Response to concerns raised regarding impoundment of contaminated soils in permafrost, Polaris Mine, Little Cornwallis Island, Nunavut.

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Prepared for S.R. Morison, Gartner Lee Ltd, and Bruce Donald, Teck Cominco Ltd.

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The author is Professor of Geography at Carleton University, and has primary research interests in Permafrost and Ground Ice. The author's research is field-based, with the principal investigations being conducted near Mayo, central Yukon, and near the western Arctic coast. In 2001, Burn completed 20 consecutive summers' in the Mayo area. The field research in the western Arctic has been continuous since 1987. Burn has published 29 articles in refereed journals, 11 of which are in the *Canadian Journal of Earth Sciences*, Canada's flagship periodical for Earth Science. Burn has been retained by Water Resources Division, DIAND, Yellowknife, to provide advice regarding permafrost aspects of diamond mine developments in the Slave Province. Further details are listed on the attached vitae.

In 1995 Burn supervised a Master's thesis at Carleton University by Kim Winnicky entitled "On the permeability of frozen silt to organic contaminants". In 1996-97 he also conducted several tests to determine the permeability of frozen soil to diesel fuel. These were falling-head permeability tests conducted at temperatures down to -10ºC with sand and silt at various water contents. The results are unpublished due to a problem with the experimental apparatus, but the general behaviour of these media was qualitatively determined.

Introduction

Mr Paul Partridge, Department of Sustainable Development, Government of Nunavut, has raised an important question in review of the Polaris Decommissioning and Reclamation Plan regarding the long-term effectiveness of permafrost as a containment medium for soil contaminated with hydrocarbons. The question is posed in Mr Partridge's letter of October 25, 2001, to Phillipe di Pizzo and Carl McLean. Mr Partridge provided further details in an email communication to Wayne Savigny, BCG Engineering, sent on November 21, 2001.

The question is whether permafrost may be considered impermeable to organic contaminants. Four recent papers were cited in support of this point, all published in the *Proceedings of a Workshop/seminar on Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates* held in Edmonton during 1999. These papers are by Biggar and Nahir, Chuvilin *et al.*, Dyke, and White. The citations are:

Biggar, K.W., and Nahir, M. 1999. The behaviour of petroleum spills in permafrost soils. In *Proceedings, Workshop/seminar on Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, Edmonton, Alta., May 3-4, 1999*. pp. 45-51.

Chuvilin, E.M., Naletova, N.S., and Miklyaeva, E.M. 1999. Behabiour mineral and organic contaminants in permafrost. In *Proceedings, Workshop/seminar on Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, Edmonton, Alta., May 3-4, 1999*. pp. 52- 56.

Dyke, L.D. 1999. Solute migration from abandoned drilling mud sumps, Mackenzie delta area, N.W.T. In *Proceedings, Workshop/seminar on Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, Edmonton, Alta., May 3-4, 1999*. pp. 57.

White, T.L. 1999. Hydraulic properties of hydrocarbon contaminated permafrost affected soils. In *Proceedings, Workshop/seminar on Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, Edmonton, Alta., May 3-4, 1999*. pp. 58.

The abstract by Dyke has recently been published in full as:

Dyke, L.D. 2001. Contaminant migration through the permafrost active layer, Mackenzie Delta area, Northwest Territories, Canada. *Polar Record*, **37**: 215-228.

This response will outline the contributions of the papers that are pertinent to the question under discussion. These points will then be discussed in the context of the Polaris decommissioning plan. The stability of permafrost in the mine will be considered with respect to potential climate change.

Contaminant migration into frozen soils

Frozen soils are multi-phase media, consisting of soil particles, ice, water, and vapour. If saturated, the pore space of frozen soils comprises ice and water. If unsaturated, the pore space comprises water and varying amounts of ice or air. The water is held in tension as films on the surfaces of the soil particles, and does not behave as free or bulk water, the substance we commonly encounter. Instead, the water is at a lower energy state due to electrical forces emanating from the edges of the soil particles. The water is adsorbed on to the soil particles and cannot move freely. As a result, frozen soil has a relatively low hydraulic conductivity.

The adsorbed water is commonly referred to as “unfrozen” water. The amount of unfrozen water in a soil depends on its temperature, the surface area of soil particles and the solute concentration in the water. The amount declines with temperature below 0ºC, but increases with the surface area of soil particles and the concentration of solutes in the pore water. The unfrozen water content of a soil is directly related to its hydraulic conductivity. So frozen sands, with a low surface area have little unfrozen water and very low hydraulic conductivity, and frozen clays the reverse. For further details see Williams and Smith (1989).

Miscible and immiscible contaminants

There are, essentially, two types of contaminants. They are termed miscible in water or immiscible in water. Miscible contaminants dissolve in water and lower the freezing point of the solution. Road salt is a well-known miscible substance. When miscible contaminants are introduced into frozen ground, the pore ice dissolves in the contaminated, unfrozen, pore water. As a result, the contaminant may migrate into “frozen” ground, because the ground, below 0ºC has less pore ice to impede the flow of the solution through the pores. This is the type of contaminant migration described by *Dyke*, in his consideration of dispersion of drilling muds from sumps in the Mackenzie Delta area. The contaminants at Polaris are hydrocarbons, which are immiscible. These alter the behaviour of freezing soil in a different way.

Hydrocarbons do not dissolve in water, but they may be adsorbed by soil particles. *White* indicates that soil contaminated with hydrocarbons may change its microstructure upon freezing and thawing, so as to increase the permeability. The reorganization of the microstructure is achieved by aggregation of silt and clay in the presence of the contaminant, which tightens the packing of these particles. In other words, the contaminant is adsorbed onto the surfaces of the soil particles and increases the inter-particle attraction. The tightening of particle packing was accompanied by an increase in void space.

Movement of hydrocarbons into unsaturated soil

Chuvilin et al. present firm evidence from the laboratory that immiscible contaminants in the free liquid form may penetrate frozen soil. The observations in the laboratory are that hydrocarbon liquids, when applied to soil that is unsaturated by water (ice) and below 0ºC infiltrate the soil. The observations were replicated by Winnicky (1995) and in our own work. However, if the soil is saturated and frozen, little or no migration of contaminant into the soil has been detected. Similar observations are reported by Neufeld and Biggar (1996) as described by *Biggar and Nahir*. In some cases, however, in the experiments of Neufeld and Biggar (1996) a small amount of contaminant migration into saturated, frozen soil was detected. This was interpreted to be the result of infiltration into shrinkage cracks, not infiltration through the pore spaces of the soil.

Biggar and Nahir present field evidence for migration of hydrocarbons into frozen soil. These data come from assessment of contaminant levels in the active layer and permafrost at sites of fuel spills at Alert and Isachsen. The extent of infiltration of the contaminant into permafrost recorded at these sites was greater than possible by diffusion (movement of contaminant through the pore network). Again, the conclusion reached by *Biggar and Nahir* was that the movement of contaminant was along fissures and cracks in the soil. These authors also reported very high concentrations of contaminants above ice lenses, interpreting the lenses as barriers to hydrocarbon migration. They also noted that at Isachsen, where the top of permafrost was relatively icy, there was little concentration of contaminant. However, beneath the ice-rich zone, where the ground has less ice, the contaminant levels were higher. This suggests (1) that the movement of contaminants was through cracks penetrating the ice-rich layer, because under diffusion we would expect higher concentrations near the source of contamination – the soil surface; (2) that the hydrocarbons were absorbed into the drier ground once they had bypassed the ice-rich zone. *Biggar and Nahir* conclude that "(t)he mechanisms responsible for the contaminant migration are believed to be gravity drainage through interconnected air voids in fill material, or through fissures in the soil induced by thermal contraction."

In all of the cases described, the movement was from a source of liquid contaminant. *Biggar and Nahir* report that the lateral movement of contaminant in the fuel spills at Alert and Isachsen was limited, even within the active layer, possibly several years after the spills occurred. These data are important, because they may confirm the laboratory observations of *White* at field scale. Over several years there would be time for lateral migration of the contaminant within the active layer, but the limited dispersal may be because it was adsorbed by the soil. These field observations are of free liquid infiltration of unsaturated frozen ground, through empty void spaces and cracks, coupled with adsorption of contaminant by soil particles.

The following points summarize the foregoing discussion of contaminant mobility:

(1) Migration of contaminants into frozen ground has only been observed in the free liquid form.

(2) Soil particles absorb hydrocarbons onto their surfaces and bind them in the soil matrix.
(3) Ice lenses act as an effective barrier to the movement of contaminants in frozen ground.

Impoundment of contaminants in permafrost at Polaris

The decommissioning plan for Polaris includes storage of contaminated soil underground. The soil has a low contaminant content, by weight up to 1.7%. There is no free liquid hydrocarbon in the contaminated soil. Rather, we must assume, following *White*, that the contaminated soils, have undergone several freeze-thaw cycles in the active layer at the ground surface, and, as a result, have adsorbed the hydrocarbons to their particle surfaces. In this state, the hydrocarbons are effectively immobilized, and as *Biggar and Nahir* reported from at Alert and Isachsen, their movement is arrested.

The data presented by *Biggar and Nahir* from field observations at Isachsen and laboratory studies by Neufeld and Biggar (1996) indicate that saturated, frozen ground, with the pore spaces blocked by ice is an apparently effective barrier to migration of contaminants. Therefore, the Polaris decommissioning plan may consider saturating and freezing the floors of the underground containment areas before depositing contaminated soil there. If the floors are marginally flooded several times with fresh water, then any pore spaces and fissures will be blocked, and the ground should be effectively impermeable to contaminants while it remains frozen.

Operational data

The successful operation of the Polaris mine is also evidence of the impermeability permafrost, because the mine is close to the Ocean and below sea level. Data collected by mine staff indicate that during drilling below the 730 level of the mine (270 m b.s.l.) flooding occurred when the drill reached about 150 m depth (420 m b.s.l.). The flooding was by salt water. This observation indicates that the groundwater beneath the mine is under hydrostatic pressure. Staff have pointed out that pumping has not been necessary for mining at Polaris, indicating that the permafrost surrounding the mine has prevented seepage of groundwater. They conclude that the permafrost surrounding the mine workings is an impermeable barrier.

Permafrost and climate change

The long-term use of permafrost to contain waste safely is predicated on the stability of ground temperatures. The prospect of climate warming due to an enhanced greenhouse effect has led to concern over the stability of permafrost in Northern Canada. The geothermal simulations presented in the Decommissioning Plan have been based on the scenarios provided by the Government of Canada for the Polaris region. These indicate an increase in mean annual air temperature of 3º to 5ºC over the next century. The diagrams describing the geothermal simulations for the landfill closure (Figs 3 – 6 in Supplementary Report 2) indicate that the present near-surface ground temperature is about –15º to -13ºC. These simulations have used a geothermal gradient of 0.0396ºC/m, obtained from earlier work by R.J.E. Brown.

Thickness of permafrost at Polaris

The thickness of permafrost, z, is given by:

[1] $$z = \frac{T_s}{g}$$

where T_s is the surface temperature and g the geothermal gradient. In this case, eq. [1] predicts a permafrost thickness of 378 m or 328 m for T_s of –15ºC or –13ºC , respectively. These predictions are validated by the ground temperatures at Polaris presented in Fig. 7 of the Reclamation Plan. Figure 7 also indicates that "frozen" ground occurs at temperatures below -3ºC, because the surrounding groundwater is saline. The depth to the -3ºC isotherm is about 300 m below ground surface.

When the ground surface temperature changes, near-surface temperatures respond relatively rapidly, but ground temperatures at depth take longer to change. As the surface warms up, there is a very gradual warming at the base of permafrost due to geothermal heat flowing from the Earth's interior.

Thawing of permafrost from below

The rate of thaw of permafrost from below depends on the geothermal heat flux and the volumetric latent heat of the permafrost. At Polaris, staff have estimated the porosity of the bedrock to be between 6 and 16%. Using a value of 10% for bedrock porosity, and 3.0×10^8 J/m^3 for the latent heat of fusion of ice, the volumetric latent heat of fusion of the bedrock is 3.0×10^7 J/m^3.

The geothermal heat flow in the Polaris area is about 0.05 W/m^2 (Judge 1973). The rate of thaw of permafrost from below is:

[2] $$\frac{dz}{dt} = \frac{0.05\ Wm^{-2}}{3.0\,x10^7\ \ Jm^{-3}} = \frac{0.05\,x\,3.15\,x10^7\ \ Jm^{-2}yr^{-1}}{3.0\,x10^7\ \ Jm^{-3}} \approx 5\,cm\,yr^{-1}$$

Time for ground to respond to climate warming

Osterkamp (1984) describes the time constant, τ, the time it takes permafrost of thickness *z* and fixed basal temperature to respond to a change in surface temperature:

[3] $$\tau = \frac{z^2}{4\kappa}$$

where κ is the thermal diffusivity. The time constant is the time for the temperature gradient to become a straight line from the new ground surface temperature to the base of permafrost. In the case of Polaris, z is approximately 300 m for the frozen ground, and κ for limestone is about 40 m^2/yr (Williams 1982, Tables 5.1, 5.2). The time constant for permafrost at Polaris is therefore about 550 years. During this time, the base of permafrost will have advanced upwards about 25 m, due to the geothermal heat flow.

The stopes proposed for impoundment of contaminated soil are presently at a temperature of between –7º and -8ºC. They are about 110 m above the -3ºC isotherm, or the base of frozen ground. If the ground surface temperature rises to -10ºC, then the equilibrium thickness of frozen ground, i.e. the depth to the -3ºC isotherm, will be about 175 m. According to Fig. 7, the contaminated soil storage areas will be above this level, i.e. in frozen ground. Therefore, the surface temperature will need to rise above -10ºC before there is a prospect of the area containing contaminated material being raised above -3ºC. However, it will take over 2,500 years for temperatures at depth to evolve to this state, due to the rate of heat flow from the Earth's interior.

Conclusion

The following points summarize the data on permafrost and climate change:

(1) Permafrost at Polaris will take over 500 years to respond at depth to changes in the ground surface temperature regime predicted for the next 100 years.
(2) During this time, the base of permafrost may migrate upwards about 15 m.
(3) A change in ground surface temperature of more than 5ºC will be needed to raise the base of permafrost into the areas where contaminated soil is to be stored.
(4) It will take several millennia for ground warming of this magnitude to occur at the depths in question.

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Curriculum Vitae

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Honours:
1981-86 Canadian Commonwealth Scholarship.
1989-98 NSERC University Research Fellowship.
1994-02 Associate Editor, *Canadian Journal of Earth Sciences*
1996 Fellow, Arctic Institute of North America
1997-98 President, Canadian Geomorphology Research Group
1998 Fellow, Royal Canadian Geographical Society
1998 Invited opening plenary lecture, 7th International Permafrost Conference
1998-01 Chair, Advisory Board to the Polar Continental Shelf Project, Natural Resources Canada
1999 Carleton University Research Achievement Award
2000 Governor, Royal Canadian Geographical Society

Industrial experience

2001 DIAND: Field course on Permafrost aspects of oil and gas development in the Mackenzie delta area.
2000 Yukon Energy Corporation: permafrost and ground ice conditions along proposed transmission line route between Mayo and Dawson City.
2000 Gartner Lee Ltd.: permafrost aspects of decommissioning of Polaris Mine, Little Cornwallis Island.
1998-2001 DIAND: permafrost aspects of Diavik Diamond Mines Application for Water Licence.
1996-1997 DIAND: permafrost aspects of mine proposals, Carmacks and Minto areas, YT.
1995 Yukon Energy Corporation and Mougeot Geoanalysis: implications for permafrost of lake level fluctuation, Aishihik Lake, YT.

1992 DIAND: permafrost aspects of pit wall design in placer mines, YT.
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