks. During the second field season of the project (1993–1994 austral summer), the research team was in Antarctica immediately following a small accidental fuel spill on the ice shelf near Williams Field. This spill served as the basis for an intensive study and provided significant information on the movement of fuel in the ice shelf.

The spill, which happened on 3 December 1993, came from a flexible pipeline midway between McMurdo Station and Williams Field, on the Ross Ice Shelf. A fuel-line-connection failure released an estimated 11,400 L of JP-8 on the ice. Because the fuel that spilled was originally above 0°C, heat transferred into the ice and created two cone-shaped holes approximately 2 meters (m) in diameter and 4 to 5 m deep. No remediation efforts were taken, and the site was marked “off limits.”

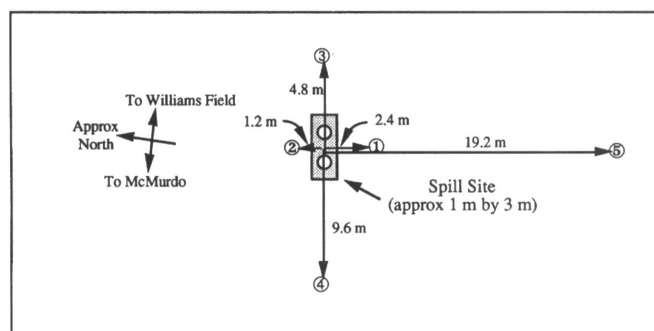
Cores were taken from five holes drilled by the Polar Ice Coring Office using a 10.16-centimeter drill. The holes were located in a spiral pattern from the spill epicenter. The figure shows the pattern and location of the five corings. Samples were taken from these cores at regular intervals of 1.5 m or less at particular points of interest such as at the top or bottom of the holes. The coring device was swabbed with butyl acetate each time before drilling to prevent cross contamination from the core barrel.

Temperature and density readings were taken at regular intervals from each hole. A standard snow/ice temperature-density kit was used at the site. Samples for laboratory analysis were cut from the ice cores with a hand saw that was swabbed with acetone between uses. The samples were stored in individual, double plastic bags and kept frozen until returned to the lab.

In the laboratory, samples were allowed to melt at 4°C. Each melted sample was transferred to an I-Chem® jar with a Teflon-lined lid and stored in a refrigerator. To prepare it for analysis by gas chromatography, each liquid sample was extracted with three successive washes of 10 milliliters (mL) of methyl chloride in a separatory funnel. The organic layer (lower layer in separatory funnel) was drained into a 40 mL glass vial with a Teflon-lined lid.

Samples were analyzed for nonvolatile hydrocarbons using a gas chromatograph. A total extractable petroleum hydrocarbon value was obtained by integrating the entire response curve. A standard curve was developed using known dilutions of JP-8 extracted under the same procedures as the samples. This method relies on the assumption that the mixture of nonvolatile hydrocarbons remains relatively constant between aged and nonaged fuels—a good assumption, given the fact that the biodegradation of the fuel, if it occurs at all, is slow. All analyses were conducted at the Crary Laboratory at McMurdo Station.

Cores were taken to approximately 18 m at all five sites. Salt water was encountered at approximately 16.5 m in all holes. Sampling had to be terminated at 18 m because the cores became too saturated with salt water. When the cores



Sampling locations and relation to spill site.

Contamination found at spill site with depth. (Total petroleum hydrocarbons is in milligrams per liter of melted ice; — denotes no sample collected at that depth; nd denotes no contaminant detected.)

Depth (m)	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0.3	4	nd	nd	nd	nd
0.6	—	914	—	—	—
1.5	nd	2,170	nd	nd	—
3.0	nd	1,861	nd	nd	nd
4.6	nd	669	2	nd	—
6.1	3	17,405	nd	nd	nd
7.6	nd	4,117	nd	nd	—
9.1	2	1,831	nd	nd	nd
10.7	nd	35,262	nd	nd	—
12.2	nd	6,748	nd	nd	nd
13.7	4	27,260	nd	8	—
15.2	10	488	12	15	nd
15.8	4,780	13,910	—	—	—
16.2	—	18,153	—	nd	nd
16.5	62,302	65,527	5	3	nd
16.8	41,574	—	15,258	29,327	nd
17.1	29,966	32,275	—	—	nd
17.4	—	17,129	74,556	5,769	nd
17.7	199	37	—	—	—
18.3	—	5	13	39	—
18.6	—	—	—	754	—

are completely saturated, the salt-water/ice mixture forms a “slush” that does not remain in the core barrel when the barrel is removed from the hole, so it is not possible to extract a core for sampling. The contamination profiles with depth for the five holes are given in the table.

The most significant finding is that almost all of the fuel had moved through the 16.5 m of snow/ice during the 1 month since the spill and spread out over 10 m horizontally. The fifth hole was drilled 19.2 m away from the spill site as a blank and showed no signs of contamination. Three of the holes (at distances of 2.4, 4.8, and 9.6 m from the spill) showed almost no contamination until the salt-water table, whereas one hole (located 1.2 m from the spill) exhibited large concentrations all the way down. This suggests that the fuel traveled almost straight down through the ice with little horizontal dispersion until it reached the point where the pores of the ice sheet were filled with salt water. At that point, the fuel then spread horizontally. Temperature and density in the ranges experienced in the ice sheet appear to have little effect in altering the direction of fuel movement.

By dividing the distance traveled by the time elapsed, we determined that the leading edge of the plume moved vertically at a minimum of 0.4 m per day. The leading edge, however, had to move much more quickly than this to allow time for the plume to spread horizontally. If we assume that the permeability in the ice that is not saturated with salt water is approximately equal in all directions (isotropic), we can estimate the minimum amount of time required for the plume to

move downward through the ice, then spread outward to the distances where contamination was found. In this way, a maximum rate of movement for the spill can be estimated. The formulas used for this calculation are

$$V_{ver} = \frac{16.5m}{T_{ver}} \quad (1)$$

$$V_{hor} = \frac{19.2m}{T_{hor}} \quad (2)$$

where T_{ver} is the time of travel from the surface to the salt-water table, and T_{hor} is calculated by

$$T_{hor} = 46days - T_{ver} \quad (3)$$

where 46 days is the total elapsed time from the spill event (3 December 1993) until the drilling of hole 5, 19.2 m away from the spill site. To estimate the rate of movement (gross permeability), first select an assumed value for T_{ver} and calculate a vertical rate. T_{ver} is then used to calculate T_{hor} and a horizontal rate. This process is repeated until the horizontal and vertical permeabilities are approximately equal. Using this method, a maximum permeability of approximately 0.8 m per day is found.

The data collected indicate that fuel spilled on an ice shelf will travel almost straight down from the spill site with very little horizontal dispersion until a confining layer of salt-water-saturated ice is encountered. At that point, the fuel will move horizontally, spreading out on top of the salt-water-saturated layer. The fuel appears to move rather rapidly, with an estimated maximum rate of 0.8 m per day, assuming isotropic conditions.

The rapid movement of the fuel downward with little to no horizontal dispersion means that recovering spilled fuel may be possible if actions are initiated rapidly after the spill. If a spill-response team were equipped with a drilling rig and a pump, the fuel could possibly be pumped out of the ice column, through one or several drill holes, before it spreads out at the salt-water level. Given the relatively high permeability of the ice as indicated by the data collected, this procedure could be relatively efficient. The fuel/ice/saltwater slurry appears pumpable. The pumping action should draw the fuel, along with the salt water, to the pump. The fuel and salt water could then be separated. The window of opportunity for such a remediation/recovery operation, however, would be small. In just a few days, the fuel would probably be too dispersed horizontally to allow for an effective recovery.

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