**University of Alberta**

# Freeze Separation for Recycling Road Salt Contaminated Melt Water

by

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# ABSTRACT

Freeze separation was examined as a method to concentrate dilute salt in snow melt and sand recycling wash water into concentrated brine at a City of Edmonton snow storage and sand recycling facility. Brine with salt concentrations as low as 15 g/L, with road sand and crystal salt, was found to be reusable as a de-icer. Field data confirmed the occurrence of natural freeze separation onsite. The first portions of the melt often had salt concentrations more than 10 times the average concentration in the bulk snow. The natural separation of salts can be further enhanced physically by collecting the first portion (high concentration) of the snow melt and subsequently spraying it into the cold winter air (spray freezing). A spray freezing field investigation showed that up to 90% of the chloride and sodium was released from the spray ice cores within the first 19% of the melt water.

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## List of Abbreviations and Symbols

| | |
|---|---|
| °C | degrees centigrade |
| C/Co | relative concentration |
| Ca | calcium |
| $CaCl_2$ | calcium chloride |
| Cl | chloride |
| CCME | Canadian Council for Ministers of the Environment |
| cm | centimetres |
| Co | initial salt concentration |
| CRREL | Cold Regions Research and Engineering Laboratory |
| EC | electro-conductivity |
| K | potassium |
| KCl | potassium chloride |
| kPa | kilopascals |
| LIDAR | Light Detection and Ranging |
| $m^3$ | cubic metres |
| Mg | magnesium |
| $MgCl_2$ | magnesium chloride |
| mM | millimolar |
| mN | millinormal |
| mS | millisiemens |
| $\mu$S | microsiemens |
| Na | sodium |
| NaCl | sodium chloride |
| $NH_4^+$ | ammonium |
| NWT | Northwest Territories |
| psi | pounds per square inch |
| $SO_4^{-2}$ | sulphate |
| SHRP | Strategic Highway Research Program |
| TAC | Transportation Association of Canada |

# 1. Introduction

## 1.1 Background

The research conducted in this study examined both natural freeze separation and spray freeze technology as methods to decontaminate the melt water and sand recycling pond water at the City of Edmonton snow storage and sand recycling facilities, to create reusable brine. A review of the current literature has shown that several freeze separation methods have been used to decontaminate a variety of wastes including saline groundwater (Otto, 2002). However, freeze separation has not been previously studied in direct relation to snow storage melt water and sand recycling wash water. The resulting concentrated brine was also examined as a reusable supplement to the dry crystal road salt which is currently used as a de-icing agent, along with sand, on roadways.

The snow removed from city roads throughout most Canadian cities contains varying degrees of salt and generally these concentrations are high enough to be of environmental concern. The City of Edmonton is very concerned with its snow storage sites and is currently supporting this $100,000, 4 year research program and has carried out a number of its own assessments of the snow storage facilities (Goulden, 2008; Fetter, 2008). The city of Calgary is facing similar problems with the Bow River and is interested in both sand recycling and salt management. The Alberta provincial governments has documented problems with approximately 1200 road salt contaminated sites and there a number of well documented cases of road salt contamination of groundwater resources (Williams et al., 2000). Careful snow disposal management practices are vital in controlling the release of salt into the environment at both existing and new snow disposal sites (Environment Canada, 2004). Currently, the melt water produced by the snow storage pile and the wash water collected from the sand recycling facilities in the City of Edmonton do not undergo any decontamination treatment. The use of freeze separation to decontaminate the melt water from the snow storage facilities was studied in order to reduce the environmental impact of snow storage sites on surface water, ground water and soil. The brine produced can then be recycled and mixed with sand and crystal salt to act as a de-icing agent.

Freeze separation has been successfully used to decontaminate many types of aqueous waste streams including brackish groundwater, hog manure and various types of industrial wastes (Elmore, 1968; Willoughby, 2004; Gao, 1998). Spray freeze technology as a particular form of freeze separation has been shown to concentrate contaminated aqueous solutions thereby reducing the volume of effluent requiring further treatment (Gao, 1998; Gao et al., 2004; Spyker, 1982).

## 1.2 Objectives

The objective of this study was to determine the viability of using freeze separation to create reusable brine from the melt water and sand recycling pond water. The research dealt with the Poundmaker snow storage Facility in Edmonton, Alberta. The investigation included field data collection to determine the characteristics of the snow pile and the melt water and two field scale spray freeze field trials. Several small laboratory experiments were completed to determine the reusability of the brine as a de-icing agent.

## 1.3 Methodology

Field and laboratory data were collected in order to provide insight into the characteristics of the snow and melt water at the City of Edmonton Snow Storage and Sand Recycling Facilities. Preliminary field work including melt water data collection, snow pile coring and site surveying was conducted along with a number of small scale laboratory experiments. Preliminary field work and the laboratory experiments were aimed at establishing the extent to which natural freeze separation is occurring onsite and to determine the reusability of the brine.

In addition, two large scale spray freeze field experiments were conducted to determine the feasibility of this method to further concentrate the melt water into reusable brine. The results of the preliminary field work, laboratory work and the field scale spray freeze operations are analyzed and discussed and recommendations for future studies are given.

## 1.4 Organization of Thesis

This thesis has been written in paper format. Chapter 1 introduces the study and gives the background, objective and methodology of the study. Chapter 2 begins with a literature review of freeze separation and introduces current road salt practices and issues. The preliminary field work and snow site characterization is discussed as well as the laboratory experiments and brine-sand-salt recipe. Chapter 3 looks at the large scale spray freeze operations which were conducted and Chapter 4 summarizes the major findings and provides recommendations for future work.

## 1.5 References

Elmore, W.W. 1968. Water Purification by Natural Freezing. M.Sc. Thesis, Department of Chemical Engineering, University of Wyoming, Laramie, Wyoming.

Environment Canada, 2004. Canadian Environmental Protection Act (CEPA, 1999), Code of Practice for the Environmental Management of Road Salts. April, 2004.

Fetter, J. 2008. City of Edmonton, Streets Engineering Branch, Value Engineering Session, Snow Storage Facilities, January 2008. Jeff Fetter, P.Eng., Associated Engineering Alberta Ltd.

Gao, Wa 1998. Partial freezing by spraying as a treatment alternative of selected industrial wastes. Ph.D. Thesis, University of Alberta, Edmonton, Alberta, Canada.

Gao, W., Smith, D.W. & Sego, D.C. 2004. Release of Contaminants from Melting Spray Ice of Industrial Wastewaters. Journal of Cold Regions Engineering. Vol. 18, No. 1, 35-51.

Goulden, W. D. 2008. Pond Sediment Settling Test Program, 17th Street Snow Storage Site, May 2008. Wanda D. Goulden, M.Sc., P.Eng., P.Geol., General Supervisor of Geo-Environmental Engineering, Engineering Services Section, City of Edmonton Permit to Practice No. P5038.

Otto, S. 2002. Evaluation of Freeze Separation as a Treatment for Salt-Contaminated Ground Water. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Canada.

Spyker, J.W. 1982. Desalination of Brackish Water by Spray Freezing: Progress Report 1981-1982. Saskatchewan Research Council Technical Report No. 140.

Williams, D. D., N. E. W. a. Y. C. (2000). Road salt contamination of groundwater in a major metropolitan area and development of a biological index to monitor its impact. Water Research. Vol. 34, No. 1, 127-138.

Willoughby, A. 2005. Freeze Separation to Remove Nutrients from Liquid Swine Manure. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Canada.

# 2. Freeze Separation of Salt Contaminated Snow, Snow and Melt water Characteristics and the Development of a Brine Recipe

## 2.1 Introduction

Winter driving conditions in Canada can be extremely hazardous, with roads in most regions of the country becoming covered in a slippery layer of ice and snow. In order to lower the freezing point of the ice on the roads and alleviate the hazardous conditions, road salts, especially sodium chloride, are spread over the roads every winter. An estimated 5 million tonnes of road salts are used on Canadian roads each year (Environment Canada, 2004). Although salts have a rather benign effect on the environment in small quantities, the large volumes of salts presently being used can be detrimental to local surface waters, aquatic life and road side vegetation. In 2004, Environment Canada published a new code of practice for road salt management highlighting the importance of ensuring environmental protection while maintaining winter roadway safety.

Road salts are also one of the many present-day causes of surface water pollution. As more water is contaminated there is an increasingly dire need for economical ways to purify this water. Freeze separation is a relatively simple technology that offers a straightforward and cost-effective means of concentrating contaminants in cold regions. The following brief literature review outlines the concepts behind freeze separation and some of its previous applications.

### 2.1.1 Background on Freeze Separation

The natural freezing process uses freeze separation to separate out contaminants through the formation of ice and snow. Impurities are further released during melting since the first portion of the melt water contains higher concentrations of impurities than the original bulk ice or snow; this phenomenon is called fractionation (Gao et al., 2004). Natural freeze separation offers many advantages for separation of salts over conventional treatment methods, especially since freezing requires approximately 15% of the energy needed to evaporate the same mass of water and in cold climates this can be done with minimal mechanical equipment (Beier et al., 2007). Freeze separation can also be accomplished through human induced processes such as spray ice technology.

The formation of crystal ice is the foundation of freeze separation. The process of freeze separation works off the principle of freeze point depression: when a solute is mixed with a pure solvent to form a solution, the solution will have a lower freezing point than the solvent alone. Therefore, at colder temperatures, the pure water will remain frozen and the liquid contaminant, in this case brine, can be drained off. The most effective desalination mechanism under cold conditions is gravity drainage, in which the cooling process causes cold, saline brine within the ice to be replaced with less saline water from lower ice layers (Thomas & Diekmann, 2003).

The crystal lattice in which water freezes is very selective and will not accept substitutes for the hydrogen and oxygen atoms, consequently if an aqueous salt solution is frozen extremely slowly, the foreign ions remain in the melt water and perfectly pure ice is formed (Pounder, 1965). However, in nature, the freezing process is generally more rapid and some impurities will become caught in the crystal lattice of the ice. The salinity of the brine contained in the interstice of the ice crystal lattice is determined by local temperature, according to the $NaCl\text{-}H_2O$ phase diagram (Oertling & Watts, 2004). Figure 2.1 shows a schematic of such a eutectic phase diagram.

The lowest point in the phase diagram is called the eutectic point, which, in the case of this sodium chloride-water solution, similar to that of seawater, is reached at a temperature of approximately -21 °C. At temperatures below this point for a

$NaCl-H_2O$ system, no liquid will exist and the remaining phases will be ice and the $NaCl-2H_2O$ Hydrohalite phase (Grant, 2000). For solutions containing more than one salt, the eutectic temperature is usually lower than for the water-single salt system (Spyker, 1982). Road salt often contains trace amounts of other salts including potassium chloride (KCl), magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$); the eutectic temperatures of these substances are shown in Table 2.1.

Colbeck et al. (1981) stated that soluble impurities contained in snow cover can be concentrated as much as five fold in the first fractions of the snowmelt. During winters with little or no snowmelt before spring, most of the pollutant load is retained in the snow pack and laboratory and field lysimeter experiments have indicated that 50-80% of the pollutant load is released with the first 30% of the melt water (Johannessen & Henriksen, 1978). However, not all the solutes contained within the snow or ice are removed with the same efficiency (Brimblecombe et al., 1987). Therefore, the chemical composition of snow and ice changes during the melting process. Johannessen and Henriksen (1978) did a study on the chemistry of snow melt water and found that the acidic impurities in the snow were released first creating a drop in pH levels in nearby surface waters. The rate at which impurities are released, not only depends on temperature and type of impurity, but it is also influenced by the degree and type of metamorphism the snow cover has experienced and the atmospheric conditions under which the snow was deposited (Colbeck, 1981).

### 2.1.2 Previous Applications of Freeze Separation

Freeze separation mechanisms have been used to desalinize sea water and brackish water as early as the 1960's (Elmore, 1968; Fertuck, 1969). Several concepts of freeze separation; including spray freeze, trickle freeze and freezing beds, have been proven to be effective on a variety of aqueous contaminants.

Spray freeze technology also known as spray ice, is a pollutant partitioning process which uses the freeze separation sequence and is similar to the procedure used by ski resorts for making snow. The process of spray freeze works by jetting the aqueous contaminant into the cold air. As the droplets slowly fall they are supercooled, the outside solidifies and then the centre nucleates into pure ice and the contaminants are pushed to the outside of the droplet. The droplets then form an ice mound, with the highly concentrated contaminant liquid flowing through to the base of the mound where it can be collected. Gao et al. (2000) carried out an experimental study to investigate this influence of the droplet size and ambient air temperature on the ice nucleation temperature for droplets of different nature – piggery wastewater, pulp mill effluent, and oil sands tailings pond water. In this study, Gao et al. (2004) concluded that the degree of freezing greatly affects the efficiency of the process, with partial freezing being desirable to allow drain water to form and carry away the impurities. Biggar et al. (2005) also successfully used spray freeze technology at the Colomac mine, NWT, to aid in the removal of dissolved chemicals such as arsenic and cyanide from tailings water.

Otto (2002) demonstrated the use of freeze separation for road salt contaminated groundwater as an alternative remediation option as oppose to the traditional use of natural attenuation or excavation and disposal. Beier et al. (2007) and Otto (2002) examined trickle freezing; a process where saline water flows through laminar sheets over an inclined ice surface, successively adding thin ice layers to the ice mass. The salts are concentrated into the unfrozen water which then drains along the ice mass for collection at the lowest point and this has proven to be successful in the treatment of saline oil sands wastewater (Beier et al., 2007). In both Gao et al. (2004) and Beier et al. (2007) it was concluded that the characteristics of the wastewater had an insignificant effect on the impurity removal efficiency. Willoughby (2005) used thin layered freezing in a pilot field study for the treatment of liquid swine manure and found it to be a viable mechanism for extracting large volumes of nutrients.

Martel (1993) applied the freeze separation concept for use in freezing beds designed to dewater municipal sludge. Studies conducted in the United States demonstrated that freezing beds can dewater both water and wastewater treatment sludges to greater than 20% total solids content (Martel, 1993). According to Martel (1993), the freeze separation process allowed for consolidation of the sludge material as well, and it seemed to be effective on any type of aqueous sludge. Freezing beds to concentrate other types of sludge were also investigated by researchers such as Halde (1980) and Parker et al. (2000).

The use of freeze separation technology to treat road salt contaminated melt water and snow from a city snow dump and settling ponds has not been previously examined. Both the natural freeze separation processes within the snow pile and the application of spray freeze technology to the settling ponds were examined as means of concentrating the melt water and sand recycling wash waters into reusable brine.

### 2.1.3 Road Salt Usage and Environmental Risks

The use of road salt is widespread throughout Canada and the northern United States. It is also used, to a lesser extent, in northern Europe where studded tires are a common winter practice. In general, as traffic passes across roads, the snow and/or ice becomes bonded to the road surface making it difficult or impossible to remove; road salts are added to break this bond so that all material can be removed (TAC, 1999). Studies have indicated that road salts can help reduce motor vehicle accidents by up to 90% when icy or snowy roads are restored to bare pavement (Vaa et al., 1996).

Once applied to the roads, salts will become mixed with the melt water and drain into roadside ditches or storm sewers. The salts will enter the water cycle through groundwater and surface water recharge. These salts affect salt sensitive vegetation and soils and also affect aquatic life once they enter the larger water bodies. Certain species are much more affected by road salts than others. For example, even very small increases in chloride concentrations (2 - 10 mg/L) can affect changes in phytoplankton community structure in lakes that have a naturally low salinity (Evans and Frick, 2001). Amphibians such as frogs have the lowest tolerance for elevated salt concentrations amongst larger organisms since they absorb contaminants easily through their skin, while larger mammals such as deer, are minimally affected.

Road salts can also cause a condition in lakes know as meromixis. This occurs when the denser salty water sinks to the bottom causing an absence of vertical mixing and the depletion of oxygen in the low layers of the lake, reducing the cycling of nutrients (Environment Canada, 2004). These conditions can result in the loss of all but the most resilient deep water benthic species (Evans and Frick, 2001).

Sodium chloride can act as an enhancer of dissolved trace metals such as cadmium, copper and zinc by competing for particulate binding sites; these metals are acutely toxic to aquatic organisms at concentrations as low as 0.001 mg/L for certain species of fish (CCME, 1991).

Environment Canada (2004), through the Canadian Environmental Protection act has identified a series of thresholds for the three major environmental compartments; surface water, groundwater and soil. For freshwater aquatic life, approximately 5 percent of species are affected from chronic exposure to sodium chloride of 210 mg/L, and the four day average should not exceed 230 mg/L more than once every three years (Environment Canada, 2004). The Canadian drinking water guideline for chloride is a concentration of less than 250 mg/L for aesthetic and operational purposes (Health Canada, 2007). For soil and groundwater, Alberta environment recommends a maximum chloride concentration of 230 mg/L for natural, residential and commercial areas and 210 mg/L for agricultural soils (Alberta Environment, 2008).

### 2.1.4 City of Edmonton Road Salting Practices

The city of Edmonton uses an average of 150,000 tonnes of sand, salt and rock chips on the city roads each year. However, the range is significant and varies greatly from year to year ranging between 100,000 tonnes for a drier winter to upwards of 190,000 tonnes for a heavy snowfall year. The City of Edmonton presently uses crystal salt mixed in with the road sand with a salt application range of 2% to 6% by weight, of the total sand-salt mixture. The salt is obtained from the potash industry and consists of upwards of 98% sodium chloride with trace amounts of potassium chloride, calcium chloride and magnesium chloride.

An operational moisture content of less than 8% is used for the road sand to allow easy removal from the trucks (i.e. lessen sticking) and prevent refreezing of the road ice due to dilution. In 2005/2006 and 2006/2007 the City of Edmonton reported that 21,137 tonnes and 24,727 tonnes, respectively, of NaCl de-icing salt were used. During the winter of 2005/2006 and 2006/2007, approximately 147,000 tonnes and 157,000 tonnes, respectively, of sand was used. Some liquid $CaCl_2$ is also used approximately 400,000 litres in 2006/2007 and 200,000 litres in 2005/2006.

The City of Edmonton presently recycles much of the road sand that is used on the streets. Street cleaners that are operational in the spring will collect the left over sand on the roads for reuse. The sand is taken to the Sand Recycling facility where it is washed, the wash water is allowed to settle using an anionic polymer and is then released into the settling pond and slowly drained into the storm sewers. Last winter approximately 32,000 tonnes of recycled sand was used on the roads, consisting of approximately 20% of the total. The snow which is collected off the streets during the winter is taken to one of the cities 5 snow storage facilities.

### 2.1.5 Site Description and Current Site Operating Issues

The Snow Storage and Sand Recycling Facility is also known as the Poundmaker Snow Dump. It is located on 184 Street and 107 Avenue, in the west end of Edmonton, Alberta, Canada. The legal description of the site is NE 1/4 sec 5- 23-55-4. The site is divided into two areas separated by a chain link fence and two access roads. The western portion of the site contains the Snow Storage Facility, a large region with a total drainage area of 7.31 hectares. This portion of the site contains a settling pond designed to allow the melt water from the snow pile to settle out and later drain into the storm sewer. The storm sewer outlet in the pond is located approximately 2 metres from the base of the pond to allow dilution to occur and settled out surface waters to flow into the storm sewer. The pond is located in the south west portion of the snow storage area and has an approximate volume of 5300 $m^3$. The base of the pond is constructed of RCC concrete to ensure protection of the local groundwater. The site is graded so that all overland flow from the snow pile flows into the Northwest corner of the pond at a grade between 0.9 and 1.7 %. The base of the snow storage area is lined with a compacted clay liner. The pond is meant to retain the runoff for a minimum of 24 hours during peak runoff periods to allow for adequate settling out of the fines. However due to sludge build up in the pond a berm had been created to hold the runoff within the larger part of the drainage area prior to its release into the pond. The snow storage settling pond was drained in the fall time due to the sludge build-up.

The Sand Recycling Facility is contained within the East portion of the site of which most of the area is occupied by the sand recycling equipment. All wash water from the sand recycling activities drain into the sand recycling pond located within the western portion of the site. This pond has an approximate volume of 4000 $m^3$. A site layout of the snow storage and sand recycling facilities are shown in Figure 2.2.

Environment Canada (2004), states that the three most important factors when considering the best management practice of road salts include salt storage, snow disposal and salt application. Proper snow disposal is critical in protecting surface and ground waters as well as surrounding wildlife and vegetation. Some important factors to consider when dealing with snow disposal include: site location, site construction, site operation, drainage management, training of personnel and monitoring (Environment Canada, 2004). Environment Canada (2004) explains that salt should be covered or blended with sand during storage and handled carefully to prevent any releases. Road salts should also be applied at the right place and time in the correct quantities to reduce any negative environmental impacts.

According to the Transportation Association of Canada (TAC) it is important for a snow storage pile to melt properly and efficiently to maintain smooth operation and long term stability of the site (TAC, 1999). As part of this assessment, mechanical ablation of the snow pile using a water jet was examined as a method of inducing the snow pile melt and the results are given in Appendix 9.

Current site operations within all of the City of Edmonton snow storage sites is the over load of fines in the melt water settling ponds. A grain size analysis indicated that approximately 60% of the soil particles found in the pond were clay sized particles, creating a sludge which had to be removed from the pond at the end of the summer. The high amount of clay sized particles found in the runoff is partially due to the dispersive properties of the clay minerals when in contact with salts. It has been found that hydraulic conductivity increases with increasing salt concentration of the soil while compressibility decreases, all due to a decrease in the diffuse double layer thickness (Mishra et al., 2005). The elevated concentration of salts produced by the snow pile is causing the clay liner below the pile to disperse and runoff into the pond as well. A sieve analysis was done on the soil particles contained in the melt water. The results indicated that the snow coming off the streets has a very high sediment load, approximately 77 g/L of soil within the melt water. Of this soil, 2.4% are fines passing through the No. 200 sieve equating to more than 920,000 kg of fines brought onsite during the 2006/2007 winter season. Results of the sieve analysis are described further in section 5.2.3.

## 2.2 Methodology

This portion of the research study is broken down into two areas: 1) characterization of snow and melt water field data and 2) the brine recipe. The first portion consists of the field and lab data completed in order to characterize the snow and melt water at the City of Edmonton Poundmaker snow storage facility. The second portion, the brine recipe, was completed in order to determine the suitability of the brine as a de-icing agent. Laboratory experiments were undertaken to determine the proportions of crystal salt required to create a standard de-icer when dealing with certain concentrations of brine.

### 2.2.1 Characterization of Snow and Melt Water Field Data and Experimental Methods

A drilling program and LIDAR (Light Detection and Ranging) survey were conducted to obtain snow cores from the snow pile and to estimate the volume of the 2006/2007 pile, respectively. Melt water was collected from the snow storage facility to monitor the out flow of salts and other contaminants from the snow pile. Melt water collection began in the winter when a small pool of brine was found near the base of the pile at the southeast corner during the drilling program on February 1, 2007. Melt water was collected from several locations near the pile as well as the settling pond, to monitor differences in salt concentrations between locations around the pile with time. Melt water was collected in one litre containers and the temperature was taken. Samples were collected every 2 to 4 weeks throughout the melting period from February to August, 2007. The electro-conductivity (EC) of the samples was measured using a Thermo Orion portable conductivity meter, Model 130A, 131S. This EC meter was equipped with automatic temperature compensation and had a detection range between 0.1 μS/cm and 1000 mS/cm.

Both the melt water samples and selected snow core samples were analyzed in the University of Alberta Applied Environmental Geochemistry research facility. Analysis was done for major ions including $Na^+$, $K^+$, $Ca^{+2}$, $Mg^{+2}$, $NH_4^+$, $SO_4^{-2}$ and $Cl^-$, using a Dionex Ion Chromatograph for all samples. The Ion Chromatograph columns used were Dionex IRFC IonPac 4 X 250 mm analytical columns with a cation column product number of CS12A and the anion product number of AS14A. The cation eluent consisted of a 22 mN (millinormal) solution of $H_2SO_4$ in deionized water. The anion eluent was an 8.0 mM (millimolar) solution of $Na_2CO_3$ and 1.0 mM solution of $NaHCO_3$ in deionized water. Anion analysis was carried out using Dionex Seven Anion Standard II, product number 057590. Similarly, cation analysis was completed using Dionex Six Cation – II Standard, product number 046070, both manufactured in Sunnyvale, California. The first portion of the anion sequence was completed using deionized water, followed by 20X, 10X, 5X, 2X and 1X dilutions of the anion standard. The samples were "checked" occasionally throughout the sequence using the 5X standard dilution. In a similar manner the cation sequence began with deionized water followed by 100X, 20X, 10X, 2X and 1X dilutions of the cation standard and the sequence was "checked" occasionally using the 10X standard dilution. Alkalinity was measured on selected samples and the Inductive Coupled Plasma – Mass Spectrometer (ICP-MS) was used to determine the concentrations of trace metals within the samples.

### 2.2.2 Brine Recipe Experimental Methods

The de-icer tests were done in accordance with SHRP H-205.4 (the U.S. Strategic Highway Research Program tests). This test requires the use of several 20 X 20 cm clear plastic dishes with a depth of approximately 2 cm. The dishes were filled with approximately 1 cm of water and allowed to freeze. The sand-brine mixtures were placed on the ice and mixed thoroughly over the ice surface. Every two minutes, the excess liquid was decanted off the ice and its volume measured. In this way the efficiency of the de-icing solution was evaluated. The solutions were mixed with different portions of salt and the decanted volumes were compared to the standard crystal salt-sand solution presently used by the city of Edmonton.

## 2.3 Characterization of Snow Storage Facility Results

The results of the field and laboratory work done in order to characterize the snow and melt water at the snow storage facility are shown here. The results include:

- Snow pile drilling program
- LIDAR survey
- Melt water collection
- Salinity to Electro-conductivity (EC) site calibration and fractionation experiment results
- Snow pile core and bulk sample analysis

### 2.3.1 Snow Pile Drilling Program

The initial drilling program took place on February 1, 2007. The air temperature varied between -20 and -14 °C throughout the day with a moderate wind coming from the Northwest. At this time the snow pile was drilled from its apex with a specially constructed "flat area" to mount the drill rig and equipment. A track mounted M5 drill rig was used to complete the drilling. A coring unit designed especially for ice coring was used to collect samples. However, core samples were not always recovered and therefore ground-up bag/bulk samples were obtained at certain depths. The pile was drilled to a depth of approximately 21.3

metres, after which time samples were unattainable due to sloughing in of the pile.

All snow samples were then transported to a chest freezer which was kept at approximately -10 °C, where they were stored for approximately four months prior to analysis. The sample bags were placed in the chest freezer with additional ice and snow to prevent sublimation of the samples during storage.

### 2.3.2 LIDAR Survey

A survey of the pile using the University of Alberta LIDAR unit was completed on April 3, 2007. Optech model ILRIS-3D Intelligent Laser Ranging and Imaging System was used with a detection range angle between 0° and 40°. With this unit 3-D images could be obtained within a distance of 3 to 1500 metres of the object in question.

The snow pile was scanned from three locations around the snow storage site; the Northeast, Southeast and Southwest areas of the pile. Due to site access limitations, a full scan of the back (west face) of the pile could not be obtained and during the computer imaging of the pile this face was extrapolated to the base using the angles obtained from the other scan points. The total volume of the 2006/2007 snow pile using the LIDAR unit was found to be approximately 500,000 $m^3$. Figure 2.3 shows the LIDAR scan taken in April of 2007.

### 2.3.3 Melt Water Collection and Snow Characteristics

As expected the highest concentration of contaminants were contained within the first portions of the melt water during spring. The concentrations during March were approximately 7 to 10 times higher than the concentrations found in the bulk snow from the snow samples taken in February. Figures 2.4 and 2.5 show the cation and anion concentrations, respectively, vs. time for the runoff water sampled from the east end of the south edge of the pile. The figures are shown with the sample concentrations on a log scale to demonstrate the decrease in each of the components with time. A sample taken on February 1, 2007 had an overall salt concentration of approximately 35,000 mg/L, the bulk snow had a melted salt concentration of less than 2,000 mg/L. During March the melt water concentrations varied between 13,000 and 19,000 mg/L. The results of the trace metal analysis are shown in the appendix. Several heavy metals were found to be present within the melt water including Boron, Iron, Arsenic, Strontium, Barium and Uranium. However, the concentrations were generally below or only slightly above surface water quality government criteria limits.

The snow removed from the streets of Edmonton presently goes to one of 5 existing Snow Storage Facilities around the city. The city of Edmonton estimates that in 2007, approximately 799,000 $m^3$ of snow was placed into the five City of Edmonton snow storage facilities. It was estimated that the snow volume reported by the city of Edmonton accounts for approximately 60 to 65% of the total volume of snow at these sites, the remainder being dumped by private contractors. The snow coming from the streets and parking lots contains a high fraction of sand, silt and clay sized particles as well as high concentrations of salts and trace amounts of heavy metals and occasional traces of hydrocarbons.

Analysis of the melt water indicated that some of the major ions, (chloride and to a lesser extent ammonium) were over the recommended surface water quality limits. However, many of the constituents have no criteria at all. Table 2.2 gives a list of several of the ions present in the pond water throughout the majority of the melting period and their corresponding government criteria taken from Alberta Environment. During the winter the melt water settling pond contained water left over from the end of the previous years melt. Therefore the highest concentrations within the melt water pond were generally found in April after the diluted melt water from the previous year had been mixed with the current melt water and washed away from the pond.

The City of Edmonton also has its own guideline for several inorganic and organic constituents. Table 2.3 shows the guidelines for some of the inorganic constituents in comparison to the pond water samples taken by the University of Alberta between March and June of 2007. None of these constituents were above the recommended criteria for the City of Edmonton, "Schedule C – Restricted wastes applicable to storm sewers and watercourses" except for the Copper and Lead concentrations during June sampling. However, the City of Edmonton also took samples of the melt water between April and August. The test parameters integrated in their analysis included heavy metals, hydrocarbons as well as other components such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and fecal coli form. During certain parts of the melt, the pond water was found to be over the Schedule C guidelines for several heavy metals including Arsenic, Chromium, Cadmium, Copper, Lead and Zinc. Phosphorous was also found to be occasionally higher than the recommended limit as well as the Chemical Oxygen Demand (COD) and fecal coli form concentrations. The City of Edmonton samples were also tested for several hydrocarbons including Benzene, Toluene, Ethyl benzene and total Xylenes (BTEX) as well as Phenol and Oil and grease. The only hydrocarbon component which was found to be occasionally over the recommended City of Edmonton Schedule C limit for organic constituents within the settling pond was Phenol. The water quality data obtained from the City of Edmonton is contained in Appendix 10.

### 2.3.4 Salinity to Electro-Conductivity Site Calibration and Fractionation Experiment Results

To estimate the road salt concentration in the snow melt samples, a correlation was made between the concentration of road salt in a given amount of water and the Electro-conductivity of the sample. Several solutions were made with salt concentrations ranging between 250 mg/L to 220,000 mg/L. De-ionized water was used to create the solution and the corresponding mass of salt was added.

The EC of each sample was recorded and plotted vs. the concentration of salt within the sample. Selected samples were analyzed for major ions to determine the chemical make-up of the road salt. The road salt was found to be primarily NaCl. The proportions of the major components of the road salt from nine samples were averaged and it was found to contain approximately 98.55% NaCl, 0.96% KCl, 0.20% $CaCl_2$ and 0.04% $MgCl_2$.

The results showed a polynomial correlation between the concentration of road salt and the EC. The R values ranged between 0.9992 and 1 and the correlation is increasingly less accurate at lower salt concentrations and the graph is shown in Figure 2.6. Therefore the graph was broken up into two sections and a separate curve was drawn for the solutions with a concentration below 110 mS/cm. However, the graph in general, was designed for higher concentration solutions and very low concentration solutions (below 500 mg/L) should be re-correlated separately. Electro-Conductivity was also correlated to the ionic strength of the solutions. The ionic strength of the melt water was intermediate to low, ranging between <0.005 mol/kg to >0.3 mol/kg.

All ions are not lost in equal preference when ice or snow melts (Johannessen and Henriksen, 1978). In order to better understand the fractionation that occurs within salt contaminated snow, a simple freezing/melting experiment was carried out.

A representative sample of the road salt was obtained and a 1 litre solution containing 10g/L of road salt in distilled water was prepared. The solution was frozen and then slowly allowed to melt at room temperature which ranged between 19.9 and 21.9 °C. Samples were collected in increments ranging from 25 mL to 65 mL and the smaller volumes were collected during the beginning of the melting processes. The total melting process took a total of 12 hours to complete.

A concentration ratio, Ci/Cm was used to compare the concentration in the melt water to the concentration in the bulk snow of each ion. Ci is the initial concentration of the ion in the bulk sample and Cm is the concentration in the subject portion of melt water. The general elution sequence of cation removal from melting snow is magnesium > potassium > sodium, where sodium is lost last from the bulk snow or ice (Brimblecombe et al., 1987). However it should be noted that when higher concentrations of a certain ion are present the elution sequence may change and the ions with a higher concentration may be lost first despite their position in the elution sequence (Brimblecombe et al., 1988). During the experiment reported here, this fact was confirmed as sodium was lost in slight preference over potassium and magnesium due to its very high concentration relative to the other cations. The "cross-over effect" as mentioned by Brimblecombe et al. (1988) and Johannessen and Henriksen (1978), is demonstrated in the cation graph. The Ci/Cm for the sodium starts out above magnesium and then crosses over as its concentration drops more rapidly to below that of the magnesium as seen in Figure 2.7.

The anions graph is shown in Figure 2.8. In the anions graph, a similar phenomenon is observed. Sulphate is generally removed in preference to chloride (Brimblecombe et al., 1987). However, again it is evident that due to the overwhelming concentration of chloride in comparison to sulphate, the removal of the two is similar with perhaps slight preferential loss remaining with the sulphate despite the fact that the concentration of chloride is more than 400 times that of the sulphate. This demonstrates the strong preference for the loss of sulphate during the melting of ice and snow.

A mass balance was performed for both the cations and anions with total masses balancing between 98.3% and 100% of their total masses within the initial bulk solution. The greatest error or loss of mass was in the cations, with the magnesium and calcium. The error there was likely due to their overall low concentrations relative to sodium.

The results show that approximately 60% of the sodium as well as 60% of the chloride was contained within the first 11% of the melt water. The EC of the melt water was 101.2 mS/cm during the first 2% of the melt and dropped to 56.2 mS/cm and lower during the following 3%.

### 2.3.5 Snow Pile Core and Bulk Sample Analysis

Snow samples collected during the drilling program were analyzed to approximate the density of the snow pile. When density analysis was complete, samples were slowly melted to gain insight into the partitioning process during natural melting. Density measurements of the snow samples were important in order to approximate the total runoff produced by the snow pile and to help quantify the total outflow of salts. Density of the snow samples was determined by using a hot wire to cut the snow into approximate cubes. Dimensions of the cubes were taken using a digital calliper measuring device and then immediately weighed using a digital weigh scale. A piece of insulation was placed on the weigh scale to prevent melting of sample when in contact with the scale. A total of 15 randomly picked samples were cut, measured and weighed for density. Cutting and measurements were done inside a cold room which was set at a temperature of -10 °C and to ensure the samples stayed intact and melting did not occur.

The density of the samples varied between 0.63 and 0.83 g/cm$^3$. Densification is suspected to have occurred during the storing of the snow samples. It is not known how much the snow had densified but a lower number of 0.65 g/cm$^3$ was used as an estimate.

Graphs were made in attempt to correlate the density of the samples with depth and the EC readings with depth. Figure 2.9 shows the graph of the density measurements versus depth. No relationship was obtained likely due to the way the snow is deposited and compacted as well as the temperature differences throughout the year.

After density determination was complete, bulk samples were melted using a 150 Watt light bulb with an ambient cold room temperature of 0 °C. The samples were placed in large plexiglass cylindrical containers approximately 30 cm in diameter. The containers were wrapped in fiberglass insulation, plastic and duct tape. Additional bubble wrap was placed around the sample to prevent melting from the sides and promote flow. Samples with approximate volumes of 2 litres, took approximately 6 to 8 hours to melt and the melt water was collected in 250 mL increments during the test. Samples were then analyzed for EC.

Cores were melted using a PVC apparatus with several holes at the bottom to allow for drainage and connective tubing so the sample could be drained into a collection container. A latex membrane was squeezed over the snow core and the core then placed on the apparatus with the membrane secured over the apparatus to hold the core in place. The core was placed in the correct position, top at the top and bottom at the bottom, with the membrane promoting downward flow so as to simulate field conditions. Core melt water samples were collected in 60 mL increments throughout melting.

In other studies, degree of impurity concentration was found to be independent of melting mode (continuous melting or melt freeze cycles), snow depth, snow temperature and initial solution concentration and removal efficiency was influenced by snow pack density and height (Rabinowitz et al., 1988).

Colbeck (1981) points out that lower melt flow rates result in higher impurity concentrations in the melt water due to the increased importance of molecular diffusion. Review of the literature has also indicated that the age of the snow samples may have an effect on the results as well. Gao (1998) ran experiments with ice cores keeping them in storage for 20 days and 40 days. It was found that the ice kept in storage for 20 days produced melt water with a higher pH than that in storage for 40 days; 9.28 as oppose to 9.03. Impurities may also be concentrated onto the ice grains surface as the snowpack gets older. Vapour transfers from warmer ice crystals to colder ice crystals causing the warmer crystals to shrink and their impurity concentration to increase (Colbeck 1981). As recrystallization continues the impurities are concentrated on the ice grain surfaces ready for transport during melting.

The EC readings for the bulk samples collected from the drilling operation were generally fairly low in comparison to the field readings collected from the melt water of the actual snow pile. They ranged between 0.2 to 10.7 mS/cm possibly due to the rapid melting and small sample size. For the core samples the EC readings were generally slightly higher and had a larger range which was between 0.1 and 12 mS/cm. The better results from the core sample analysis was due to the slower melting and the use of the latex membrane to restrict flow along the sides of the sample and force the formation of brine drainage through the sample which allowed for more efficient contaminant removal. The EC vs. accumulated volume graphs also exhibited a more realistic classic shape for the core samples compared to the bulk samples. An example of a core sample EC graph is shown in Figure 2.10. The EC was used to estimate the salt content of the of the melt water as the sample melted.

Contaminants within the snow were shown to be further concentrated in the older snow. The snow kept in storage for three months had an average EC between 0.4 and 3.7 mS/cm, while the samples that were kept in storage for a whole year had EC's ranging between 3 and 5 mS/cm on average, a fairly significant change.

During the bulk and core sample melting, the leftover soil remaining after the melting was complete was collected for 17 samples at various depths. The total melt water volume was approximately 20125 mL and the total mass of soil collected was 1.54 kg. Therefore the total sediment load in the snow at the snow storage facility was approximately 77 g/L of soil within the melt water. The total fines content within this soil was determined by the total percentage of soil passing through the No. 200 sieve and was found to be 2.4%. The total mass of soil within the snow pile during the 2006/2007 winter was 38.5 million kilograms. The total mass of fines within that soil was equivalent to approximately 920,000 kg, not including suspended solids. The soil contained within the snow at the snow storage facility was found to be approximately 83.8% sand, 14.4% gravel and 2.4% fines.

The snow contained within the pile also had a high concentration of total suspended solids (TSS). TSS was determined using randomly selected samples of the melted snow and was found to be between 1,200 and 2,000 mg/L, with an average of approximately 1,800 mg/L. Therefore the total amount of solids in the melted snow was approximately 79,000 mg/L with the TSS accounting for approximately 2% of the total solids.

## 2.4 Brine Recipe Experimental Results

Free drainage tests and brine de-icing tests were carried out in order to create a brine-sand-salt recipe and to evaluate the performance of various brine concentrations as a de-icing agent. Before beginning the de-icing tests it was necessary to determine some characteristics of the road sand. The field moisture content of the sand was between 2% and 4%. The City of Edmonton recommends a maximum moisture content of 7% to be used for the sand that is applied to the roads due to application difficulties and localized dilution and refreezing. For this experiment the free drainage moisture content was determined and used for the de-icing experiments. The free drainage moisture content was determined to be the moisture content resulting when saturated sand is allowed to drain via gravity.

### 2.4.1 Free Drainage Tests

The free draining moisture content of the washed sand was used to determine approximately how much brine can be added to the sand stock piles for "pickling", a process meant to coat the sand with brine. Tests carried out included the free draining moisture content with both water and a brine solution of approximately 35 g/L of road salt. A total of 4 tests were done to include moisture contents obtained in both a regular room and in the moisture room which is kept at 100% humidity resulting in zero evaporation loss. The samples were left to drain for approximately 24 hours.

The results showed that moisture content of the free draining brine/sand mixture was lower than that with water. This was expected since the brine solution is denser and will drain more readily than pure water. The free draining moisture contents of the samples left in the moisture room were approximately 15% for the de-ionized water and 16% for the brine showing that there was less variation between the water and brine mixtures when no evaporation was occurring. The free draining moisture content for the brine and sand solution at room temperature was 10% and for the de-ionized water and sand it was 11.3% Although $CaCl_2$ is hydroscopic, NaCl is the major component in the road salt and it is not hydroscopic. Therefore some evaporation was expected to occur for both the water and the subject brine solution under regular atmospheric conditions.

### 2.4.2 De-icing Tests and Brine Recipe

A series of freezing and de-icing tests were done to evaluate the use of brine in combination with crystal salt as a de-icing agent. The first step that was taken was to come up with a target brine concentration. The target brine concentration was taken to be the concentration of brine which, when added to sand, would cause the sand to remain friable at temperatures as low as -20 °C. This temperature was chosen because it is very near the eutectic temperature of a

$NaCl-H_2O$ mixture, and it is the temperature at which salt is no longer added to the roads. This experiment was completed by creating a number of different brine solutions of various concentrations and adding them to sand at its free drainage moisture content which was determined to be approximately 10%. The sand was mixed well and placed in a cold room held at -20 °C. After a period of 24 hours the condition of the sand mixtures were assessed. It was found that a concentration of at least 90 g/L with an Electro-conductivity of 120 mS/cm was required to maintain optimal friability at this temperature.

A concentration of 90 g/L was not obtained during the spray freeze operation. However, samples of runoff from the large snow pile taken on March 19, 2008 had EC's ranging between 32.8 and 35.5 mS/cm corresponding to road salt concentrations of 17.5 and 19 g/L. Therefore de-icing tests were conducted using a brine mixture of 15 g/L as well as 90 g/L and 50 g/L. Recipes were obtained for these three concentrations.

The solutions used as "standards" for the de-icing tests consisted of sand with a 7% moisture content containing 4% salt by weight. The moisture content of 7% is near the present maximum allowable moisture content for City of Edmonton Road sand. The results for the brine tests showed that with the use of a 15 g/L brine solution, the addition of the brine and 1% salt would adequately result in similar de-icing characteristics as the traditional mixture consisting of the addition of 4% crystal salt added to the regular sand (no brine added). A graph of the results obtained for the 15 g/L brine solution is presented in Figure 2.11. For a 50 g/L brine solution added to sand the result was that approximately 0.8% crystal salt was necessary and when a 90 g/L solution was added to sand, 0.5% crystal salt was required. The sand should be thoroughly mixed with the brine solution and allowed to free drain, permitting the excess brine to drain out of the sand through gravity drainage. Free drainage of the brine must be done in a protected/lined area where the excess brine can be collected and re-used properly. A similar test was done for brine solutions of 50 g/L and 90 g/L and a recipe for three ranges of brine concentrations were produced. For a 15 g/L up to 50 g/L brine solution the recommended recipe is as follows:

Sand with 2% salt = 15 – 50 g/L free drained brine sand with 0.5% crystal salt
Sand with 3% salt = 15 – 50 g/L free drained brine sand with 0.8% crystal salt
Sand with 4% salt = 15 – 50 g/L free drained brine sand with 1% crystal salt
Sand with 5% salt = 15 – 50 g/L free drained brine sand with 2% crystal salt
Sand with 6% salt = 15 – 50 g/L free drained brine sand with 3% crystal salt

For a 50 g/L to 90 g/L brine solution the recommended recipe is as follows:

Sand with 2% salt = 50 – 90 g/L free drained brine sand with 0.3% crystal salt
Sand with 3% salt = 50 – 90 g/L free drained brine sand with 0.5% crystal salt
Sand with 4% salt = 50 – 90 g/L free drained brine sand with 0.8% crystal salt
Sand with 5% salt = 50 – 90 g/L free drained brine sand with 1.5% crystal salt
Sand with 6% salt = 50 – 90 g/L free drained brine sand with 2.5% crystal salt

For a >90 g/L brine solution the recommended recipe is as follows:

Sand with 2% salt = >90 g/L free drained brine sand with 0.2% crystal salt
Sand with 3% salt = >90 g/L free drained brine sand with 0.3% crystal salt
Sand with 4% salt = >90 g/L free drained brine sand with 0.5% crystal salt
Sand with 5% salt = >90 g/L free drained brine sand with 1% crystal salt
Sand with 6% salt = >90 g/L free drained brine sand with 2% crystal salt

Careful re-use of the brine is necessary so that the possibility of seepage into local groundwater or surface water is sufficiently reduced or eliminated. The brine produced from the freeze separation process could also be used alone as a liquid de-icing agent, eliminating the need for mixing with the sand and the possibly costly precautionary measures required during mixing and free draining. Application of the liquid brine alone would increase the free water content of the snow and allow the snow from the streets to be more readily removed by traffic (Gray and Male, 1981). Alternatively the NaCl brine liquid could be applied to the roads as a spray in the same manner traditional liquid $CaCl_2$ de-icer is applied. However, further research on its use alone would need to be conducted to determine the detailed effects and necessary concentrations for this application.

## 2.5 Discussion

The data collected in 2007 relating to the Poundmaker snow storage facility revealed that large amounts of sediment and salts were present in the snow. The volume of the snow pile was estimated to be approximately 500,000 $m^3$, with an average Electro-conductivity of 2.3 mS/cm. This EC was correspondingly correlated to an average road salt content of 1.2 g/L using the laboratory calibration. Using an average density of 0.6 $g/m^3$, approximately 300,000 $m^3$ of runoff was produced and a total of 360,000 kg of road salt was present in the 2007 Poundmaker snow pile. This represents approximately 1.5% of the total amount of salt that was used on the roads during the 2006/2007 winter.

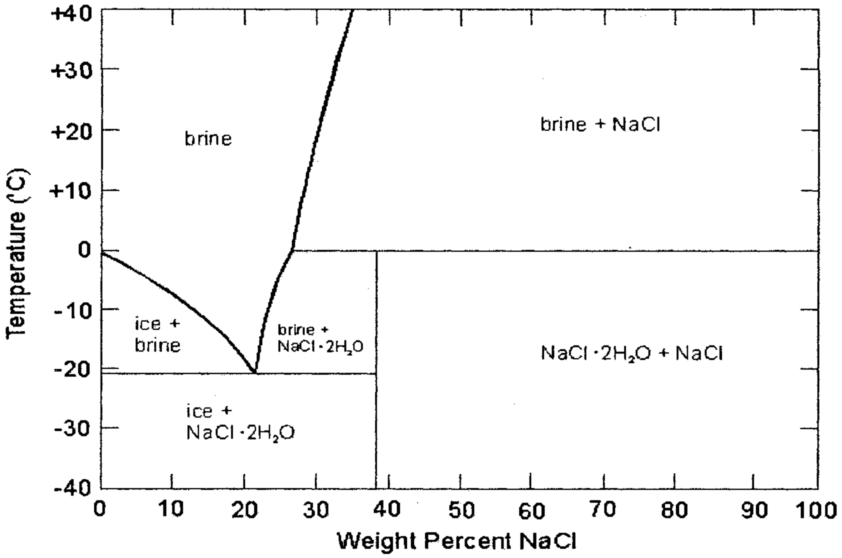
The snow pile was also found to contain a very high sediment load within the snow of 77 g/L, or 7.7%, consisting mainly of sand sized particles. The snow contained within the pile also had a high concentration of total suspended solids (TSS) between 1200 and 2000 mg/L. Therefore the total amount of solids in the snow was approximately 79 g/L. The City of Edmonton, found that the pond water had TSS concentrations between 10 and 15,100 mg/L varying greatly from sample to sample depending on when the sample was taken, with larger concentrations of TSS being observed during the latter part of the snow melt when salt concentrations were the lowest and flow rate was the highest. The source of fines within the settling pond/melt water seems to vary greatly depending on the time of year. When high flow rates and low salt concentrations are observed as in July, up to 90% of the fines may be coming from the clay liner beneath the snow storage area. Whereas when the suspended solid content in the pond is lower during the first portions of the melt, the opposite may be true where majority of the fines found in the settling pond are originating from the snow itself.

## 2.6 Conclusions

The site data collection provides a general understanding of the characteristics of the snow pile. From the information collected it was also observed that several contaminants are present in the City of Edmonton snow and melt water, some of which are above the recommended criteria. However, the melt water was shown to contain a large portion of the contaminants within the first portion of the melt, i.e. salt concentrations during March were up to 10 times more concentrated than those seen in the bulk snow. Therefore, natural freeze separation is evidently taking place onsite. The corresponding laboratory work offers some insight into brine concentration requirements. Salt concentrations as low as 15 g/L, in combination with road sand and additional crystal salt would allow the release water to be used as a de-icer.

## 2.7 Figures

### Figure 2.1 Schematic of the eutectic phase diagram for a NaCl-$H_2O$ system



*(Adapted from Muldrew and McGann, 1997)*

Figure 2.2 Site layout of the snow storage and sand recycling facilities

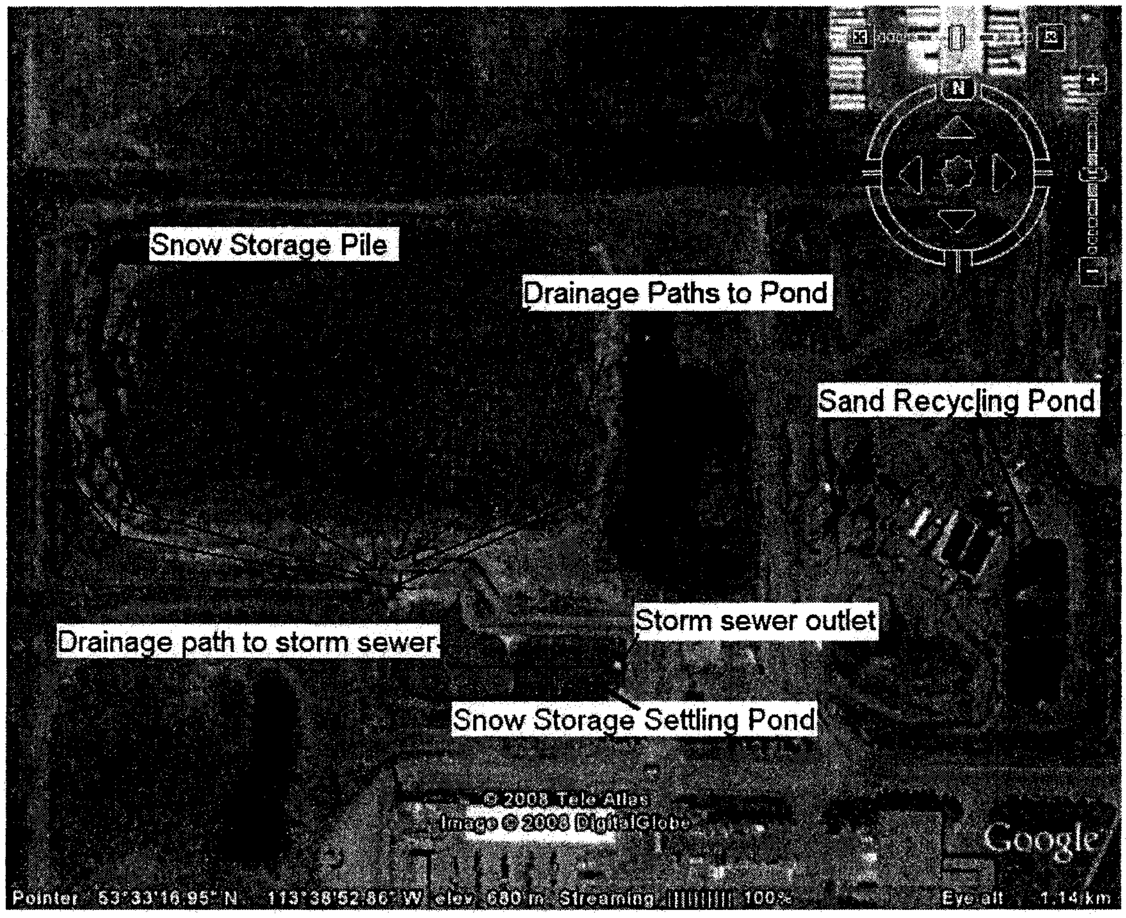


Figure 2.3 LIDAR scan of the Poundmaker snow pile, April 2007

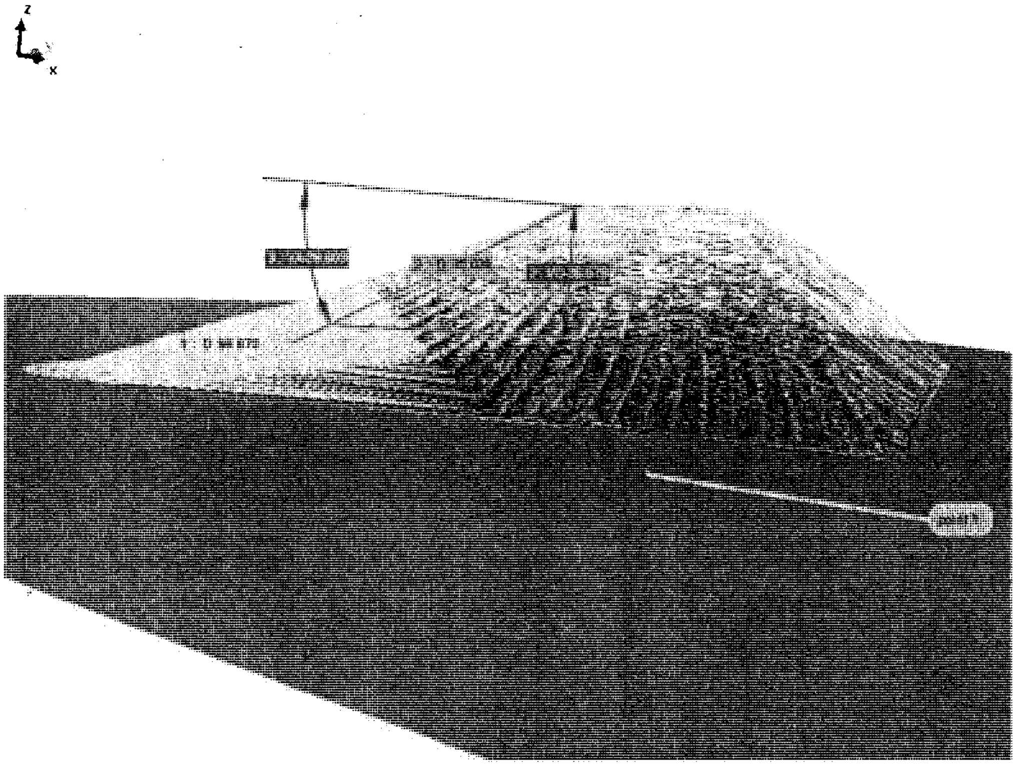


Figure 2.4 Concentrations of cations (log scale) in melt water with time

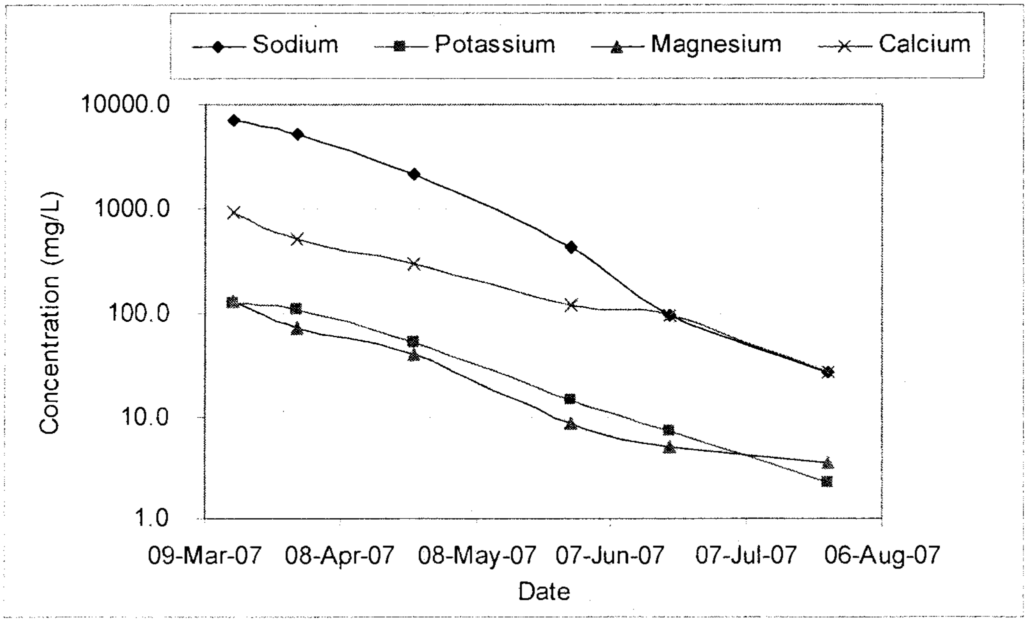


**Figure 2.5 Concentrations of anions (log scale) in melt water with time**

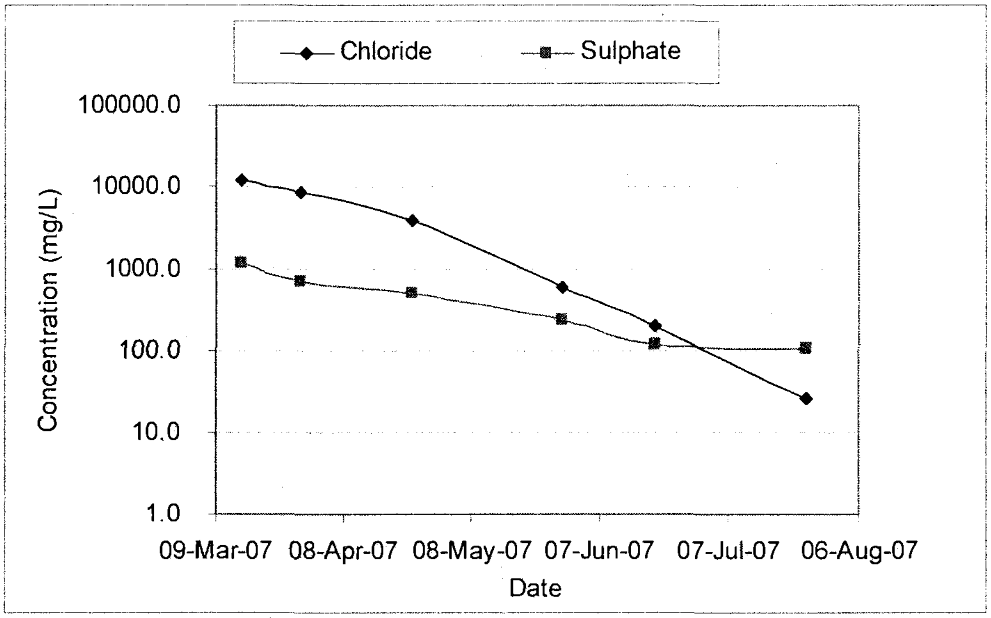


**Figure 2.6 Site calibration – road salt concentrations to electro-conductivity**

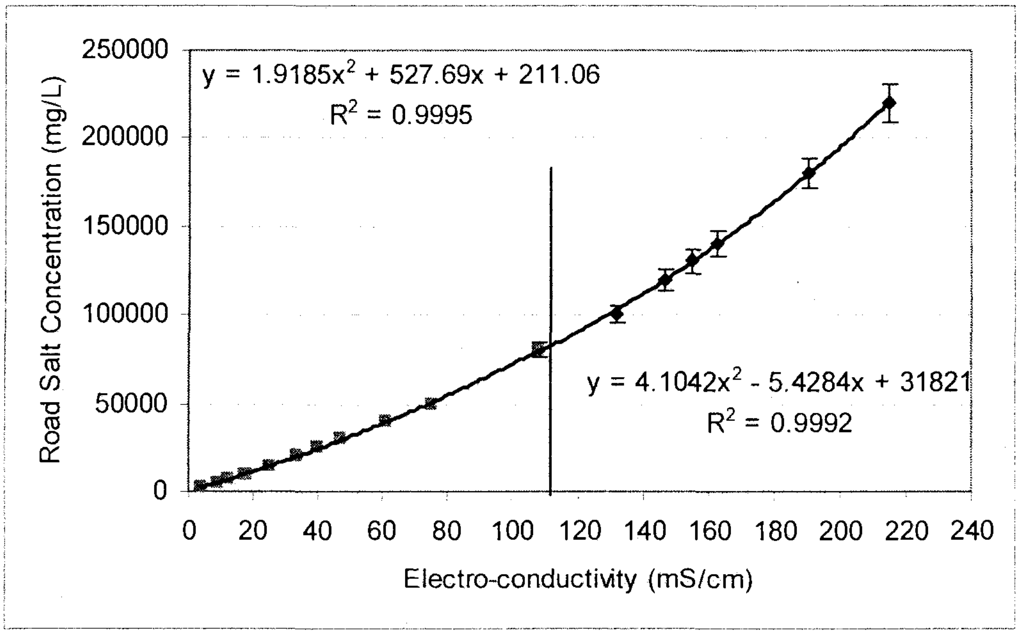


**Figure 2.7 Fractionation test – cation concentration factors vs. time**

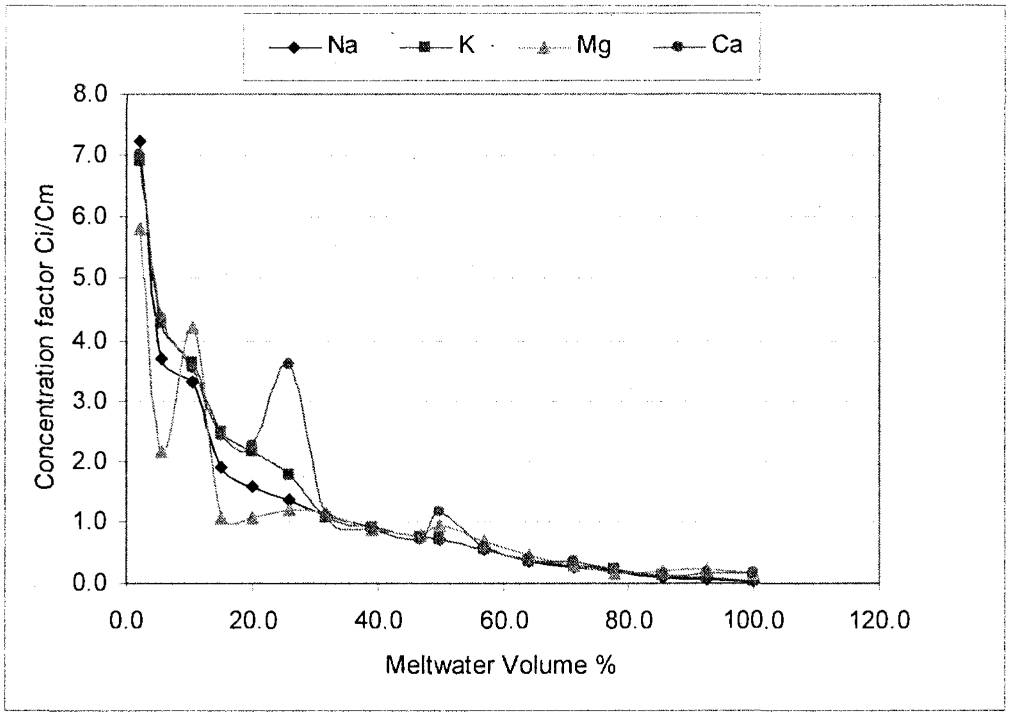


**Figure 2.8 Fractionation test – *anion concentration factors vs. time***

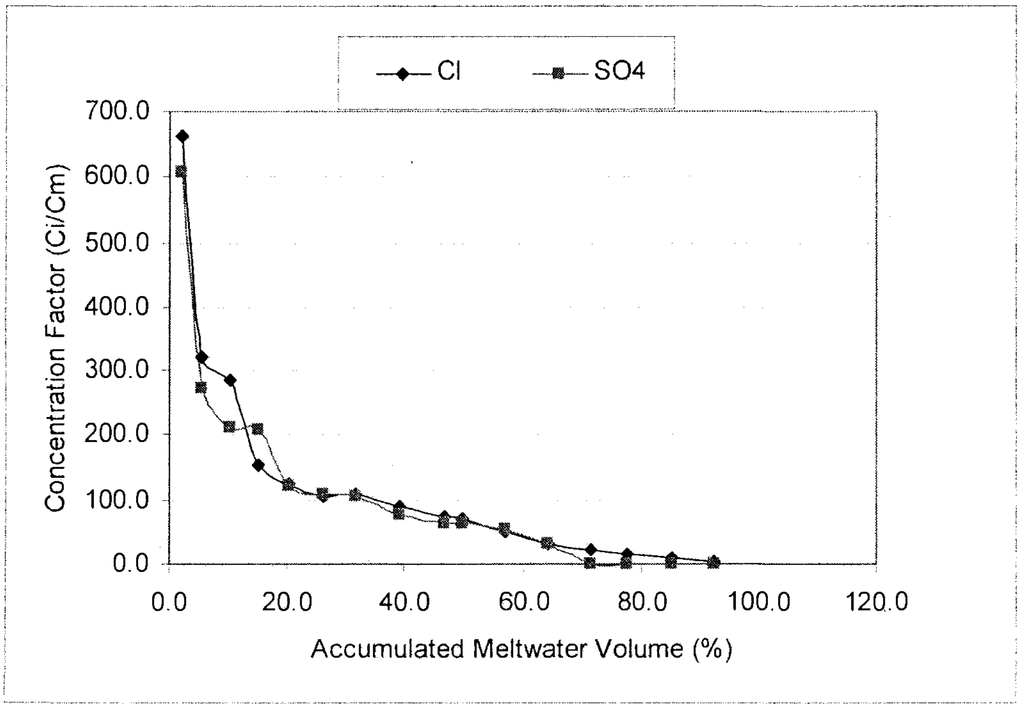


**Figure 2.9 Snow pile density vs. depth**

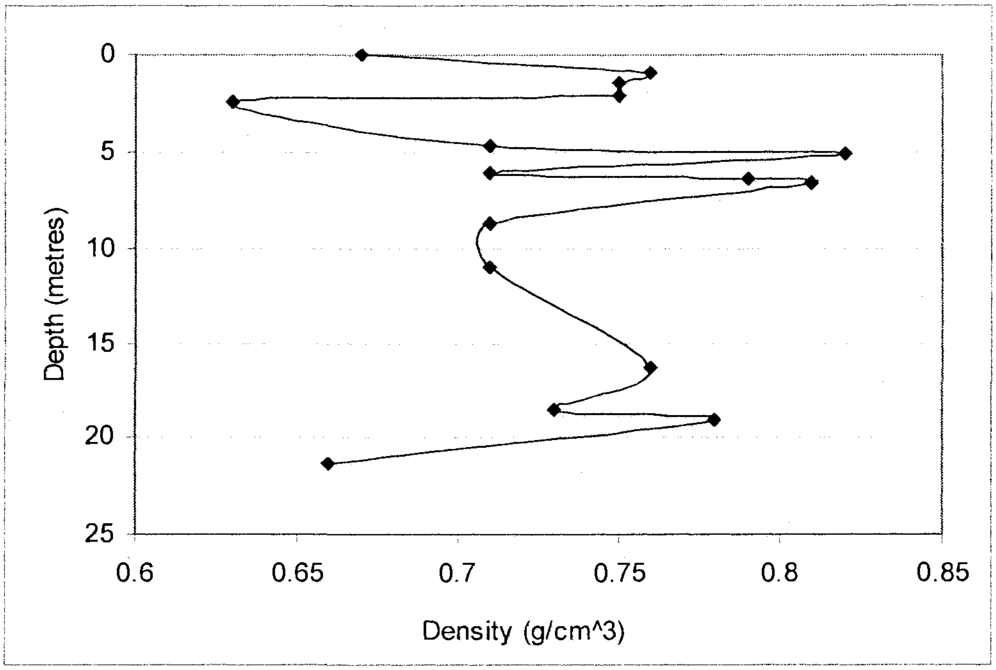
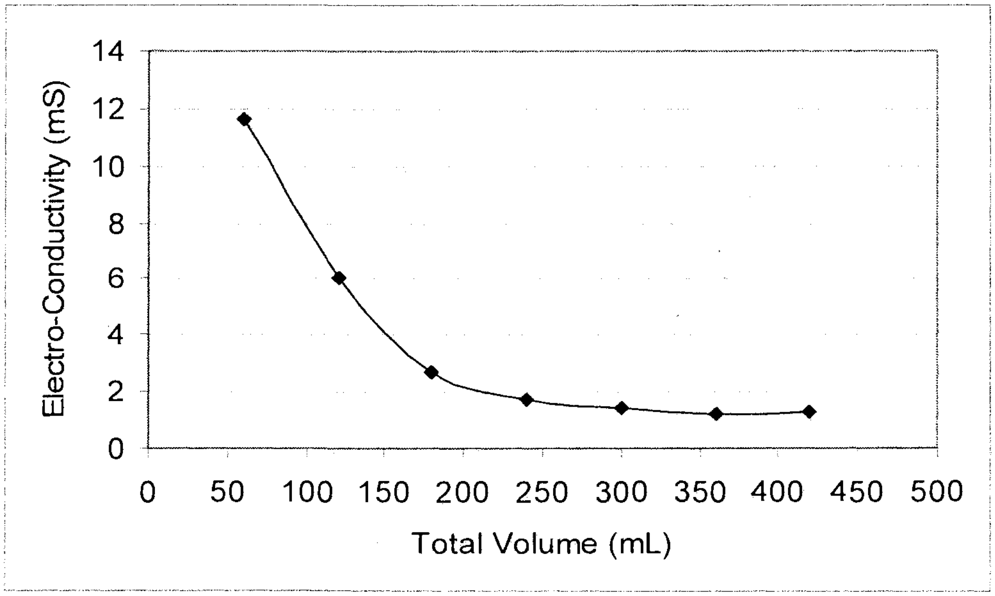
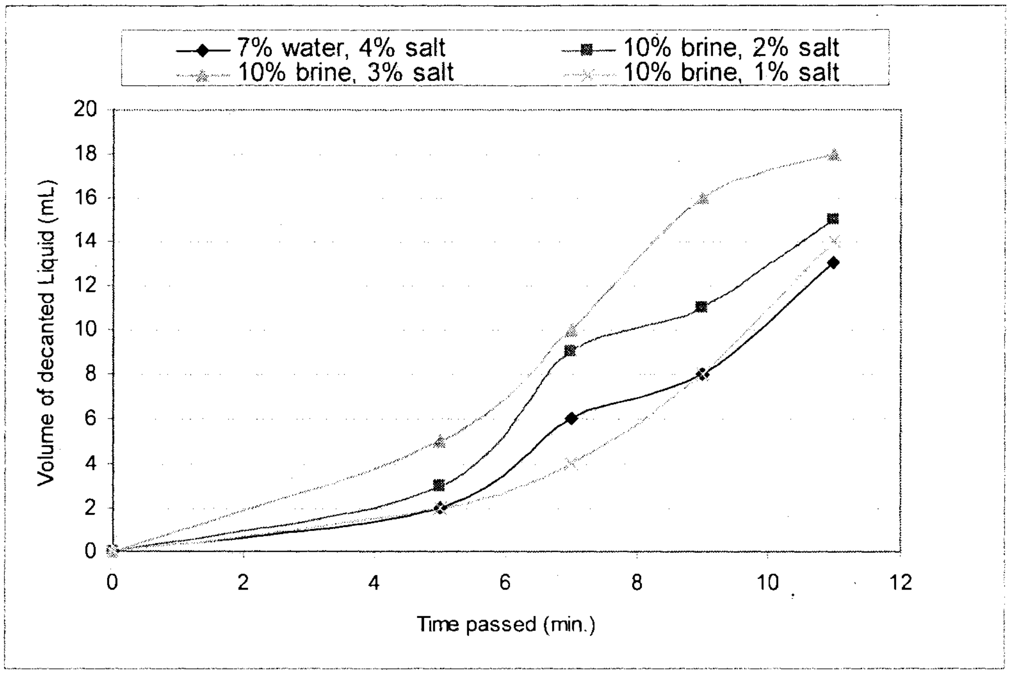


**Figure 2.10 Typical core melt taken from a depth of 8.55 to 8.7 metres**



## Figure 2.11 De-icer test results for a 15 g/L brine solution



## 2.8 Tables

### Table 2.1 Eutectic temperatures of various aqueous solutions

| *Substance* | *Eutectic Temperature (°C)* |
|---|---|
| potassium chloride | -10.7 |
| sodium chloride | -21.2 |
| magnesium chloride | -33.6 |
| calcium chloride | -55 |

(*Adapted from Lock, 1990)*

## Table 2.2 Surface water quality guidelines – Alberta Environment 1999

| Ion | Sample ID | Date Sampled | Concentration mg/L | Regulatory Limit mg/L |
|---|---|---|---|---|
| **NH4+ as N** | P07-1 | 15-Mar-07 | 9.0 | 2.2 (CCME) |
| | P07-2 | 29-Mar-07 | 0.0 | |
| | P07-3 | 24-Apr-07 | 0.0 | |
| | P07-4 | 29-May-07 | 0.0 | |
| | P07-5 | 20-Jun-07 | 0.0 | |
| **Calcium** | P07-1 | 15-Mar-07 | 158.0 | None Given |
| | P07-2 | 29-Mar-07 | 160.1 | |
| | P07-3 | 24-Apr-07 | 294.7 | |
| | P07-4 | 29-May-07 | 129.2 | |
| | P07-5 | 20-Jun-07 | 69.9 | |
| **Chloride** | P07-1 | 15-Mar-07 | 637.1 | 860 (US EPA) |
| | P07-2 | 29-Mar-07 | 1424.6 | |
| | P07-3 | 24-Apr-07 | 3995.2 | |
| | P07-4 | 29-May-07 | 914.2 | |
| | P07-5 | 20-Jun-07 | 103.4 | |
| **NO2- as N** | P07-1 | 15-Mar-07 | 0.0 | 0.06 (CCME) |
| | P07-2 | 29-Mar-07 | 0.0 | |
| | P07-3 | 24-Apr-07 | 0.0 | |
| | P07-4 | 29-May-07 | 0.0 | |
| | P07-5 | 20-Jun-07 | 0.0 | |
| **NO3- as N** | P07-1 | 15-Mar-07 | 0.6 | Avoid concentrations that stimulate weed growth |
| | P07-2 | 29-Mar-07 | 0.4 | |
| | P07-3 | 24-Apr-07 | 0.9 | |
| | P07-4 | 29-May-07 | 0.0 | |
| | P07-5 | 20-Jun-07 | 0.0 | |
| **Sodium** | P07-1 | 15-Mar-07 | 428.4 | None Given |
| | P07-2 | 29-Mar-07 | 804.1 | |
| | P07-3 | 24-Apr-07 | 2176.7 | |
| | P07-4 | 29-May-07 | 563.9 | |
| | P07-5 | 20-Jun-07 | 177.6 | |

## Table 2.3 City of Edmonton Schedule C – Restricted wastes applicable to storm sewers and water courses

| Inorganic Constituent | Sample ID | Date Sampled | Concentration µg/L | Regulatory Limit µg/L |
|---|---|---|---|---|
| **Arsenic** | P07-1 | 15-Mar-07 | 3 | 50 |
| | P07-2 | 29-Mar-07 | 3 | |
| | P07-3 | 24-Apr-07 | 7 | |
| | P07-4 | 29-May-07 | 1 | |
| | P07-5 | 20-Jun-07 | 1 | |
| **Cadmium** | P07-1 | 15-Mar-07 | 0.0 | 0.5 |
| | P07-2 | 29-Mar-07 | 0.1 | |
| | P07-3 | 24-Apr-07 | 0.4 | |
| | P07-4 | 29-May-07 | 0.0 | |
| | P07-5 | 20-Jun-07 | 0.0 | |
| **Chromium (Total)** | P07-1 | 15-Mar-07 | 3 | 89 |
| | P07-2 | 29-Mar-07 | 3 | |
| | P07-3 | 24-Apr-07 | 29 | |
| | P07-4 | 29-May-07 | 6 | |
| | P07-5 | 20-Jun-07 | 8 | |
| **Copper** | P07-1 | 15-Mar-07 | 22 | 160 |
| | P07-2 | 29-Mar-07 | 19 | |
| | P07-3 | 24-Apr-07 | 32 | |
| | P07-4 | 29-May-07 | 36 | |
| | P07-5 | 20-Jun-07 | 235 | |
| **Lead** | P07-1 | 15-Mar-07 | 0.8 | 20 |
| | P07-2 | 29-Mar-07 | 1.4 | |
| | P07-3 | 24-Apr-07 | 2.5 | |
| | P07-4 | 29-May-07 | 0.0 | |
| | P07-5 | 20-Jun-07 | 72.9 | |
| **Selenium** | P07-1 | 15-Mar-07 | 1.4 | 10 |
| | P07-2 | 29-Mar-07 | 1.1 | |
| | P07-3 | 24-Apr-07 | 0.0 | |
| | P07-4 | 29-May-07 | 0.0 | |
| | P07-5 | 20-Jun-07 | 0.0 | |
| **Silver** | P07-1 | 15-Mar-07 | 0.1 | 1 |
| | P07-2 | 29-Mar-07 | 0.1 | |
| | P07-3 | 24-Apr-07 | 0.1 | |
| | P07-4 | 29-May-07 | 0.3 | |
| | P07-5 | 20-Jun-07 | 0.7 | |
| **Thallium** | P07-1 | 15-Mar-07 | 0.3 | 8 |
| | P07-2 | 29-Mar-07 | 0.3 | |
| | P07-3 | 24-Apr-07 | 2.5 | |
| | P07-4 | 29-May-07 | 2.0 | |
| | P07-5 | 20-Jun-07 | 1.8 | |
| **Zinc** | P07-1 | 15-Mar-07 | 0 | 300 |
| | P07-2 | 29-Mar-07 | 0 | |
| | P07-3 | 24-Apr-07 | 60 | |
| | P07-4 | 29-May-07 | 36 | |
| | P07-5 | 20-Jun-07 | 0 | |

## 2.9 References

Alberta Environment 1999. Surface Water Quality Guidelines for Use in Alberta: 1999. Alberta Environment, Environmental Service. Publication T/483. Edmonton, Alberta, Canada.

Alberta Environment 2008. Alberta Tier 1 Soil and Groundwater Remediation Guidelines. Edmonton Alberta, Canada.

Beier, N., Sego, D., Donahue, R., Biggar K. 2007. Laboratory Investigation on Freeze Separation of Saline Mine Wastewater. Cold Regions Science & Technology. Vol. 48, No. 3, 239-247.

Biggar K., Donahue, R., Sego, D., Mathieu, J., Birch, J. 2005. Spray Freezing Decontamination of Tailings Water at the Colmac Mine. Journal of Cold Regions Science and Technology, 42, 106-119.

Brimblecombe, P., Clegg, S, Davies, T., Shooter, D., Tranter, M. 1987. Observations of Preferential Loss of Major Ions from Melting Snow and Laboratory Ice. Water Resources. Vol. 21, No. 10, 1279-1286.

Brimblecombe, P., Clegg, S, Davies, T., Shooter, D., Tranter, M. 1988. The Loss of Halide and Sulphate Ions from Melting Ice, Water Resources, Vol. 22, No. 6, pages 693-700.

City of Edmonton. 2007. Sewers Use Bylaw, No. 9675. Schedule C – Restricted Wastes Applicable to Storm Sewers and Watercourses.

Canadian Council for Ministers of the Environment (CCME). 1991. Canadian Water Quality Guidelines. Environment Canada, Ottawa.

Colbeck, S. C. 1981. A Simulation of the Enrichment of Atmospheric Pollutants in Snow Cover Runoff. Water Resources Research, Vol. 17, No. 5, 1383-1388.

Elmore, W.W. 1968. Water Purification by Natural Freezing. M.Sc. Thesis, Department of Chemical Engineering, University of Wyoming, Laramie, Wyoming.

Environment Canada, 2004. Canadian Environmental Protection Act (CEPA, 1999), Code of Practice for the Environmental Management of Road Salts. April, 2004.

Evans, M., Frick, C. 2001. The Effects of Road Salts on Aquatic Ecosystems. National Water Research Institute, Saskatoon, SK, Canada.

Fertuck, L. 1968. Water Purification by Freezing Reservoirs, work done during 1968 to 1969. Saskatchewan Research Council Report E 69-12, November 1968.

Gao, Wa 1998. Partial freezing by spraying as a treatment alternative of selected industrial wastes. Ph.D. diss., University of Alberta, Edmonton, Alberta, Canada.

Gao, W., Smith, D.W. & Sego, D.C. 2004. Release of Contaminants from Melting Spray Ice of Industrial Wastewaters. Journal of Cold Regions Engineering. Vol. 18, No. 1, 35-51.

Grant, S.A. 2000. Physical and Chemical Factors Effecting Contaminant Hydrology in Cold Environments. US Army Cold Regions Research and Engineering Laboratory TR-00-21.

Gray M., Male D.H. 1981. Handbook of Snow. Pergamon Press, Ontario, Canada, 21, 324-325, 397-398.

Health Canada, 2007. Guidelines for Canadian Drinking Water Quality. Health Canada, Ottawa, Canada, 8.

Johannessen, M. & Henriksen, A. 1978 Chemistry of Snow Meltwater: Changes in Concentration during Melting. Water Resources Research, Vol. 14, No. 4, 615-619.

Lock, G.S.H. 1990. The Growth and Decay of Ice. Cambridge University Press, Cambridge, Great Britain. 31-34.

Martel, J. 1993. Fundamentals of Sewage Sludge. Water Science and Technology. Vol. 28, No. 1, 29-35.

Mishra, A., Ohtsubo, M., Li, L., Hagshi, T. 2006. Effect of Salt Concentrations on the Hydraulic Conductivity of the Mixtures of Basalt Soil and Various Bentonites. Journal of the Faculty of Agriculture, Kyushu University, Vol. 51, No. 1, 37-53.

Muldrew, K., McGann, L. 1997. CryoBiology – A Short Course, University of Calgary, Calgary, Alberta, Canada.

Oertling, A., Watts, R. 2004. Growth of and Brine Drainage from NaCl-$H_2O$ Freezing: A Simulation of Young Sea Ice. Journal of Geophysical Research, Vol. 109, C04013, 1-10.

Otto, S. 2002. Evaluation of Freeze Separation as a Treatment for Salt-Contaminated Ground Water. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Canada.

Parker, P.J., Collins, A.G., and Dewolfe, J. R. 2000. Freeze Thaw Residuals Conditioning. Journal of American Water Works Association, **92**:4, 168-181.

Pounder E. R. 1965. Physics of Ice. Pergamon Press, Ltd, London, UK. 3-5, 26.

Rabinowitz, B., Vassos, T.D., Hyslop, W.F. 1988. The Use of Snow Making for Wastewater Treatment and Disposal. Proceedings from the 11th International Symposium on Wastewater Treatment. Montreal, Quebec, Canada.

Spyker, J.W. 1982. Desalination of Brackish Water by Spray Freezing: Progress Report 1981-1982. Saskatchewan Research Council Technical Report No. 140.

Strategic Highway Research Program, SHRP-H-332. 1992. Handbook of Test Methods for Evaluating Chemical De-icers. National Research Council, Washington, DC, USA.

Thomas, D., Diekmann, G. 2003. Sea Ice. Blackwell Science Ltd., Oxford, UK, 54-56.

Transportation Association of Canada (TAC) 1999. TAC Road Salt (NaCl) Management Guide. December, 1999.

Vaa, T., Sakshaug, K., Resen-Fellie, O.P. 1996. Road Salting and Traffic Safety – The Effect of Road Salt on Accidents and Driving Speed. Fourth International Symposium on Snow Removal and Ice Control Technology, Nevada, USA.

Willoughby, A. 2005. Freeze Separation to Remove Nutrients from Liquid Swine Manure. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Canada.

# 3. Design of Field Scale Spray Freeze Separation System for Salt Contaminated Water

## 3.1 Introduction

Several factors affect the design of an effective spray freeze system. The process involves the supercooling of water droplets. The efficiency of the supercooling process that leads to ice nucleation will in turn affect the runoff concentration. Both of these topics are discussed as well as other important physical factors which may affect the successfulness of a spray freeze system.

### 3.1.1 Factors Affecting Supercooling of Water Droplets

The freezing of a water droplet is a dynamic and complex process that is dependant on a number of variables. As water droplets freeze they solidify from the outside in and push the impurities to the centre of the drop. When freezing is near completion, the outer shell will fracture releasing the liquid impurities to the outside of the drop. For a successful spray freezing operation, an adequate amount of air resistance time is important to allow a sufficient amount of freezing to take place. Gao (1998) found that the air resistance time for a water droplet from a nozzle is dependant on many factors such as droplet size, angle of spraying and nozzle pressure, however in a well set-up spray freezing operation it typically takes about 10 seconds for the droplet to hit the ground. Droplet nucleation generally takes longer than 10 seconds and therefore, only a portion of each drop will freeze before it hits the ground (Gao 1998).

When the droplets freeze there is also a possibility that fragmentation will occur; this is a process in which the droplet shatters into pieces due to pressure changes within the drop as it freezes. Many factors affect whether or not a drop will fragment after freezing. A warmer nucleation temperature or a faster rate of freezing as well as a higher amount of dissolved gases such as carbon dioxide within the droplets will increase fragmentation (Dye and Hobbs, 1968). In the spray freezing experiment carried out, it was not possible to predict if fragmentation of the droplets was occurring in the air as the droplets fell. However, for droplets in which at least some freezing occurred, shattering of the ice shell certainly took place as the droplets hit the ground surface, releasing the unfrozen concentrated internal liquid. This is evident during the spray freeze process because of the formation of a spray ice mound and the corresponding runoff that is more concentrated than the source water.

One of the most important factors affecting the super cooling of a water droplet is the volume of the droplet or droplet size. In order for droplets to freeze homogeneously, impurities are required within the liquid to initiate nucleation. For example, a freely suspended droplet of pure water will freeze at a lower temperature than a rainwater droplet which is much more likely to contain a spec of dust or other impurity, to aid in initiating nucleation. If there are no impurities present, as in the case of extremely pure water, the water may be supercooled far below its equilibrium phase temperature and heterogeneous nucleation will take place (Hobbs, 1974). Homogeneous nucleation takes place when the ice embryo grows on a foreign particle within the liquid. Bigg (1953) also found that cooling rate has an important effect on freezing of water droplets, with deeper supercooling being possible at higher cooling rates.

Bigg (1953) also confirmed that smaller droplets will generally freeze at colder temperatures because a smaller drop has a lower probability of containing an impurity required for nucleation. In this study it was also established that the logarithm of the drop diameter is directly proportional to the nucleation temperature by the equation:

$$-\ln V = aT_s - b \tag{1}$$

Where *a* and *b* are constants, *V* is the drop volume and $T_s$ is the degree of supercooling (or $T_s = T_0 - T$, where $T_0$ is 0 °C and *T* is the temperature) (Bigg, 1953).

Although droplet volume and cooling rate are significant factors in the supercooling of water droplets, evaporation rate and pH have also been shown to have an effect. Ramachandra and Rama (1972) confirmed that when supercooling drops are subject to evaporation they will freeze more readily due to what has been called the "dynamic effect". When sodium sulphate was added to the droplets their probability of freezing also increased (Ramachandra and Rama, 1972). However, other molecules such as sucrose may have a significant retarding effect on a drops probability to freeze (Langer et al., 1963). Dye and Hobbs (1986) also showed that dissolved gases within a drop will effect its nucleation and that the probability of fragmentation increased with increased concentrations of carbon dioxide. Cissé and Bolling (1971) found that gases contained in freezing water droplets can nucleate bubbles and change particle contact, effecting nucleation.

Droplets formed from a wastewater with a higher pH take longer to freeze than those with a lower pH (Gao, 1998). In the experiments conducted by Gao (1998) it was found that a 7.1 pH wastewater at a temperature of -10.3 °C took 16 seconds to nucleate and 23 seconds with a pH of 11.0. Also when the temperature was reduced to -18 °C the time to nucleate was significantly reduced to about 3 seconds for the 7.1 pH wastewater (Gao, 1998). From this it is clear that higher alkalinity droplets will have a longer nucleation time.

Determination of the average droplet size produced by the nozzle may be useful in figuring out the required nucleation temperature for the given wastewater. Knowledge of this relationship will enhance the success of the spray freeze operation. However, in field operations the temperature may vary significantly throughout the day. If the droplet size to temperature variation relationship cannot be directly determined for the wastewater in question, alternatively, it will be necessary to adjust the spray nozzle to produce an average droplet size in which nucleation of majority of the droplets will freeze at the given temperature and conditions. This can be achieved through onsite observation and corresponding alterations of the nozzle setting as environmental conditions change.

### 3.1.2 Factors Effecting the Runoff Concentration

As melt water or spray freeze liquid flows through a snow pack, homogeneous flow is generally not achieved. Thomas and Diekmann (2003) noted that in salt contaminated snow or ice, fluid will flow in vertically elongated systems of brine tubes or brine channels, which are important for brine drainage. However, when more homogeneous flow is achieved, generally a higher removal efficiency of contaminants is obtainable. In a study done by Rabinowitz et al. (1988), higher removal efficiencies were achieved with increasing pack height and decreasing snow densities and lower impurity removal was observed for high snow densities and lower pack height. Therefore, it should be noted that a lower density snowpack is more desirable for higher impurity removal and the creation of more concentrated brine. Rabinowitz et al. (1988) recommended a snow density of 400 kg/m$^3$ or less as a target for efficient contaminant removal by spray freezing. Generally a lower snow density is obtainable at colder temperatures during spray freezing operations (Gao, 1998).

When the spray ice mound becomes larger during the spray freezing process, the spray water has a larger area to cover and a slower rate of percolation results. A larger spray ice mound will then result in greater concentrations of ions in solution, since there is likely to have been more diffuse flow through the snow column, giving rise to a greater opportunity for solute leaching by the percolating spray water (Tranter et al., 1992). Biggar et al. (2005) found that the contaminant concentrations in the runoff were similar to that in the source water until the ice mound was substantial and after about four hours of continuous spraying the runoff concentration reached its peak efficiency. Therefore three important factors effecting brine concentration during spray freezing are: spray ice mound density, ambient temperature and the size/height of the spray ice mound.

### 3.1.3 Physical Factors

A spray freezing operation is highly affected by a number of uncontrollable physical factors associated with nature and the ambient environment. As mentioned, air temperature plays an important role, but wind direction and velocity as well as relative humidity may also greatly affect the success of the spray freezing operation. A low relative humidity and the presence of wind may increase the evaporation rate of the droplets sequentially causing the drops to freeze faster. During their experiment, Biggar et al. (2005) found that spray nozzle direction in reference to the wind direction was also important since back spray could cause the pumps to ice up.

Gao et al. (2000) demonstrated that the initial contaminant concentrations in the source water will have a huge effect on the spray freezing operation and obviously, the efficiency of droplet freezing. However these initial concentrations did not effect the concentration of the runoff from the pile during spraying (Gao et al., 2000; Beier et al., 2005).

## 3.2 Spray Freezing Methodology

As a part of the freeze separation evaluation at the City of Edmonton snow storage facility, spray freezing was assessed as a method to further concentrate melt water. The snow storage settling pond was drained in the fall time due to the sludge build-up and therefore the sand recycling settling pond was used as source water for the spray freezing field experiments.

### 3.2.1 Spray Freeze Set-up

Due to the long distance between the sand recycling pond and the location of spraying, 2 pumps in series were required. For the first spray freezing experiment in January of 2008, the first pump was placed near the edge of the pond and 100 mm (4 inch) hose was run across the sites to the second pump located approximately 300 m from the source pond, at the edge of the snow storage pond. Approximately 70 metres of hose was run from the second pump to the fire fighting monitor and the attached spray nozzle located near the southwest corner of the site. A total of approximately 370 metres of hose was used in this operation. During the second operation in February of 2008, only about 15 metres of hose was run from the pump to the monitor in an attempt to minimize head loss and deliver higher pressure at the nozzle. The spray runoff was allowed to trickle across the snow storage site to a small sump in a low area. Figure 3.1 shows a site photograph of the spray freezing operation layout.

### 3.2.2 Field Work Program #1

The first field work program took place on January 15, 2008. Set-up of the hoses and pumps began at 9:00 am and was completed at 3:30 pm. The ice on the pond was approximately 20 centimetres thick. A hole for the intake line was drilled using an ice auger and widened using a pick. A small screen was attached to the end of the 100 mm suction line to prevent large debris from entering the intake hose. The total depth of the water underneath the ice was slightly less than 1 metre. The intake end was attached to a miniature crane which was used to adjust the depth of the intake hose in the pond without having to continuously step on the ice. The diameter of the open hole was approximately 300 mm and the hole remained open throughout the course of the pumping operation.

The hose used throughout the system was 100 mm lay-flat hose designed for a maximum pressure of 1034 kPa (150 psi). The last 25 metres of hose near the fire fighting nozzle was standard 50 mm (2 inch) fire fighting hose. The nozzle was mounted on a steel frame fire fighting monitor that was pinned into the ground using steel pins. The vertical angle of the monitor was easily adjusted during spraying and the horizontal angle was adjusted and set for the prevailing Northwest winds prior to start up of the pumps. A small sump had been dug earlier to collect the initial portions of the runoff. The site was graded towards this area although no defined drainage path was constructed. The area available for spray freezing was more than 50 X 50 metres and the underlying clay liner along with the overlying ice and snow was considered adequate runoff control given the large available area.

Pumping commenced at approximately 3:45 pm, however the water did not make it past the first pump due to a slush jam in the hoses. After cleaning and reconnecting the hoses, pumping recommenced, however several holes were observed in the second last section of the hose and that had to be replaced. Successful commencement of the spraying began at approximately 4:30 pm when the ambient air temperature was approximately -11 °C. The air temperature was monitored continuously with two thermistors hooked up to a data logger. Ambient air temperature readings were logged every five minutes. An average of the two readings vs. time is shown in Figure 3.2.

Low freezing was observed during the majority of the evening spraying especially during the initial 3 to 4 hours. Much of the water was not freezing at all and was running off the spray ice pile creating a large pool which slowly seeped across the site towards the low area about 50 metres down slope from the spray ice mound. The height of the water jet was only 6 metres at its highest point, and evidently more retention time was required for majority of the droplets to freeze at the ambient air temperatures during the experiment. However, the spray ice mound continued to form with the greatest addition to the spray ice mound being made during the night when the temperatures dropped to -20 °C. The ice mound was yellowish in color at the beginning of the experiment but became whiter with time as it froze and the impurities continued to drain from the pile. At the end of the experiment the spray ice mound was white in color.

Pumping continued until approximately 8:30 am on January 16, 2008 when the temperatures began to rise dramatically and unacceptably low freezing efficiency was being observed. The height of the pile upon completion was approximately 2.5 metres from the ground. The University of Alberta Light Detection and Ranging (LIDAR) unit was used to scan the pile and obtain dimensions and overall pile volume after spraying was complete. Figure 3.3 shows a photo of the final spray ice mound with standard pylons mounted on the top for scale. The overall pile volume was calculated using LIDAR software to be approximately 220 $m^3$. Figure 3.4 shows a graph of the flow rate with time during the pumping operation.

Electrical conductivity (EC) measurements of the runoff and the source water were made continuously throughout the experiment. The value of the EC is compared to the concentration of dissolved ions (i.e. salts) in the water and therefore a good indication of the effectiveness of the freeze separation process taking place. Several samples of the spray water were taken and the slush/snow was separated out to get a mass balance and an indication of the portion of the spray which was freezing compared to the portion that ran off.

### 3.2.3 Field Work Program #2

The second field work program took place on February 4, 2008. The methodology was similar to the previous field experiment however; less hose was used after the pump and a nozzle, with adjustable flow rate settings, was attached to the monitor. Three holes were drilled in the pond ice on February 1, 2008, prior to spraying, in order to estimate the remaining volume of water in the pond and hence the spraying time available. Approximately 40 cm of ice was found throughout the surface of the pond, followed by 30 to 55 cm of water depending on location. Below the water was a 10 cm layer of sludge or suspended solids at the base of the pond which had to be avoided to prevent clogging of the intake and/or nozzle.

Comparative observations were made during this experiment which commenced at 2:00 pm on February 4, 2008, however greater freezing efficiency was observed compared to the first trial. A lower ambient air temperature ranging between -16 and -22 °C was observed during this experiment and the height of the water jet reached approximately 10 metres during the first portion of the experiment and was reduced to about 6 or 7 metres when ice and debris cause a decrease in flow rate. As the evening progressed, several issues such as an ice jam in one of the pumps as well as a plugged nozzle required the spraying system to be shut down several times to deal with these issues. A flow meter was used, with a data logger properly calibrated to read flow rates up to 108 $m^3$/hr. Evidence of the many shutdowns and continuity issues are evident in the flow rate graph presented in Figure 3.5. Spraying continued until about 11:50 pm on February 4, 2008 at which time several complications, mainly frozen hose and a lack of pond water, required the experiment to be terminated.

EC measurements of the runoff and spray water were made as in the first experiment. The second spray ice mound was also scanned with the LIDAR and had a volume of 170 $m^3$ with a height of 1.7 metres at its highest point. The LIDAR scan for the second pile is shown in Figure 3.6.

### 3.2.4 Spray Ice Sampling

On January 23, 2008, a core sample of the first spray ice mound was taken using a 1 metre long, 100 mm diameter, CRREL fibreglass core barrel. One vertical hole was drilled from the top of the ice mound. The first 1 metre of core was drilled using the electrical motor and the final section was drilled manually due to lack of an adapter for the extension. A total of approximately 2.15 metres of core were obtained. Therefore roughly 0.35 metres of the base ice mound material was not sampled. The cores were extruded, bagged and labelled and packed in a cooler with snow for safe transport back to the University of Alberta. The cores were stored in a cooler at -10 °C. When core analysis could not be done, within the following two days, the bagged core samples were surrounded by crushed ice and snow to minimize sublimation.

The second spray ice mound was sampled approximately one hour after the completion of spraying at around 1:30 am on February 5, 2008. The pile was cored until liquid was reached at the bottom of the pile and approximately 1.90 metres of core was obtained. The second spray ice pile was cored again on February 13, 2008 after sufficient drainage of the brine was allowed to take place within the pile. The pile was drilled to the very bottom and a total of 1.98 metres of core was obtained. The core obtained directly after spraying was more yellow in colour and contained more liquid than the core obtained a week after drilling. The core samples were dealt with in a similar manner as the ones obtained from the first spray ice mound.

## 3.3 Results

The results of the spray freeze operation included determining the spray ice volume, the freezing efficiency, chemical removal efficiency and a mass balance of the chemical species.

### 3.3.1 Spraying Operation

During the first spray freeze operation on January 15 and 16, 2008, the pumps were run for approximately 16 hours and a total of approximately 800 $m^3$ of water was pumped. The flow rate was at or above 54 $m^3/hr$ for the first 8 hours (the first half) of the experiment. The flow meter was not calibrated to read flows above 54 $m^3/hr$ however it is not expected that the flow rate went significantly above this number and therefore 54 $m^3$/hr was used as the maximum rate. A graph of the flow rate during the first field trial is shown in Figure 3.4. During the final 8 hours, at around 12:00 am on January 16, 2008, the flow rate began to decrease as the nozzle became plugged with debris from the pond. The flow rate had decreased to about 38 $m^3$/hr when the system was shut off at around 8:00 am on January 16, 2008.

The LIDAR scan indicated that the spray ice pile had a volume of 220 $m^3$. The average density of the spray ice was 0.57 Mg/$m^3$. Therefore, approximately 125 $m^3$ of the 780 $m^3$ of water that was pumped had frozen, for a freezing efficiency of approximately 16%. Figure 3.3 shows a photo of the first spray ice mound.

The second spray freeze operation which took place on February 4, 2008 and was notably more efficient than the first. Pumps ran for approximately 10 hours between 2:00 pm and midnight, with several shutdowns in between. A total of approximately 390 $m^3$ of water was pumped and the maximum flow rate reached was 49 $m^3$/hr. The adjustable nozzle used during the second field trial allowed for an increase in pressure at the nozzle resulting in a higher water jet which allowed for better retention time of the spray water droplets. As in the first spray freeze trial, peak freezing efficiency was not achieved until the system had been running for a few hours. Biggar et al. (2005) found that the runoff rate appeared to remain constant after about 4 hours of operation at which time "peak efficiency" was obtained.

The LIDAR scan indicated that the second spray ice mound had a volume of 170 $m^3$ with an average drained density of 0.56 Mg/$m^3$. Therefore approximately 95 $m^3$ of the pumped water had frozen representing a freezing efficiency of 24%, about 8% higher than the first trial. Figure 3.6 shows the LIDAR scan for the second spray ice mound.

The electrical conductivity of the source water during the first spray freeze trial ranged between 6.8 and 7.1 mS/cm and the runoff concentrations were between 7.4 and 9.8 mS/cm. The second spray freeze trial in February of 2008, had source water electrical conductivities (EC) between 7.4 and 8.3 mS/cm and runoff EC's ranging between 9.0 and 12.1 mS/cm. From these numbers it is evident that the second trial was more efficient in concentrating the source water than the first. Higher source water concentrations were observed during the second spray freezing trial due to the tendency of the denser more concentrated liquid to sink, however a profile of the brine concentration with pond depth was out of the scope of this experiment. The spray freeze process behaved as expected and further validated the results and expectations obtained by Biggar et al. (2005) and Gao (1998). Analytical analysis of the chemical constituents in the source water and runoff further confirm the concentration process and are shown in Figures 3.11 and 3.12.

### 3.3.2 Ice Core Analysis

As previously mentioned, the ice core from the first spray ice pile, Core 1, had an average density of 0.56 Mg/m$^3$, from a core taken 7 days after completion of spraying. The second spray ice pile had a similar density of 0.57 Mg/m$^3$ from a core taken 8 days after spraying, Core 3. Core 2 was taken from the second spray ice mound approximately one hour after the completion of spraying. The characteristics of this core were much different than those of the cores taken several days after spraying. With an average density of 0.72 Mg/m$^3$, it was evident that much of the liquid brine had not been drained from the pile when this core sample had been taken. When examining the spray ice mound during and directly after spraying, evidence of a wetting front was visible. Typical hillside drainage was noticeable, similar as that which would be seen in a groundwater recharge area. Density readings were taken at various depths for each of the three core samples and there appeared to be no relationship between depth and density of the spray ice piles. Occasional dense lenses of more solidified brine liquid were visible in the cores. Figure 3.7 shows the density readings with depth taken for each of the 3 cores.

Electro-conductivity readings of the core samples were taken at various depths for each core. The EC readings as well as the concentrations of the major ions within the cores seemed to have no relation to depth. EC readings for the samples which were cored several days after spraying ranged between 0.28 and 0.54 mS/cm. EC readings for the sample cored only one hour after spraying were much higher, ranging between 1.9 and 2.6 mS/cm, however these readings were still lower than the source water.

### 3.3.3 Melting of Ice Cores

The first spray ice core melting experiment was conducted on the ice core obtained from the first spray ice mound, Core 1. Approximately 1.1 metres of ice core was melted from 0 to 1.1 metres in depth. The ice core was placed on the melting apparatus from top down and was encased in a latex membrane. The membrane was placed on the core so that it was overlapping upwards to prevent leakage where overlapping occurred and to simulate the realistic through flow of the brine. A 60 Watt light bulb was placed approximately 80 to 150 mm away from the surface of the ice core in order to provide a sufficient amount of heat to melt the core at an adequate rate. The ice core was originally in 4 pieces from 0 m to 0.28 m, 0.28 m to 0.86 m, 0.86 m to 0.96 m and 0.96 m to 1.09 m and the pieces were held together in consecutive order with the latex membrane. A PVC pipe was split in half and used as additional support around the latex membrane. A layout of the ice core melting apparatus is shown in Figure 3.8.

The first core took approximately 6.5 days to completely melt. Samples were collected at approximately 12 hour intervals on average. The volume of the samples ranged between 94 and 464 mL with the final sample having a volume of 42 mL. The melting rate increased noticeably at first and then slowly decreased with time. Some small ups and downs are visible in the graph and these are due to an increase in the distance from the sample to the light bulb with time as it melted and then subsequent lowering of the light bulb. For the first half a day no melting took place. The melt rate at its peak was approximately 31 mL/hour which took place approximately 48 hours into the melting process. There after the melt rate dropped to less than 25 mL/hr near completion as seen in Figure 3.9.

EC of the collected melt water samples were also taken after the completion of the melt. EC began at approximately 4.3 mS/cm and dropped dramatically to 1.63 mS/cm. Figure 3.10 shows the results of the analysis done on the ice core melt water which demonstrates the high concentration of contaminants contained with the first portion of the melt. After about 60 hours or about 40% through the melt, the EC remained low and did not change significantly.

Spray ice from the second spray ice pile, Core 3, was melted in the same manner. This core was approximately 1 metre long and was originally in 3 pieces. The spray ice pieces began at a depth of 0.36 metres below the top of the spray ice pile and were arranged in the following order: 0.36 m to 0.53 m, 0.53 m to 0.94 m, and 0.94 to 1.40 m. This ice core took about 7.5 days to completely melt and the EC readings were similar to those seen during the melting of Core 1. They began at approximately 3.3 mS/cm and dropped quickly to 1.66 mS/cm. The EC continued to drop slowly and remained between 0.07 and 0.2 mS/cm for the final portions of the melt. Melt rate patterns were similar as well; near 30 mL/hr at peak and slowed to approximately 19 mL/hr near completion.

Core 2 was the core taken from the second spray ice pile immediately after the completion of spraying. The section of Core 2 which was used for melting was 1.04 metres in length and was taken between 0.53 and 1.57 metres in depth. It was separated into three pieces; 0.53 to 0.84 m, 0.84 to 1.16 m and 1.16 to 1.57 m. This core was denser and contained a higher concentration of major ions which was also evident in the higher EC readings. These readings began at 15.2 mS/cm for the first 3% of the melt water and dropped rapidly during the first portion of the melt stabilizing between 0.13 and 0.20 mS/cm for the last 50% of the melt water. The melt rate was slightly slower, but similar to the first two cores that were melted, peaking at about 27 mL/hr and slowing to 18 mL/hr at the end of the melt.

### 3.3.4 Chemical Removal Efficiency

The chemical removal efficiency was shown to be related to the overall freezing efficiency of the spray freeze operation, where better freezing resulted in higher concentrations in the spray freeze runoff. The second spray freeze trial in which a higher freezing efficiency was observed saw an average concentration factor between 1.3 and 1.4 for the majority of the major ions. The first spray freeze trial, in which the freezing efficiency was 8% lower, showed the average concentration rose by a factor of 1.1 between the source water and the runoff. Figure 3.11 and 3.12 show bar graphs of the average concentration in the source water compared to the concentrations in the runoff for the major ions observed for the first and second spray freeze trials. In comparing the source water concentrations to the runoff concentrations, it was evident that all ions were removed with similar efficiency; ions of especially high concentrations such as sodium and chloride were concentrated to a similar extent as those with lower initial concentrations such as potassium and magnesium.

Supply water concentrations of sodium ranged between 1240 to 1350 mg/L during the first spray freeze operation. Concentrations within Core 1, taken from the first spray ice mound, showed that 70% of the sodium was removed during the first 10% of the melt and 90% within the first 19%. During the final 70% of the melt, sodium concentrations were below 72 mg/L and continued to fall to less than 8 mg/L during the last half of the melting process. For the second spray freeze operation sodium concentrations ranged between 1450 to 1470 mg/L. For spray ice Core 3, approximately 72% of the sodium was released within the first 21% of the melt water and concentrations remained below 103 mg/L for the final 79% of the melt. The higher source water concentrations during the second spray freeze operation were again attributed to the fact that water was pumped closer to the bottom of the pond, where the denser brine was found in higher concentrations.

A similar trend can be seen with the removal of chlorides. The supply water concentration for chlorides during the first spray freeze operation was 2620 to 2890 mg/L and between 3080 and 4390 mg/L during the second spray freeze trial. During the melting of the core 1 taken from the first spray freeze trial, it was observed that 90% of the chlorides were released during the first 19% of the melt with concentrations lower than 121 mg/L produced during the melting of the remainder of the core. Core 3, taken from the second spray ice mound; saw the lowest contaminant removal efficiency. Approximately 72% of the chlorides were released within the first 21% of the melt water, while chloride concentrations were below 188 mg/L for the final 79% of the melt.

Although there was no available Canadian guideline for chloride concentrations, the US EPA recommends that concentrations not exceed 860 mg/L for the protection of aquatic life (Alberta Environment, 1999). The concentrations observed during the last 80% of the core melt were well below this guideline.

Core 2 had contaminant concentrations several times higher than the other two cores (5 to 10 times). The release of contaminants during the melting of core 2 was similar to the other two cores. For both sodium and chloride approximately 78% was removed within the first 12% of the melt water and more than 96% was removed within the first 25%. Sodium concentrations for the remaining 75% of the melt stayed below 78 mg/L while chloride concentrations were below 143 mg/L.

### 3.3.5 Mass Balance

A mass balance was preformed to ensure the freezing efficiency obtained as well as the concentrations in the runoff, spray ice and source water, were reasonably accurate. The mass balance was done by using the flow rate obtained during spraying to estimate the total volume of water that was pumped. By subtracting the total volume of water pumped from the volume of water frozen within the spray ice mound, the total volume of runoff was acquired. Masses for each of the chemical constituents were obtained by multiplying the average concentrations by the total volume of water within each of the spray realms including the runoff, spray ice and source water pumped. If the data obtained was reasonably accurate then the total mass of the each chemical constituent within the runoff plus the spray ice should be reasonably close to the mass within the supply water. Table 3.1 and Table 3.2 show the mass balance done for Core 1 and Core 2 respectively, for both the first and second spray freeze field trials. The masses of each of the constituents seem to be within reasonable limits. The greatest discrepancies appear to be within the constituents with the smallest overall concentrations. This is likely due to the compounded imprecision resulting from the small errors in the concentrations leading to greater inaccuracy in the mass balance.

## 3.4 Discussion

The discussion includes a brief look at the factors affecting the freezing efficiency, the layer freezing effect that took place onsite after the spray freeze program and the application of freeze separation with spray freeze technology.

### 3.4.1 Freezing Efficiency

The two most important factors influencing the freezing efficiency of a spray freeze system are:

- Ambient air temperature
- Droplet size and retention time

Characteristics of the source water will also play a role in freezing efficiency. The freezing efficiency observed during the two spray freezing field trials done here was quite low due to relatively warm ambient air temperatures and an un-optimized system. Adequate pump pressures as well as a high quality, adjustable spray nozzle are required to obtain proper retention times. During the first spray freeze trial, the air temperature was closely monitored and the average temperature was -13 °C. During the second spray freeze trial the average air temperature was approximately -18 °C, a difference of 5 °C. The colder temperature, combined with an improved retention time for the spray freeze droplets resulted in a freezing efficiency increase of 8%. However in a fully optimized system with sufficiently cold ambient air temperatures, it should not be unrealistic to see efficiencies as high as 50% or more (Instanes et al., 1994).

### 3.4.2 Layer Freezing Effect

The high volumes of runoff during spraying caused the constructed sump area to fill up quickly. As a result a large volume of water was spread over the vast spray freeze area producing a layer freezing effect. The layer freezing effect is a concept similar to the trickle freezing described by Beier (2007) and Otto (2002). As the layers of runoff freeze, rejected brine is expelled from the ice and if the layers are thinner, better freezing will take place. During the cold spell which occurred shortly after the first spray freeze program this effect was evident as large amounts of brine were found beneath a thick layer of frozen runoff. Brine with a concentration of 20 mS/cm corresponding to a total road salt concentration of 11 g/L was found onsite; approximately 3 times the concentration of the original pond water that was sprayed and more than 2 times more concentrated than the runoff itself. The area had approximately 0.3 metres of ice with 0.5 metres of the concentrated brine liquid found below the ice layer. A core sample of the ice was taken and melted slowly in order to examine the removal of salts during the melting process. The ambient air temperature when this sample was taken was -22 °C. The core sample of ice had a salt concentration of 3 g/L. During melting approximately 62% of the salts were released within the first 8% of the melt water.

### 3.4.3 Application of Natural Freeze Separation with Spray Freeze Technology

There are a number of items that need to be assessed when considering spray freeze technology as means of contaminant separation. A number of the variables that must be considered are outlined by Biggar et al. (2005) and include the thickness of the ice that can be melted annually, location of the ice mound, target concentrations and the final disposition of the melt water. From the collection of melt water at the City of Edmonton Poundmaker snow storage facility, and the melting of the spray ice cores, it is apparent that melting is far more efficient in separating out contaminants than freezing. It is a slower process and allows more time for rejection of the contaminants from the $H_2O$ crystal lattice. The natural melting process at the City of Edmonton Snow storage facilities occurs slowly and is generally not complete until late August. Fractionation of the contaminants and release of the majority of the salts during the first portion of the runoff is highly visible in this scenario. For this reason it may be wise to use a combination of both natural freeze separation and spray freezing technology in the situation of city snow storage facilities.

If extremely high freezing efficiencies can be obtained then greater contaminant removal can be accomplished through the collection of the first portions of the melt water from the spray ice mound.

## 3.5 Cost Analysis

The costs for a standard spray freeze operation depend on a variety of important issues. The most significant issues include:

- Distance from source water to spray freeze area
- Labour costs
- Volume of Water to be pumped

The total pumping distance is the largest concern when dealing with cost. If this distance is substantial, then a huge increase in the amount of hose will be required, possibly two pumps will be needed instead of one and a road ramp could be required if the hose crosses a vehicle access route. Also, for a spread out, long distance operation a lot more human power is needed to set-up and take-down the system which will cause an increase in labour costs. The costs for the first spray freeze operation were approximately $12,000. The second spray freeze operation cost was $6,095 with the largest costs associated with the rental and delivery of two large pumps as well as the operator labour. The total pumping distance for the field trials was 300 metres (nearly 1000 feet). Table 3.3 shows the theoretical costs associated with a spray freeze operation held in closer proximity to the source water i.e. 45 metres (150 feet). For a pond approximately 6000 $m^3$ in volume or less, a total of one week of spraying, 24 hours per day, would be more than sufficient to empty the pond if an average flow rate of 40 $m^3$/hour was maintained.

Other costs which were not included in the total costs stated above or in Table 3.3 are as follows:

- Site Preparation Costs
- Additional Material Costs
- Monitoring and other labour Costs

### 3.5.1 Site Preparation Costs

Site preparation costs may include creating proper site drainage, which would require a backhoe or other specialized equipment. Site preparation costs may also include smaller matters, such as details as simple as ensuring snow is cleared and access is made available for vehicles entering the site and the spray freeze work area.

- Drainage system construction
- Site access
- Site reconnaissance

Safety concerns around the site may also require special consideration and may lead to additional costs such as ensuring the hoses and pumps are secured and well marked and will not be run over by onsite vehicle traffic.

It is also recommended that for optimal results of the freeze separation system in general, a special storage pond be built for catching the first portions of the melt water. This would optimize the total amount of salts being collected from the snow storage facility. Construction of an additional pond may not be an option at existing snow storage facilities due to lack of space, but it may be a reasonable selection for newly constructed facilities where recycling road salt from the melt water is being considered.

### 3.5.2 Additional Material Costs

Other small additional materials will certainly be required for the spray freeze operation such as:

- Nozzle
- Monitor
- Tools
- Safety clothing i.e. hard hats, steel toed boots, safety vests
- Cold weather gear

- Generator
- Fuel for pumps and generator

Other small items used for monitoring purposes such as thermometers, an EC meter and log books will be required as well. A variety of tools were found to be necessary onsite. It may also be required to bring a trailer onsite with heating for the spray freeze operating personnel. This may require the additional use of propane for heating the trailer, lights and other equipment.

### 3.5.3 Monitoring and Other Labour Costs

Monitoring of the spray freezing equipment was not included in any of the cost estimates and this will depend on the local labour costs as well as the amount of water being sprayed and the time required. For safety purposes, it is imperative that all onsite personnel work in groups of two or more, no one should be left on site alone. Other monitoring and additional labour costs include

- 24 hour monitoring costs for two people
- Removal of effluent brine
- Labour costs for set up and take down
- Transportation to and from site for personnel
- Equipment transport

The effluent brine that is deemed to be reusable will need to be pumped into a more convenient place such as a specially designed storage pond or storage tanks. This will require additional pump rental costs and fuel costs.

## 3.6 Conclusions

The pilot spray freezing field study had only 15% and 24% of the water freeze as spray ice during the first and second spray freezing trials, respectively. However, freezing efficiency is expected to be easily increased with a higher pressure system allowing more retention time for the spray droplets and with colder ambient air temperatures.

During melting of the first spray ice core it was found that up to approximately 90% of the chlorides were released within the first 19% of the melt water and up to 90% of the sodium was also released within the first 19% of the melt water. Natural freeze separation through melting of the large snow pile was also evident as early runoff in March had salt concentrations 7 to 8 times higher on average, and often more than 10 times higher, than the bulk snow.

The use of spray freeze technology to concentrate salts at city snow dumps seems feasible, but for optimal success it is recommended that the first portions of the snow melt water be collected from the snow pile in a separate holding pond which can then be sprayed to further increase salt concentrations during the coldest days. Concentrations as low as 15 g/L seem to be reusable with road sand as a supplement to varying portions of crystal salt as a de-icer for treatment of icy roads. Successful reuse of this brine could prevent large amounts of salts from being released into local waterways.

## 3.7 Figures

Figure 3.1 Spray freeze operation layout

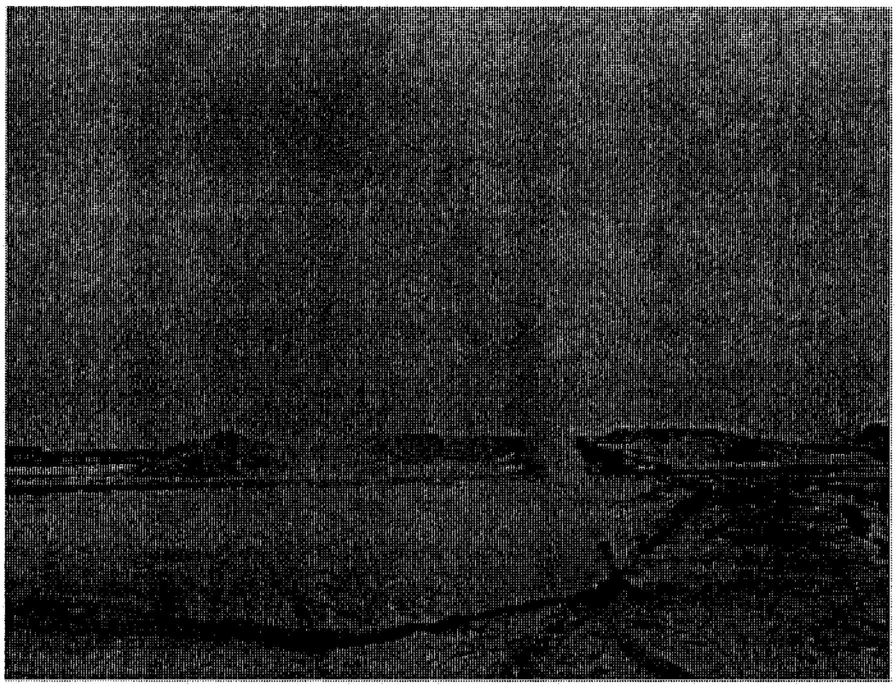


Figure 3.2 Jan. 15 & 16, 2008 – temperature vs. time

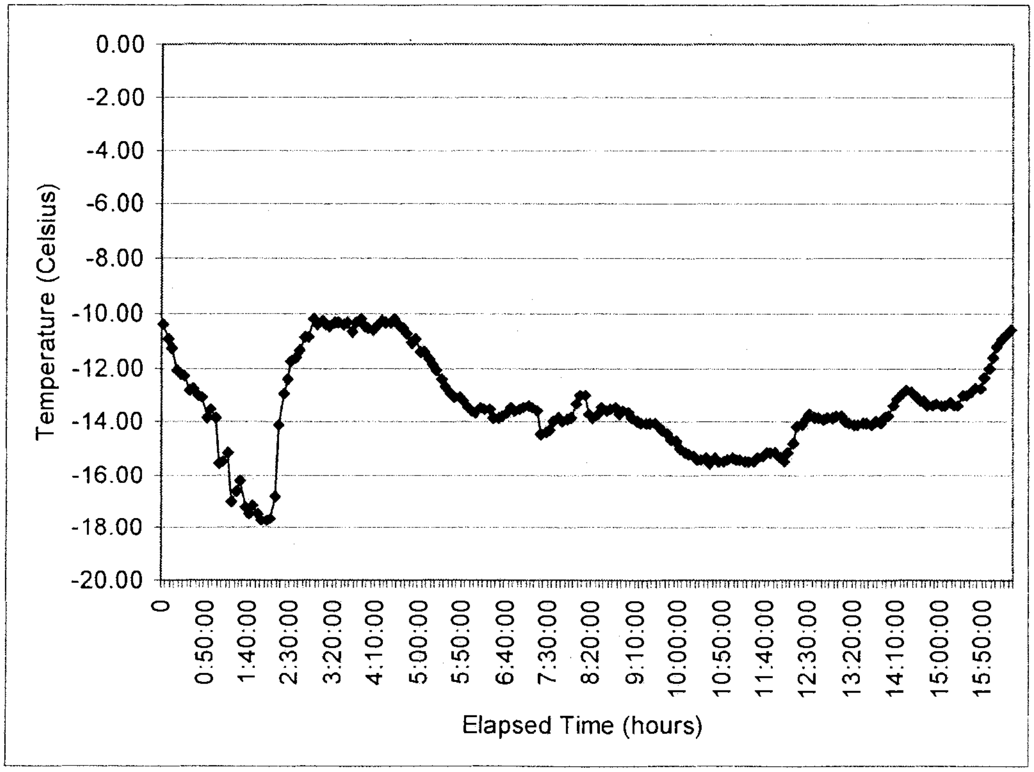


**Figure 3.3 Spray ice mound #1**

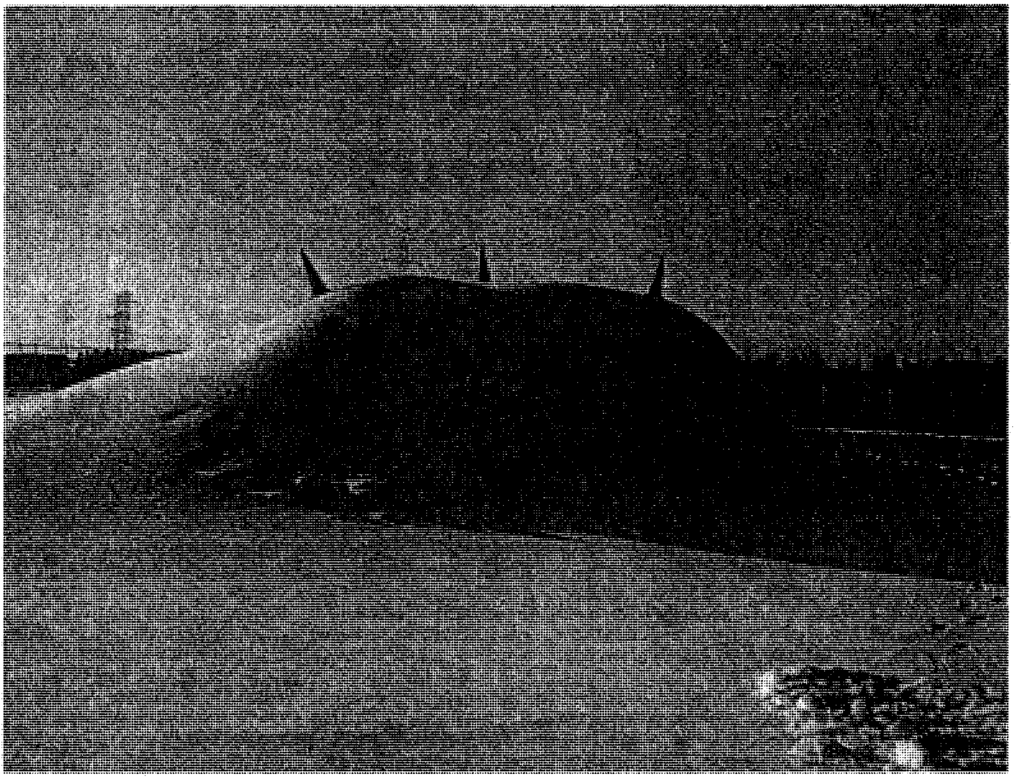
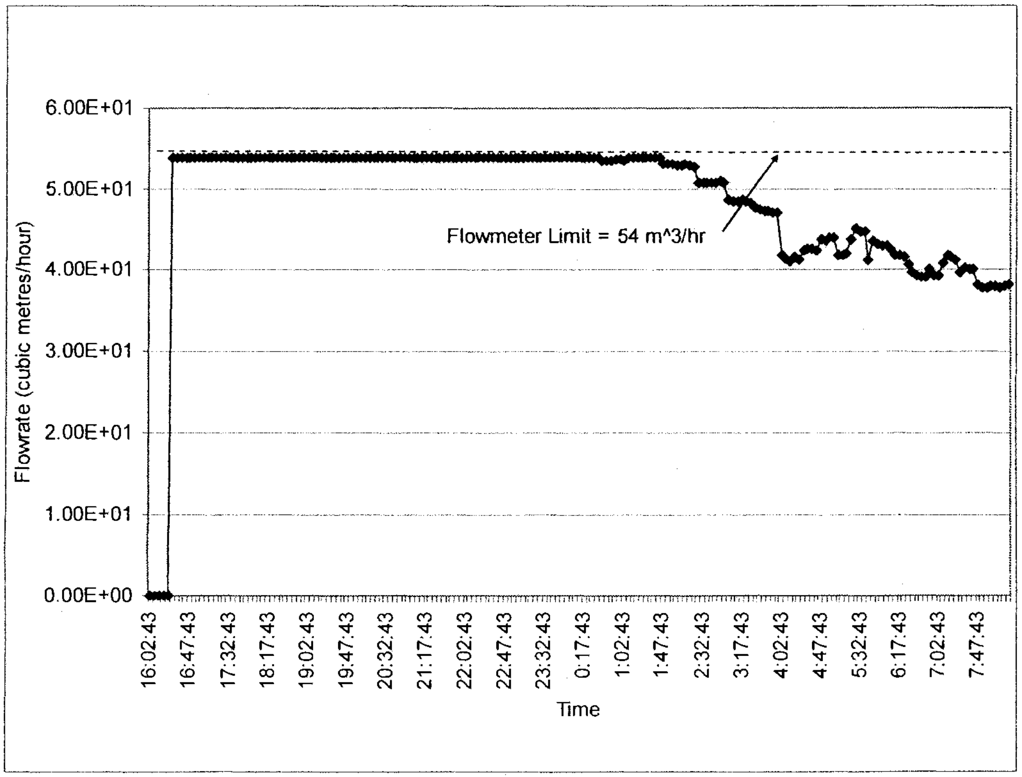
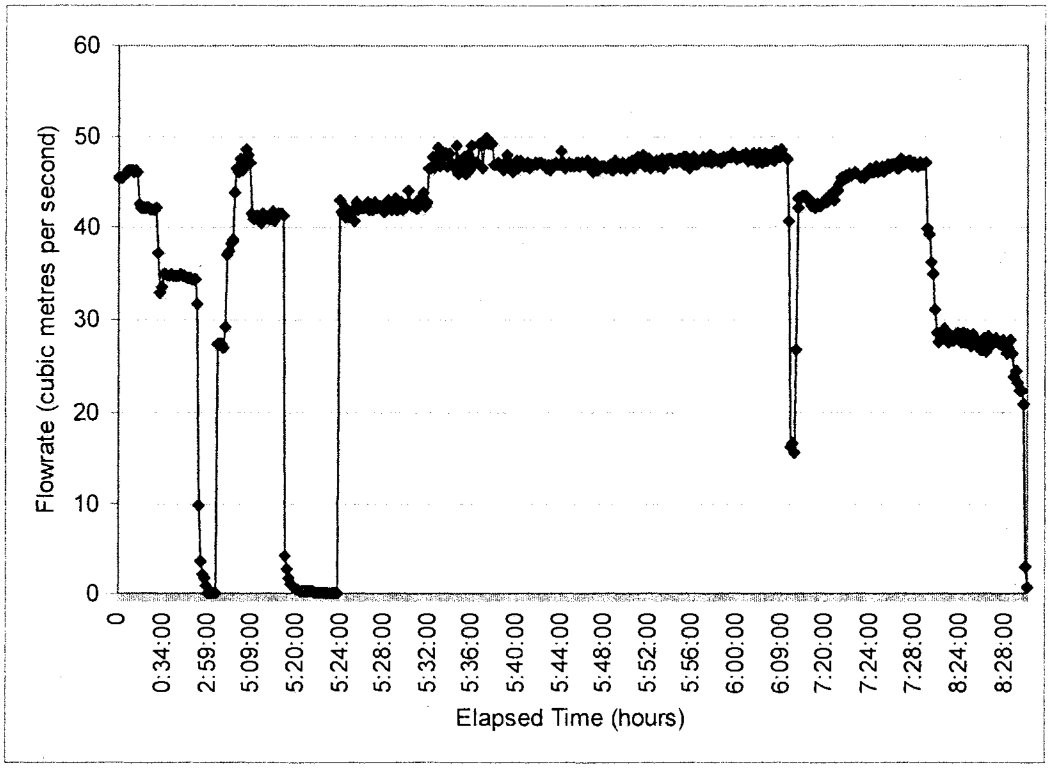


**Figure 3.4 Jan. 15 & 16, 2008 – flow rate vs. time**



## Figure 3.5 February 4, 2008 – flow rate vs. time



## Figure 3.6 LIDAR scan – spray ice mound #2

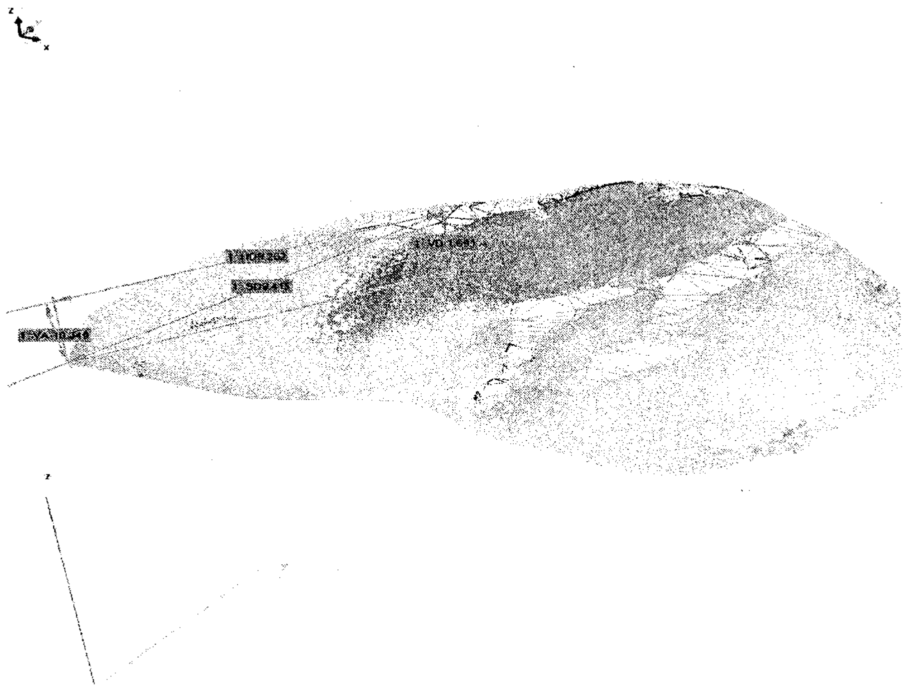


**Figure 3.7 Spray ice density vs. depth**

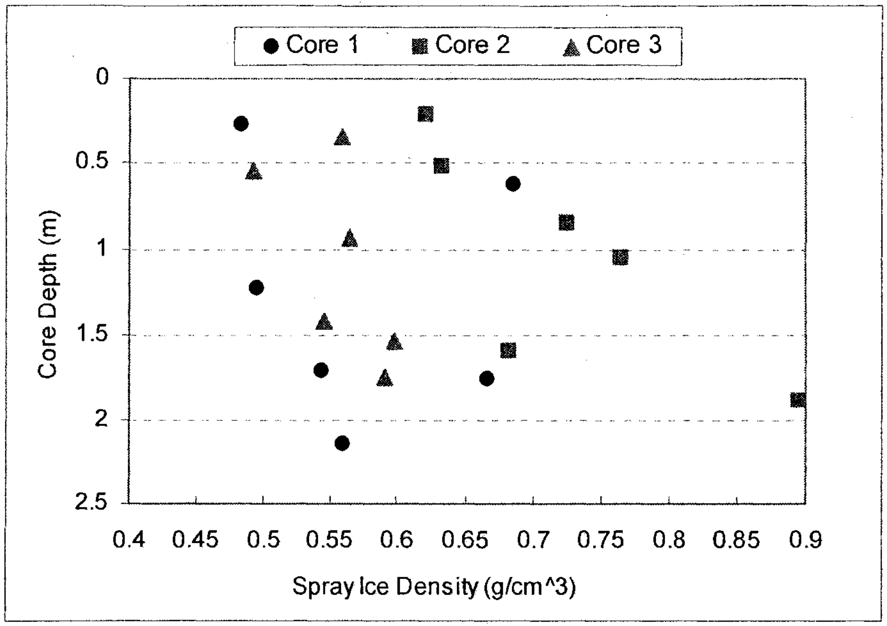


Figure 3.8 Ice core melting apparatus

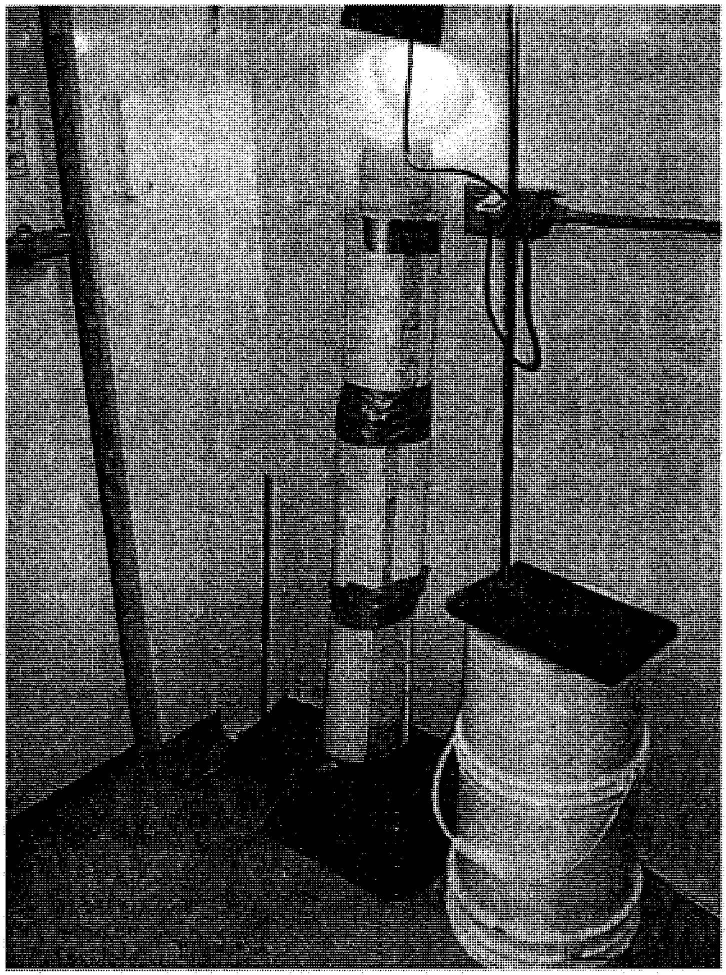


Figure 3.9 Melt rate of core 1

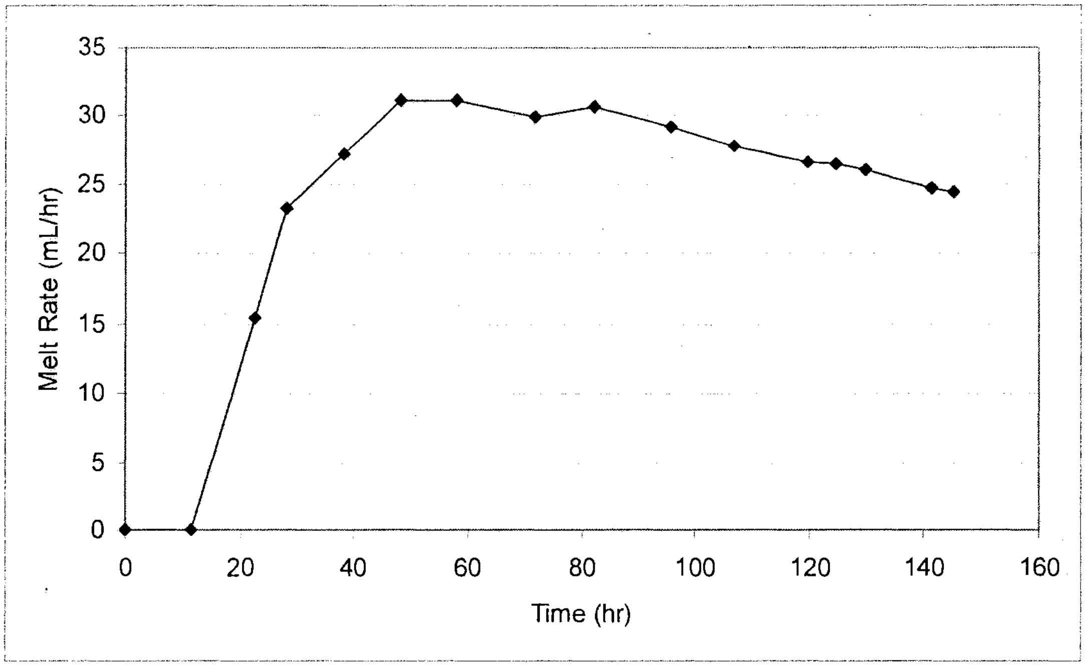


Figure 3.10 Ice core chemical removal - spray ice core #1

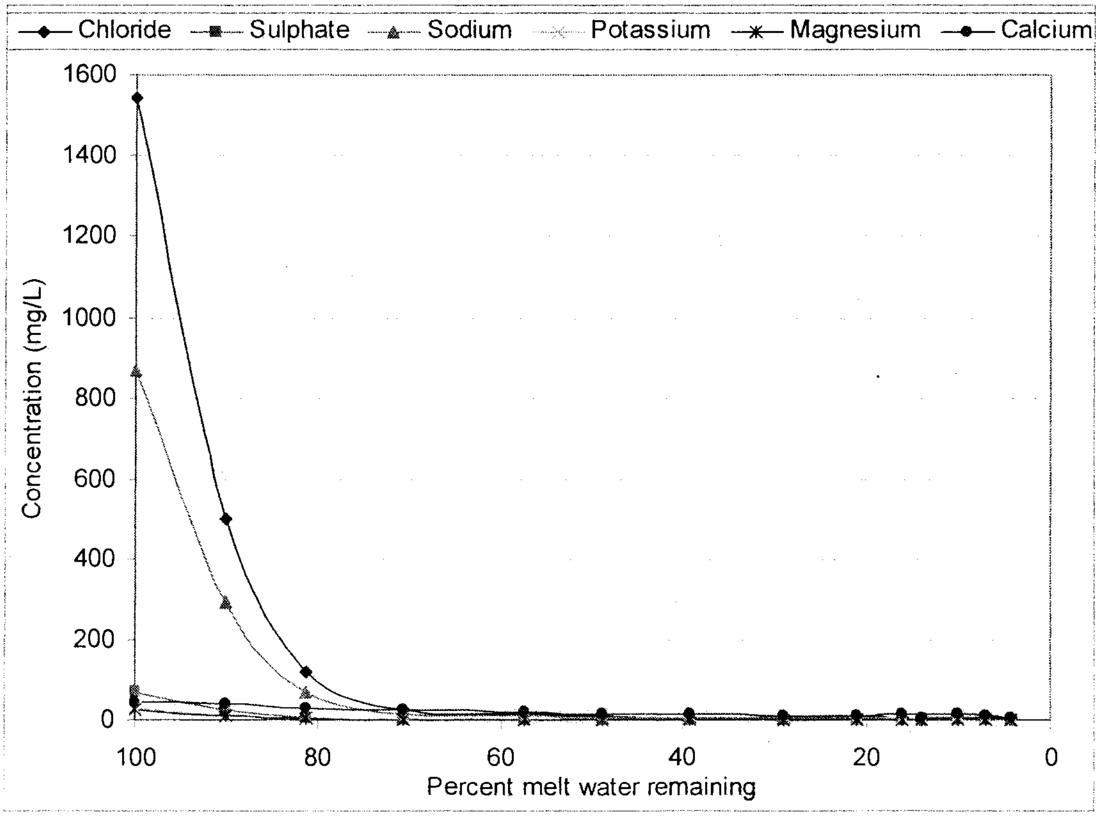


Figure 3.11 Major ion concentrations in supply & source water, spray freeze trial #1

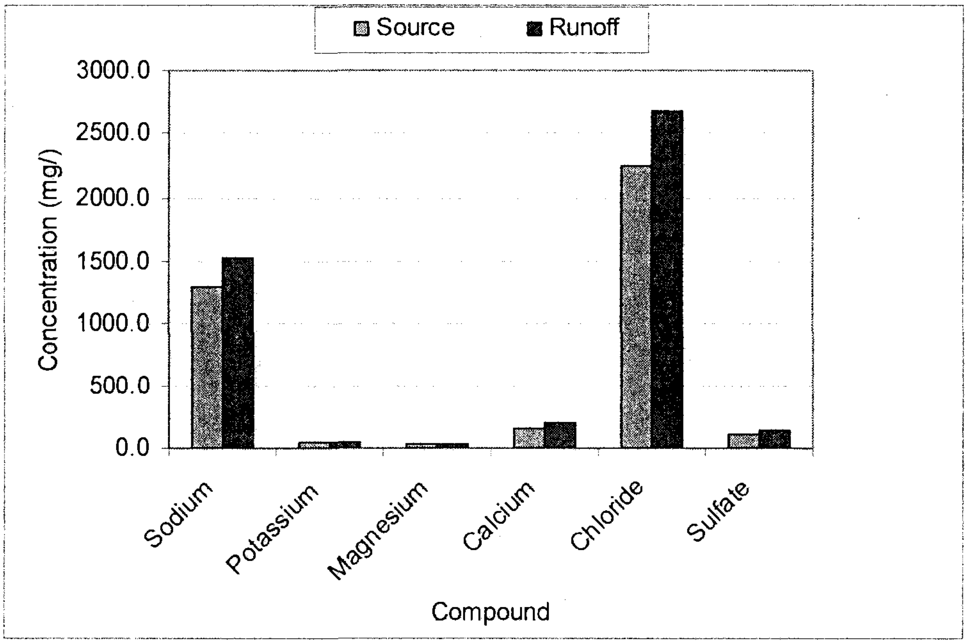
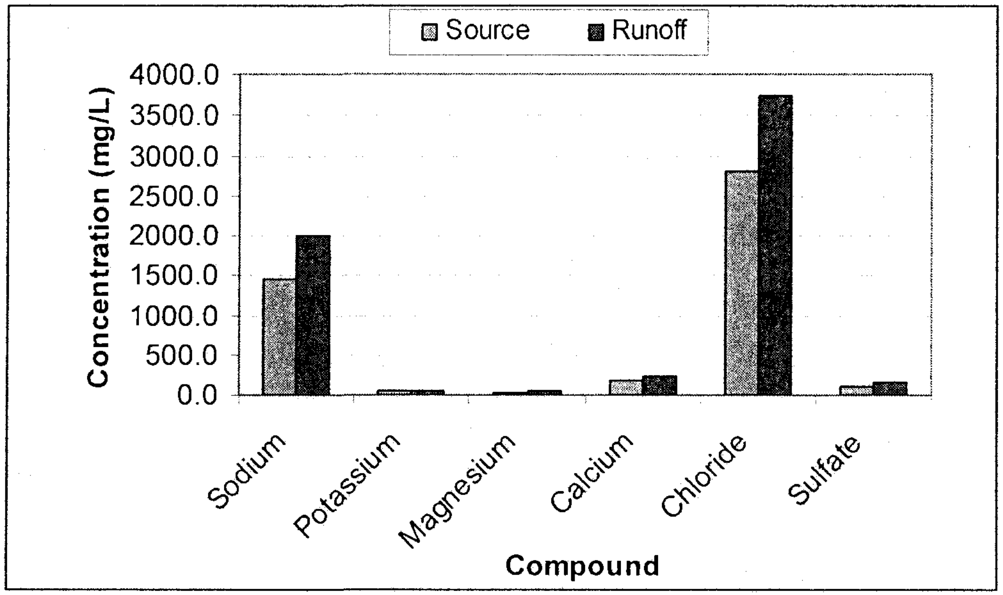


Figure 3.12 Major ion concentrations in supply & source water, spray freeze trial #2



## 3.8 Tables

### Table 3.1 Mass balance – spray ice operation #1

| Constituent | in ice (g) | in runoff (g) | Ice+runoff (g) | In supply (g) | Difference |
|---|---|---|---|---|---|
| **Sodium** | 8475 | 1029805 | 1038280 | 1034022 | **-0.4%** |
| **Potassium** | 439 | 32214 | 32653 | 32631 | **-0.1%** |
| **Magnesium** | 685 | 19053 | 19737 | 21361 | **7.6%** |
| **Calcium** | 1585 | 133821 | 135406 | 119573 | **-13.2%** |
| **Chloride** | 20018 | 1742058 | 1762076 | 1742384 | **-1.1%** |
| **Sulphate** | 1016 | 94477 | 95493 | 83821 | **-13.9%** |

### Table 3.2 Mass balance – spray ice operation #2

| Constituent | in ice (g) | in runoff (g) | Ice+runoff (g) | In supply (g) | Difference |
|---|---|---|---|---|---|
| **Sodium** | 5314 | 586835 | 592149 | 569878 | **-3.9%** |
| **Potassium** | 153 | 17455 | 17608 | 17032 | **-3.4%** |
| **Magnesium** | 200 | 15781 | 15981 | 14421 | **-10.8%** |
| **Calcium** | 1001 | 67372 | 68373 | 66565 | **-2.7%** |
| **Chloride** | 769 | 1104779 | 1119993 | 1092085 | **-1.2%** |
| **Sulphate** | 46 | 46009 | 46776 | 43243 | **-6.5%** |

**Table 3.3 Spray freeze costs**

| Description | Unit | Quantity | Unit Price | | | Total Charges | |
|---|---|---|---|---|---|---|---|
| | | | Daily | Weekly | | 1 Day | 1 Week |
| Pump, Dri Prime Diesel, high head | Each | 1 | $330.00 | $1,320.00 | | $330.00 | $1,320.00 |
| Hose suction - 4" | Feet | 100 | $0.70 | $1.95 | | $70.00 | $195.00 |
| Hose Discharge High Pressure - 4" 200 PSI | Feet | 50 | $1.00 | $3.80 | | $50.00 | $190.00 |
| Adapter, Cam Female x Female - 3" | Each | 1 | $1.50 | $4.50 | | $1.50 | $4.50 |
| Screen Suction - 4" | Each | 1 | $10.00 | $20.00 | | $10.00 | $20.00 |
| Light Tower | Each | 1 | $155.00 | $620.00 | | $155.00 | $620.00 |
| Freight Charges | Each | 1 | $1,000.00 | $1,000.00 | | $1,000.00 | $1,000.00 |
| Operator | Hour | 7 | $65.00 | $65.00 | | $455.00 | $455.00 |
| Operator | Hour | 7 | $65.00 | $65.00 | | $455.00 | $455.00 |
| Equipment & Km's | Each | 1 | $95.00 | $95.00 | | $95.00 | $95.00 |
| | | | | | Sub. Total | $2,621.50 | $4,354.50 |
| | | | | | Tax (5%) | $131.08 | $217.73 |
| | | | | | **Total** | **$2,752.58** | **$4,572.23** |

## 3.9 References

Alberta Environment. 1999. Surface Water Quality Guidelines for Use in Alberta: 1999. Alberta Environment, Environmental Service, Publication No. T/483.

Beier N. A. 2006. Freeze Separation of Saline Oil Sands Mine Waste Water, M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Canada.

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| Light Tower | Each | 1 | $155.00 | $620.00 | | $155.00 | $620.00 |
| Freight Charges | Each | 1 | $1,000.00 | $1,000.00 | | $1,000.00 | $1,000.00 |
| Operator | Hour | 7 | $65.00 | $65.00 | | $455.00 | $455.00 |
| Operator | Hour | 7 | $65.00 | $65.00 | | $455.00 | $455.00 |
| Equipment & Km's | Each | 1 | $95.00 | $95.00 | | $95.00 | $95.00 |
| | | | | | Sub. Total | $2,621.50 | $4,354.50 |
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Beier N. A. 2006. Freeze Separation of Saline Oil Sands Mine Waste Water, M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Canada.

Beier, N., Sego, D., Donahue, R., Biggar K. 2007. Laboratory Investigation on Freeze Separation of Saline Mine Wastewater. Cold Regions Science & Technology. Vol. 48, No. 3, 239-247.

Bigg, E.K. 1953. The Supercooling of Water. Proceedings of the Physical Society (London) B. Vol. 66, 688-694.

Biggar K., Donahue, R., Sego, D., Mathieu, J., Birch, J. 2005. Spray Freezing Decontamination of Tailings Water at the Colmac Mine. Journal of Cold Regions Science and Technology, Vol. 42, No. 2, 106-119.

Brimblecombe, P., Clegg, S, Davies, T., Shooter, D., Tranter, M. 1987. Observations of Preferential Loss of Major Ions from Melting Snow and Laboratory Ice. Water Resources. Vol. 21, No. 10, 1279-1286.

Cissé, J., Bolling, G.F. 1971. A Study of the Trapping and Rejection of Insoluble Particles During the Freezing of Water, Journal of Crystal Growth, Vol. 10, 67-76.

Colbeck, S. C. 1981. A Simulation of the Enrichment of Atmospheric Pollutants in Snow Cover Runoff. Water Resources Research, Vol. 17, No. 5, 1383-1388.

Dye, J.E., Hobbs, P.V. 1968. The Influence of Environmental Parameters on the Freezing and Fragmentation of Suspended Water Drops. Journal of Atmospheric Science, Vol. 25, 82-96

Elmore, W.W. 1968. Water Purification by Natural Freezing. M.Sc. Thesis, Department of Chemical Engineering, University of Wyoming, Laramie, Wyoming.

Environment Canada, 2004. Canadian Environmental Protection Act (CEPA, 1999), Code of Practice for the Environmental Management of Road Salts. April, 2004.

Fertuck, L. 1968. Water Purification by Freezing Reservoirs, work done during 1968 to 1969. Saskatchewan Research Council Report E 69-12, November 1968.

Gao, W. 1998. Partial freezing by spraying as a treatment alternative of selected industrial wastes. Ph.D. diss., University of Alberta, Edmonton, Alberta, Canada.

Gao, W., Smith, D.W. & Sego, D.C. 2000. Freezing Temperatures of Freely Falling Industrial Wastewater Droplets, Journal of Cold Regions Engineering. Vol. 14, No. 3, 101-118.

Gao, W., Smith, D.W. & Sego, D.C. 2004. Release of Contaminants from Melting Spray Ice of Industrial Wastewaters. Journal of Cold Regions Engineering. Vol. 18, No. 1, 35-51.

Hobbs, P.V. 1974. Ice Physics. Clarendon Press, Oxford.

Instanes, Arne 1993. An experimental study of the mechanical behaviour of spray ice. Dr. Ing. dissertation, Universitetet i Trondheim Norges Tekniske Hogskole, Norway.

Langer, G., Rosinski, J., Bernsen, S. 1963. Organic Crystals as Icing Nuclei. Journal of Atmospheric Sciences, Vol. 20, 557-562

Martel, J. 1993. Fundamentals of Sewage Sludge. Water Science and Technology. Vol. 28, No. 1, 29-35.

Oertling, A., Watts, R. 2004. Growth of and Brine Drainage from NaCl-$H_2O$ Freezing: A Simulation of Young Sea Ice. Journal of Geophysical Research, Vol. 109, C04013, 1-10.

Otto, S. 2002. Evaluation of Freeze Separation as a Treatment for Salt-Contaminated Ground Water. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Canada.

Pounder E. R. 1965. Physics of Ice. Pergamon Press, Ltd, London, UK. 3-5, 26.

Rabinowitz, B., Vassos, T.D., Hyslop, W.F. 1988. The Use of Snow Making for Wastewater Treatment and Disposal. Proceedings from the 11th International Symposium on Wastewater Treatment. Montreal, Quebec, Canada.

Ramachandra Murty, A. S., Ramana Murty, Bh. V. 1972. Conditions Governing Drop Freezing at Warm Temperatures. Journal of Atmospheric Sciences. Vol. 29, No. 7, 1322-1328.

Strategic Highway Research Program, SHRP-H-332. 1992. Handbook of Test Methods for Evaluating Chemical De-icers. National Research Council, Washington, DC, USA.

Thomas, D., Diekmann, G. 2003. Sea Ice. Blackwell Science Ltd., Oxford, UK.

Tratner, M., Tsiouris, S., Davies, T.D., Jones, H.G. 1992. A Laboratory Investigation of the Leaching of Solute from Snowpack by Rainfall. Hydrological Processes. Vol. 6, No. 2, 169-178.

Transportation Association of Canada (TAC) 1999. TAC Road Salt (NaCl) Management Guide. December, 1999.

Willoughby, A. 2005. Freeze Separation to Remove Nutrients from Liquid Swine Manure. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Canada.

# 4. Conclusions and Recommendations

## 4.1 Experimental Results

Both natural freeze separation and spray freezing technology were examined as methods to concentrate melt water into reusable brine. The runoff produced during the spray freezing process was between 1.1 to 1.5 times the concentrations of the source water. Melting was proven to be much more efficient at separating out contaminants than freezing. Up to 90% of the contaminants could be concentrated into one fifth of the original volume during melting of the spray ice core. Low freezing efficiency during spray freezing was seen as a result of insufficient retention time for the water droplets cause by reduced pressure at the nozzle as well as inadequate ambient air temperatures for freezing. Natural melting of the snow pile also proved that the slow melting produced in the field is a highly efficient contaminant removal process. Melt water salinity during March were on average 8 times higher than those occurring in the bulk snow.

## 4.2 Freeze Separation Field Design and Limitations

Since melting rather than freezing, is the most efficient portion of the freeze separation process, a well designed drainage system is required to capture the first portions of the melt water during spring. Spray freezing alone is not seen as adequate in producing highly concentrated reusable brine. For an optimized system it is recommended to use a combination of both natural freeze separation and spray freezing technology.

For example, a total of approximately 300,000 $m^3$ of runoff was produced from the subject City of Edmonton snow storage facility during the spring of 2007. If the first 2% of this melt water can be collected in a large pond of 6000 $m^3$ then at least 10% of the salt within the pile could be collected. EC readings during March of 2007 were between 25 and 35 mS/cm with total salt concentrations between

13 and 19 g/L. This melt water could then be further concentrated using spray freeze technology to 1.1 to 1.5 times its original concentration to between 14 and 28 g/L. It may also be useful to incorporate a full drainage system so that the spray freeze runoff can be collected re-sprayed and refroze for further contaminant removal efficiency. If most of this water can be frozen, then the first portions of the runoff from the spray ice mound can be collected and potentially much higher concentrations could be obtained. This runoff will need to be properly managed so that it is not released into the environment.

Brine concentrations as low as 15 g/L were tested in the laboratory and deemed reusable as a de-icer in combination with crystal salt. However, further testing in the field is required to confirm the recipe and the addition of crystal salt may also be based on future field observations as well as those made during this study. It is also being considered to use the NaCl brine as a liquid de-icer in place of the $CaCl_2$ which is presently occasionally added to the road sand, if high enough concentrations are achieved. Additional experimentation will be required to confirm the quantities and concentrations of NaCl brine used for this application.

## 4.3 Recommendations for Future Work

It is recommended that further research be carried out in the area of decontamination of snow storage melt water by spray freezing with the following additional items taken into special consideration:

- Spraying water during the winter involves many complications and it is therefore imperative that the distance from the source to the spray area be kept at a minimum to reduce risk of freezing up and blockage by frazil ice in the hoses and pumps.
- A large area is required for spray freezing and is determined by the amount of water pumped. For the pumping of 1000 $m^3$ of water an area of 50 X 50 metres is required.

- The spray nozzle should be checked frequently for clogging and a proper screen should be placed at the suction end of the hose to prevent particles from reaching the nozzle.
- A full drainage system and adequate collection pond for the runoff should be constructed so that re-spraying of the runoff can take place.
- Ambient air temperatures should not be warmer than -20 °C in order to maintain adequate freezing efficiencies.
- Droplet size and retention time of the spray droplets play an important role in the spray freezing process. Adequate velocities are required at the nozzles to produce sufficient air retention times for partial freezing/super cooling of the droplets.

An adequate drainage system for the general site and collection of the first 2-5% of the melt water from the snow dump pile and then spray freezing of this collected water is recommended. If extremely high freezing efficiencies can be obtained then greater contaminant removal can be accomplished through the collection of the first portions of the melt water produced by the spray ice mound. Field testing of the brine and crystal salt mixtures is recommended to ensure it is a practical alternative and it performs adequately under normal field conditions.

## APPENDIX 1 - Electro-Conductivity Relationship to Road Salt (Sodium Chloride) Concentration.

### A1.1 Sample Relationship to Electro-conductivity

In order to reduce the amount of analytical testing required, a relationship between road salt concentration and Electro-conductivity was found. The samples in the Lab were prepared using actual road salt obtained from the City of Edmonton. The road salt is not a pure substance and the concentrations of certain ionic species/salts varied slight from sample to sample. However, majority of the salt consists of sodium chloride as shown in Table A1.1. The total road salt, $C_{(Total\ Salt)}$, as described here, consists of the NaCl, $Ca_2Cl$, KCl and $Mg_2Cl$ contained within it, as all of these species are salts contributing to the overall electro-conductivity readings.

When the Electro-conductivity is especially low or high, the relationship between EC and salt concentration begins to change. Equations were developed using the curve fitting tool for two intervals. These equations are not deemed relevant for very low salt concentrations, i.e. less than 500 mg/L. However for concentrations above this threshold they considered reasonably accurate.

$$C_{(Total\ Salt)}\mathrm{mg/L} = 1.9185\,(EC)^2 + 527.69\,(EC) + 211.06\ (EC<110\ \mathrm{mS/cm}) \qquad [A1.1]$$

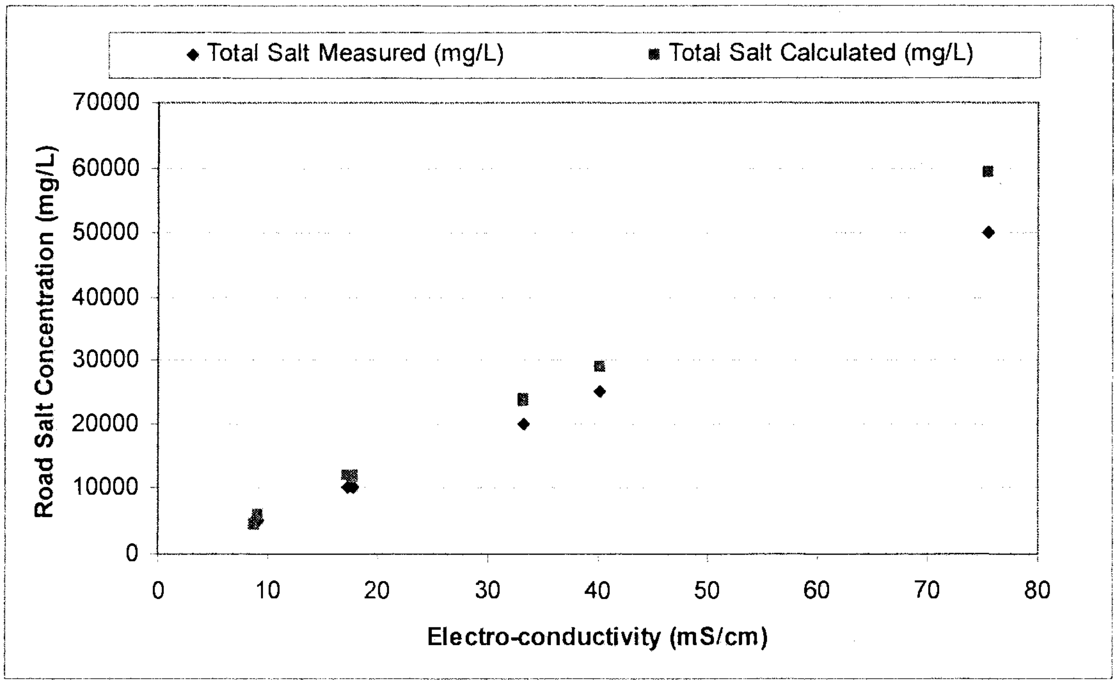
$$C_{(Total\ Salt)}\mathrm{mg/L} = 4.1042\,(EC)^2 + 5.4284\,(EC) + 31821\ (EC>110\ \mathrm{mS/cm}) \qquad [A1.2]$$

### A1.2 Measured concentrations vs. Calculated concentrations

Concentrations measured in the lab were then measured analytically using ion chromatography. Figure A1.1 shows the results of these measurements. The graphs shows the concentrations of the total salt (Road salt) which includes all salt species, as mentioned above. In general the calculated total salt concentrations are slightly higher than the measured concentrations with the distinction becoming more pronounced as the concentrations become higher. The variation between measured and actual concentrations is expected since the road salt will contain some impurities and the distilled water used to prepare the samples may have been contaminated from time to time as well.

## A1.3 Figures

Figure A1.1 Comparison of Measured and Calculated Salt Concentrations vs. Electro-conductivity



## A1.4 Tables

Table A1.1. Road Salt Constituents

| Sample ID | | | NaCl (%) | KCl (%) | $MgCl_2$ (%) | $CaCl_2$ (%) |
|---|---|---|---|---|---|---|
| **Salt-01** | | | 98.64 | 0.90 | 0.06 | 0.17 |
| **Salt-02** | | | 98.59 | 0.91 | 0.01 | 0.24 |
| **Salt-03** | | | 98.79 | 0.82 | 0.00 | 0.19 |
| **RS1** | | | 98.46 | 1.33 | 0.00 | 0.10 |
| **RS2** | | | 98.15 | 0.77 | 0.06 | 0.48 |
| **RS3** | | | 98.67 | 0.96 | 0.06 | 0.13 |
| **RS4** | | | 98.72 | 0.84 | 0.06 | 0.16 |
| **10 Str.** | | | 98.34 | 1.19 | 0.07 | 0.17 |
| **20 Str.** | | | 98.56 | 0.92 | 0.05 | 0.21 |
| **Average** | | | **98.55** | **0.96** | **0.04** | **0.20** |

## APPENDIX 2 - Poundmaker Snow Pile – Melt Water Field Data

### A2.1 Electro-conductivity of the Melt Water and Pond Water and Changes with Time

Melt water data was collected for the 2007 melting season from February to August 2007. Figure A1.1 shows the Electro-conductivity of the runoff samples taken within the east portion of the south edge of the snow pile. The EC of the runoff starts out high and by the end of May it has reached a fairly constant point remaining below 2 mS/cm. Figure A1.2 shows the electro-conductivity within the settling pond and how it changes over time. During the first part of the melt it is still quite low as the highly concentrated, first portions of the melt water are diluted with the pond water that remained from the previous year.

### A2.2 Raw Field Data

Table A2.1 shows the samples taken in the field, the location and field temperature of each sample. Table A2.2 shows the corresponding Electro-conductivity, Alkalinity and pH of each sample taken in the lab. Below Table A2.2 is a legend explaining the Sample ID codes used in the tables. Table A2.3 is the flow rate data collected from the melting snow pile on July 25, 2007 and gives an estimate of the melt water flow rate at that time.

## A2.3 Figures

Figure A2.1 Electro-conductivity of Runoff with time

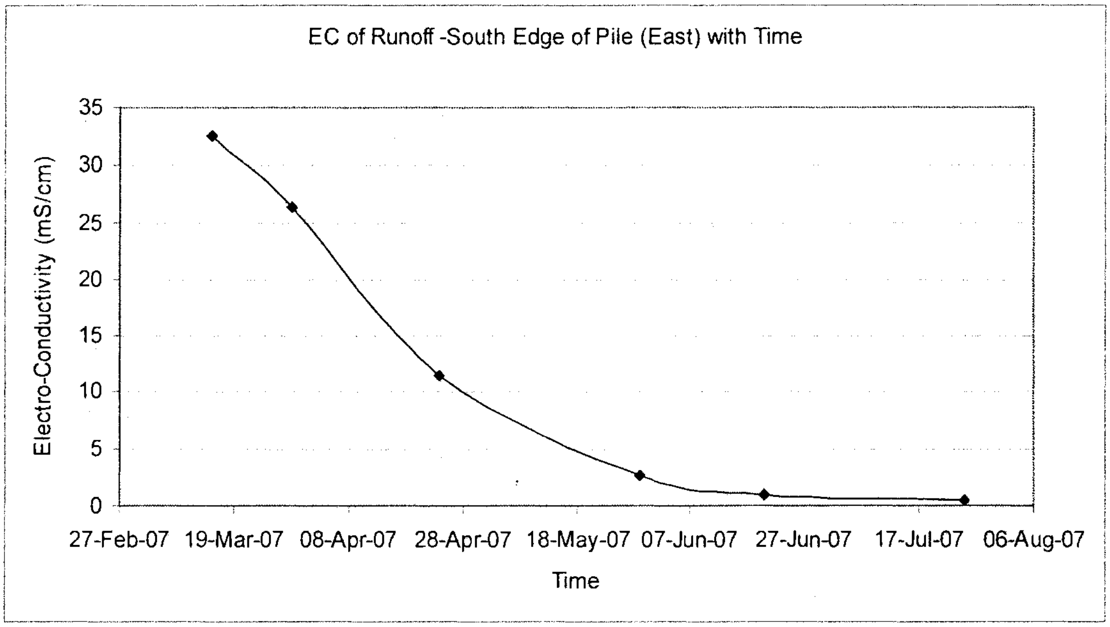
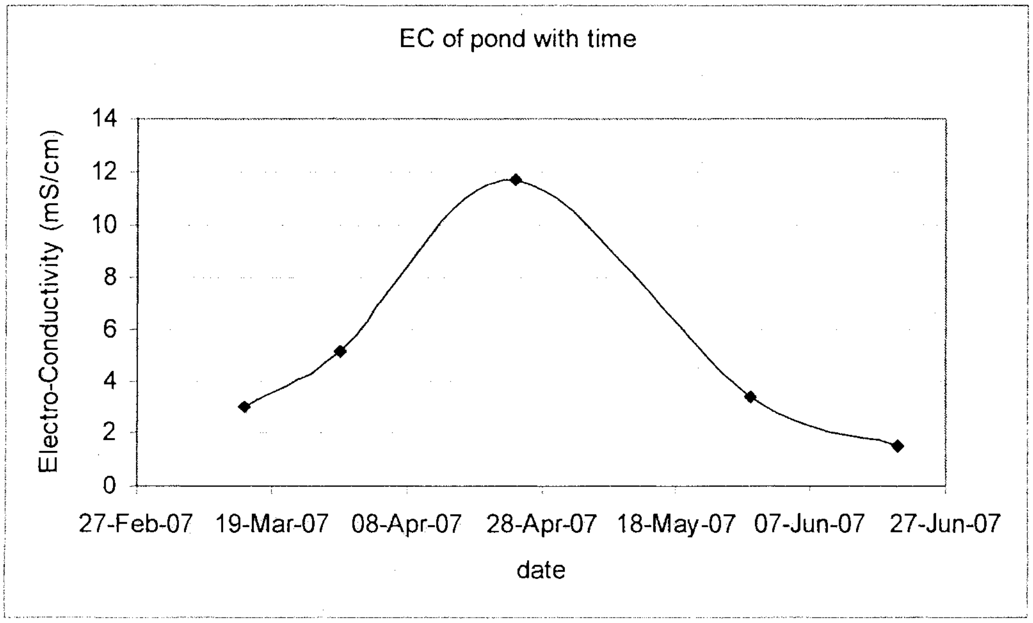


Figure A2.2 Electro-conductivity Within the Melt Water Settling Pond with Time



## A2.4 Tables

### Table A2.1 Melt Water Collection Field Data

| Field Data | | | Location | | |
|---|---|---|---|---|---|
| Date | Sample | Field Temp. © | North. | East. | Location Description |
| 15-Mar-07 | **R07-1** | -1 | 7202 | 4523 | Runoff Puddle - South Edge of Pile (East) |
| 15-Mar-07 | **R07-2** | -1 | 7202 | 4523 | Runoff Puddle - South Edge of Pile (East) |
| 15-Mar-07 | **R07-3** | -1 | 7189 | 4489 | Runoff Stream - South Edge of Pile (middle) |
| 15-Mar-07 | **R07-4** | -1 | N/A | N/A | Runoff Puddle - South Edge of Pile (West) |
| 15-Mar-07 | **R07-5** | -1 | 7189 | 4489 | Runoff Stream - South Edge of Pile (middle) |
| 15-Mar-07 | **P07-1** | -1 | N/A | N/A | Pond - East side of pond, near manhole |
| 29-Mar-07 | **R07-6** | -0.1 | N/A | N/A | Runoff Stream - East side of Pile (South) |
| 29-Mar-07 | **R07-7** | 1.7 | N/A | N/A | Runoff Puddle - Southeast corner of pile |
| 29-Mar-07 | **R07-8** | 0 | N/A | N/A | Runoff Stream - South Edge of Pile (East) |
| 29-Mar-07 | **R07-9** | 0 | N/A | N/A | Runoff Stream - South Edge of Pile (middle) |
| 29-Mar-07 | **R07-10** | 0 | N/A | N/A | Runoff Stream - South Edge of Pile (West) |
| 29-Mar-07 | **P07-2** | 0 | N/A | N/A | Pond - Northwest corner of pond |
| 03-Apr-07 | **R07-11** | -0.8 | 7210 | 4603 | Runoff Puddle - Southeast corner of Pile |
| 03-Apr-07 | **R07-12** | -0.2 | 7189 | 4542 | Channel outside pond (middle) |
| 24-Apr-07 | **R07-13** | -0.4 | N/A | N/A | Runoff Stream - Southeast corner of Pile |
| 24-Apr-07 | **R07-14** | 4 | N/A | N/A | Runoff Stream - South Edge of Pile (East) |
| 24-Apr-07 | **R07-15** | 4 | N/A | N/A | Runoff Stream - South Edge of Pile (East) |
| 24-Apr-07 | **R07-16** | 4 | N/A | N/A | Runoff Stream - South Edge of Pile (West) |
| 24-Apr-07 | **R07-17** | 4 | N/A | N/A | Runoff Stream - West Edge of Pile (South) |
| 24-Apr-07 | **P07-3** | 4 | N/A | N/A | Pond - West end of pond (North) |
| 29-May-07 | **R07-18** | 6 | N/A | N/A | Runoff Stream (from front) - South (East) |
| 29-May-07 | **R07-19** | 6 | N/A | N/A | Runoff Stream - South Edge of Pile (East) |
| 29-May-07 | **R07-20** | 6 | N/A | N/A | Runoff Stream - South Edge of Pile (middle) |
| 29-May-07 | **P07-4** | 6 | N/A | N/A | Pond - Northwest corner of pond |
| 20-Jun-07 | **R07-21** | 13 | N/A | N/A | Runoff Puddle - South Edge of Pile (East) |
| 20-Jun-07 | **R07-22** | 13 | N/A | N/A | Runoff Puddle - South Edge of Pile (West) |
| 20-Jun-07 | **P07-5** | 13 | N/A | N/A | Pond - NW corner of pond |
| 20-Jun-07 | **SP07-1** | 15 | N/A | N/A | Sand Recycling Pond Sample |
| 20-Jun-07 | **SP07-2** | 15 | N/A | N/A | Sand Recycling Pond Sample |
| 20-Jun-07 | **W07-1** | 15 | N/A | N/A | Sand wash water (prior to flocculent addition) |
| 20-Jun-07 | **W07-2** | 15 | N/A | N/A | Sand wash water (prior to flocculent addition) |
| 25-Jul-07 | **R07-23** | 19 | N/A | N/A | Runoff Stream - South Edge of Pile (East) |
| 25-Jul-07 | **R07-24** | 19 | N/A | N/A | Runoff Stream - South Edge of Pile (West) |
| 08-Aug-07 | **R07-25** | 18 | N/A | N/A | Runoff Stream - South Edge of Pile (East) |
| 08-Aug-07 | **R07-26** | 18 | N/A | N/A | Runoff Stream - South Edge of Pile (West) |
| 15-Sep-07 | **P07-6** | 19 | N/A | N/A | Pond - West end of pond (North) |
| 15-Sep-07 | **P07-7** | 19 | N/A | N/A | Pond - West end of pond (North) |

Table A2.2 Melt Water Collection Lab Data

| Lab Data | | | | Alkalinity | | | |
|---|---|---|---|---|---|---|---|
| Date | Sample | EC (mS/cm) | Temp. © | H2SO4 (mL) | Vol. (mL) | CaCO3 (mg/L) | orig. pH |
| 16-Mar-07 | **R07-1** | 32.5 | 7.1 | 21.67 | 99 | 218.89 | 7.10 |
| 16-Mar-07 | **R07-2** | 34.4 | 6.5 | 22.25 | 100 | 222.50 | 7.18 |
| 16-Mar-07 | **R07-3** | 16.83 | 6.2 | 18.55 | 100 | 185.50 | 7.49 |
| 16-Mar-07 | **R07-4** | 15.79 | 7 | 20.7 | 150 | 138.00 | 7.62 |
| 16-Mar-07 | **R07-5** | 9.83 | 6.2 | 17.75 | 100 | 177.50 | 7.47 |
| 16-Mar-07 | **P07-1** | 3.01 | 6.9 | 9.47 | 100 | 94.70 | 7.18 |
| 04-Apr-07 | **R07-6** | 25.3 | 5.8 | 27.65 | 100 | 276.50 | 7.00 |
| 04-Apr-07 | **R07-7** | 7.56 | 5.8 | 14.14 | 100 | 141.40 | 7.20 |
| 04-Apr-07 | **R07-8** | 26.4 | 5.8 | 25.85 | 100 | 258.50 | 6.92 |
| 04-Apr-07 | **R07-9** | 10.86 | 5.8 | 15.49 | 100 | 154.90 | 7.46 |
| 04-Apr-07 | **R07-10** | 5.4 | 5.8 | 11.88 | 100 | 118.80 | 7.58 |
| 04-Apr-07 | **P07-2** | 5.18 | 5.8 | 9.15 | 100 | 91.50 | 6.86 |
| 04-Apr-07 | **R07-11** | 26.3 | 18.5 | 60.05 | 100 | 600.50 | 7.27 |
| 04-Apr-07 | **R07-12** | 28.5 | 17.9 | 32.3 | 100 | 323.00 | 6.87 |
| 03-May-07 | **R07-13** | 36.5 | 7.4 | 48.1 | 100 | 481.00 | 6.92 |
| 03-May-07 | **R07-14** | 11.45 | 7.4 | 23.42 | 100 | 234.20 | 7.27 |
| 03-May-07 | **R07-15** | 11.94 | 7.6 | 23.6 | 100 | 236.00 | 7.10 |
| 03-May-07 | **R07-16** | 4.57 | 8.3 | 13.28 | 114 | 116.49 | 7.55 |
| 03-May-07 | **R07-17** | 4.94 | 9 | 14.8 | 100 | 148.00 | 7.06 |
| 03-May-07 | **P07-3** | 11.68 | 8.8 | 21.4 | 100 | 214.00 | 7.29 |
| 09-Jun-07 | **R07-18** | 2.25 | 10 | 13 | 100 | 130.00 | 7.62 |
| 09-Jun-07 | **R07-19** | 2.6 | 10 | 15.5 | 100 | 155.00 | 7.30 |
| 09-Jun-07 | **R07-20** | 8.77 | 10 | 20.5 | 100 | 205.00 | 7.20 |
| 09-Jun-07 | **P07-4** | 3.35 | 10 | 13.95 | 100 | 139.50 | 7.51 |
| 25-Jun-07 | **R07-21** | 0.872 | 5.8 | 11.85 | 120 | 98.75 | 7.20 |
| 25-Jun-07 | **R07-22** | 1.45 | 5.5 | 10.3 | 100 | 103.00 | 7.15 |
| 25-Jun-07 | **P07-5** | 1.48 | 6.3 | 11.5 | 100 | 115.00 | 7.32 |
| 25-Jun-07 | **SP07-1** | 4.04 | 7 | 32.7 | 100 | 327.00 | 7.25 |
| 25-Jun-07 | **SP07-2** | 3.95 | 7.4 | 32.9 | 100 | 329.00 | 7.28 |
| 25-Jun-07 | **W07-1** | 4.2 | 6.9 | 33.3 | 100 | 333.00 | 7.35 |
| 25-Jun-07 | **W07-2** | 4.2 | 6.9 | 33.8 | 100 | 338.00 | 7.31 |
| 25-Jul-07 | **R07-23** | 0.45 | 12 | 20.5 | 100 | 205.00 | 7.22 |
| 25-Jul-07 | **R07-24** | 0.3 | 12 | 21.2 | 100 | 212.00 | 7.15 |
| 10-Aug-07 | **R07-25** | 0.55 | 14 | 19.8 | 100 | 198.00 | 7.10 |
| 10-Aug-07 | **R07-26** | 0.77 | 14 | 19.5 | 100 | 195.00 | 7.14 |
| 27-Sep-07 | **P07-6** | 2.56 | 15.5 | 18.2 | 100 | 182.00 | 6.95 |
| 27-Sep-07 | **P07-7** | 2.67 | 15.5 | 18.9 | 100 | 189.00 | 7.20 |

Legend:
R – Runoff, taken from the melt water produced by the snow pile
07 – Year the sample was taken, i.e. 07 = 2007
P – Pond, taken from the melt water settling pond

W – Wash water, taken from the sand recycling facility
SP – Sand Recycling Pond water, taken from the water at the in the sand recycling pond

Table A2.3 Flow Data from Pile – July 25, 2007

| | |
|---|---:|
| 1) Runoff from the West | |
| Time (s) | 8.7 |
| Dist. (m) | 7.5 |
| Avg. Depth 1 | 0.075 |
| Avg. Width 1 | 0.787 |
| Area (m$^2$) | 0.059 |
| Flow rate 1 | 0.051 |
| Avg. Depth 2 | 0.060 |
| Avg. Width 2 | 0.965 |
| Area (m$^2$) | 0.058 |
| Flow rate 2 (m$^3$/s) | 0.050 |
| Avg. Flow rate (m$^3$/s) | 0.050 |
| | |
| 1) Runoff from the East | |
| Time (s) | 8.6 |
| Dist. (m) | 4.8 |
| Avg. Depth 1 | 0.040 |
| Avg. Width 1 | 0.480 |
| Area (m$^2$) | 0.019 |
| Flow rate 1 | 0.011 |
| Avg. Depth 2 | 0.037 |
| Avg. Width 2 | 0.600 |
| Area (m$^2$) | 0.022 |
| Flow rate 2 | 0.012 |
| Avg. Flow rate (m$^3$/s) | 0.011 |
| | |
| **Total avg. flow (m$^3$/s)=** | **0.062** |
| gal/s | 16.35595 |
| gal/min | 981.357 |

# APPENDIX 3 - Snow Coring Field Observations

## A3.1 Drill Data

The Field notes shown in Figure A3.3 were taken during drilling with the following accompanying observations:

Field Notes: Thursday, February 1, 2007
Location: City of Edmonton Snow Dump, 107 Avenue & 184 Street

Temperature: (@7:30am) -19 C, Light wind, Sunny
Borehole location: North end of snow dump, top of pile
Observations: Brine fluid at bottom of pile, steaming.

Figures A3.1 and A3.2 are photos depicting an image of a typical core and the coring process respectively.

## A3.2 Figures

Figure A3.1 Typical Snow Core

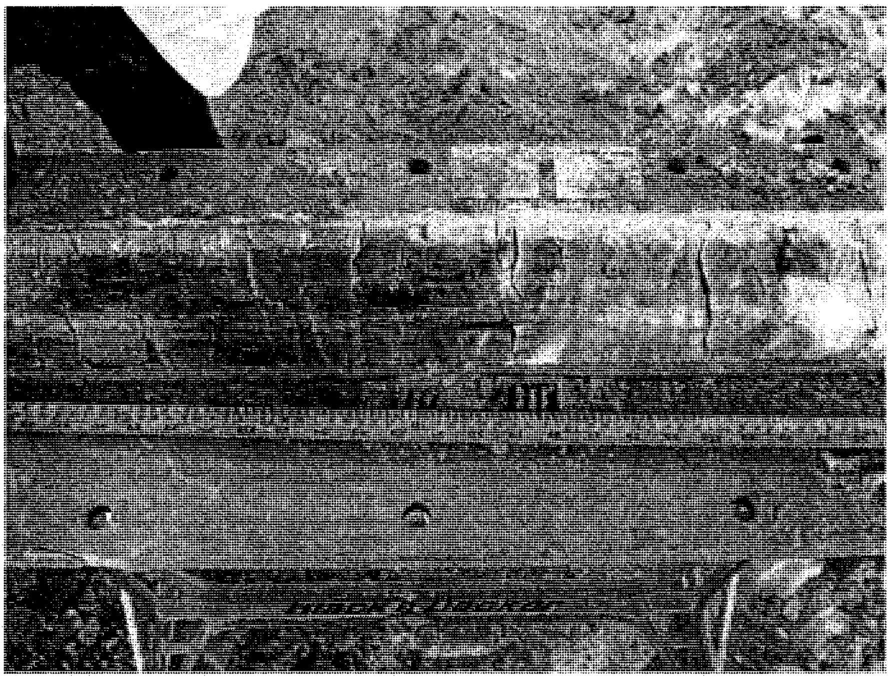


Figure A3.2 Snow coring Drill Rig Set-up

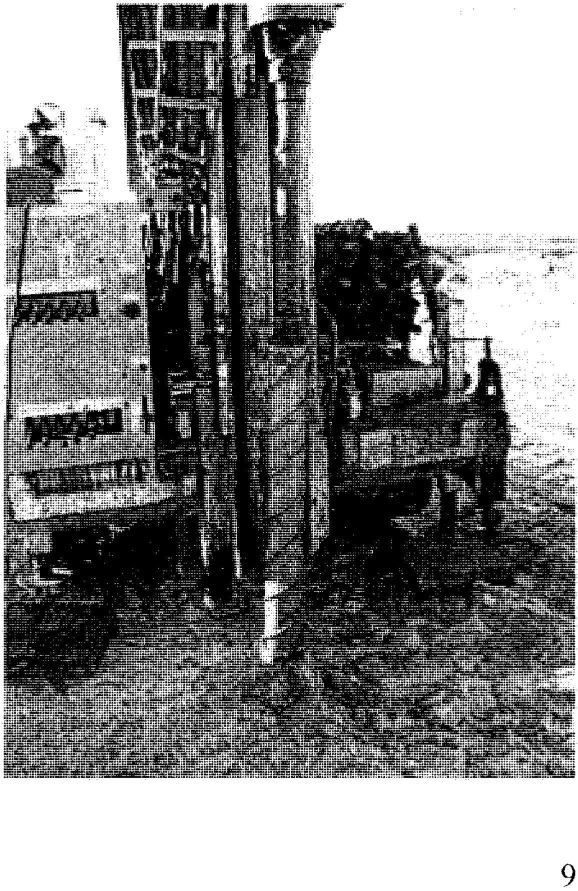


Figure A3.3 Drill Data - February 1, 2007

| Time | Core (ft) | Recovery | Slough | Comments | Temp. © |
|---|---|---|---|---|---|
| 9:00 AM | 0 -1' | full | no | disturbed sample | |
| 9:05 AM | 1-3' | full | no | top 1', lots of sand. Below 2', less sandy, denser. | |
| 9:20 AM | 3-4'<br>4-5'<br>5-6' | full<br>full<br>full | no | | |
| 9:30 AM | 6-7'<br>7-8'<br>8-9' | full<br>full<br>full | trace | 2" of slough | |
| 9:40 AM | 9-11.5' | 2' of 2.5' | trace | 0.5' not recovered, 2' of slough | |
| 9:50 AM | 11.5-14' | full | trace | 6" of slough, some slough as barrel goes down hole. | |
| 10:00 AM | 14-17' | full | no | 14-15.5' dirty snow, 15.5-17' clean white snow | |
| 10:15 AM | 17-18' | full | 2' | slough from 15-17' | |
| 10:22 AM | 18-20' | full | 1' | | |
| 10:33 AM | 19-22' | 2' of 3' | 1' | Top of slough at 21' | |
| 10:55 AM | 21-24' | 2' of 3' | 1' | 1' of slough | |
| 11:08 AM | 24-27' | full | no | loose, no structure, no large compacted chunks<br>(indication of salt?) | |
| 11:18 AM | 27-30' | full | no | from 27-28.5' loose, 28.5-30' dense with compacted chunks | |
| 11:30 AM | 30-33' | full | no | relatively loose (possibly top-bottom reversed) | |
| 11:50 AM | 33-35.5' | full | no | | |
| 11:56 AM | 35.5-38.5' | full | 6" | 6" slough | |
| *12:20 PM - 12:55 PM LUNCH* | | | | | |
| 12:55 PM | 38.5-41' | full | 6" | | |
| 1:25 PM | 41-44' | 2' of 3' | 1' | 1' slough (bags labelled 41-44', should be 41-43') | |
| 1:40 PM | 43-46' | full | trace | | |
| 1:55 PM | 46-49' | full | no | | -5.4 |
| *2:00 PM* | | | *Air Temperature: -12.7 C (without wind)* | | |
| 2:05 PM | 49-52' | full | 1' | 1' slough at the bottom | -5.6 |
| 2:30 PM | 52-55' | full | no | | |
| 2:44 PM | 54-57' | 2' of 3' | 1' | 1' slough | |
| 3:00 PM | 57-60' | full | | slough? | -7.3 |
| 3:15 PM | 57-58' | full | no | | |
| 3:30 PM | 58-61' | full | no | | -7 |
| 3:45 PM | 61-64' | full | no | Temperature may be obscured due to cracks | -8.8 |
| *4:00 PM* | | | *Air Temperature: -14.0 C (without wind)* | | |
| 4:10 AM | 62.5-65' | 1' of 2.5' | 1.5' | 1.5 feet of slough<br>Temperature may be obscured due to cracks | -8.8 |
| 4:30 AM | 64-67' | full | no | | |
| 4:55 AM | 68-70' | auger | | switched to regular auger, disturbed bag samples<br>lost lots bringing up the auger out of the hole | |
| 5:50 PM | 70-75' | auger | | "" | |

## APPENDIX 4 - Core and Bulk Snow Sample Data

### A4.1 Core and Bulk Snow Sample Melt Set-up and EC Relationship with Depth

Figures A4.1 and A4.2 are photos of the bulk and core snow sample melting processes respectively. Figure A4.3 shows the Electro-conductivity of the samples taken from the snow pile with depth. No relationship between EC and depth is visible in the data.

### A4.2 Figures

Figure A4.1 Bulk Sample Melt Apparatus

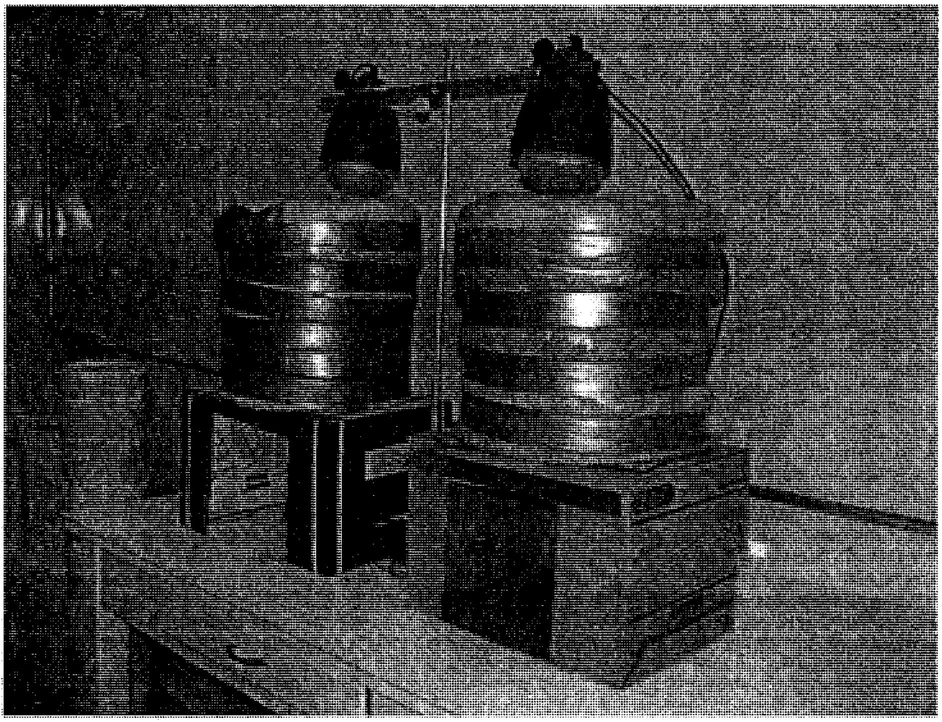


Figure A4.2 Core Sample Melt Set-up

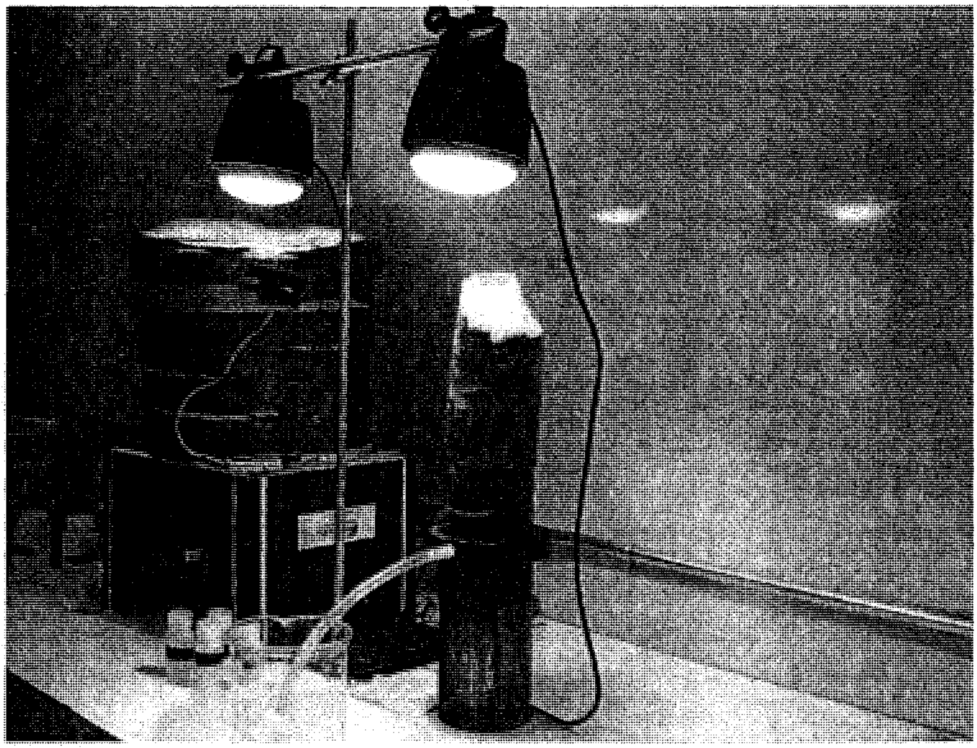
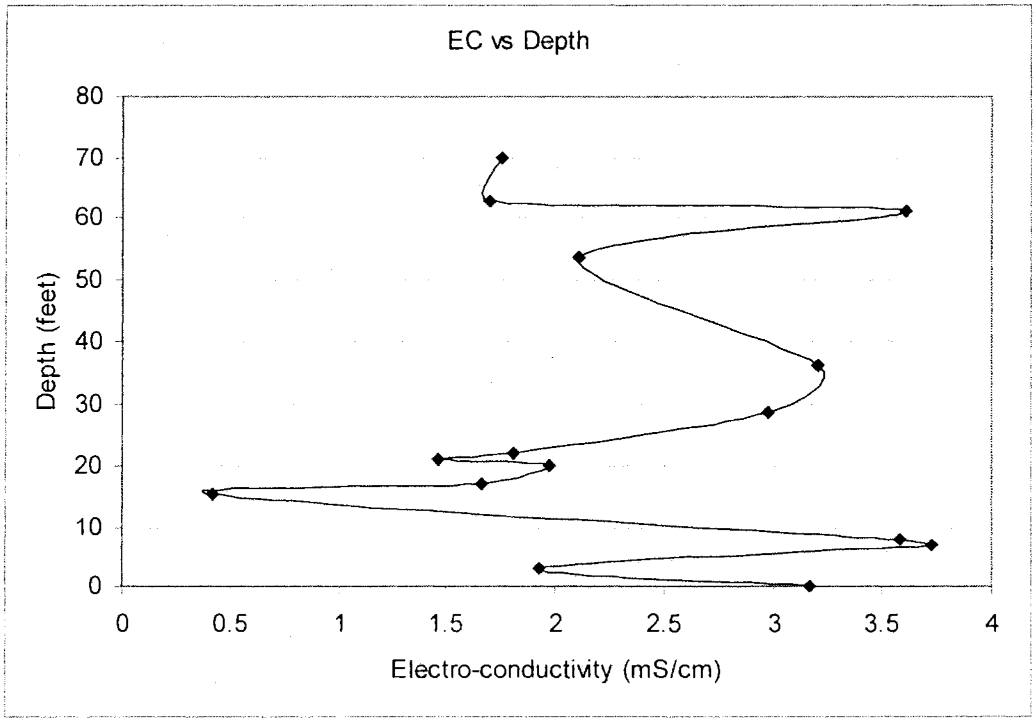


Figure A4.3 Electro-conductivity of Snow vs. Depth of Sample



# APPENDIX 5 - Spray Freeze Field Data

## A5.1 Figures

Figure A5.1 January 14 & 15, 2007 Sample Collection Data

| Source Water | | |
|---|---|---|
| Sample ID | Time | EC (mS) |
| SRP 1 | 3:00 PM | 7.05 |
| SRP 2 | | 6.98 |
| SRP 3 | 11:30 PM | 6.81 |
| SRP 4 | | 7.04 |
| Noz 1 | 2:00 AM | 7.09 |
| Noz 2 | 3:30 AM | 6.98 |
| Noz 3 | 4:45 AM | 7.14 |

| Run-off | | |
|---|---|---|
| Sample ID | Time | EC (mS) |
| Run-1 | 5:20 PM | 8.74 |
| Run-2 | | 8.70 |
| Run-3 | 9:50 PM | 8.49 |
| Run-4 | 1:15 AM | 7.42 |
| Run-5 | | 7.75 |
| Run-6 | | 8.14 |
| Run-7 | 3:30 AM | 7.91 |
| Run-8 | | 8.52 |
| Run-9 | 4:45 AM | 8.41 |
| Run-10 | | 8.25 |
| Run-11 | | 8.20 |

| Spray Water (Liquid) | | |
|---|---|---|
| Sample ID | Time | EC (mS) |
| BR-A1 | 5:20 PM | 8.35 |
| BR-A2 | | 8.76 |
| BR-B1 | 8:15 PM | 7.82 |
| BR-B2 | | 7.79 |
| BR-B3 | | 8.00 |
| BR-B4 | | 8.19 |
| Spray 2A | 1:15 AM | 9.00 |
| Spray 2B | | 8.85 |
| Spray 2C | | 8.75 |
| Spray 2D | | 8.80 |
| Spray 2E | | 8.42 |
| Spray 2F | | 8.53 |
| Spray 2G | | 8.61 |
| Spray 2H | | 8.46 |
| Spray 4A | 4:45 AM | 8.94 |
| Spray 4B | | 8.96 |
| Spray 4C | | 9.51 |
| Spray 4D | | 8.60 |
| Spray 4E | | 8.65 |
| Spray 4F | | 8.80 |
| Spray 4G | | 8.82 |
| Spray 4H | | 9.60 |
| Spray 4J | | 9.15 |
| BR-C1 | 10:30 AM | 9.85 |
| BR-C2 | | 9.82 |

| Spray Water (Frozen Constituent) | | |
|---|---|---|
| Sample ID | Time | EC (mS) |
| SN-A1 | 5:20 PM | 5.55 |
| SN-B1 | 8:15 PM | 5.41 |
| Spray 1a | 1:15 PM | 4.64 |
| Spray 1b | | 5.52 |
| Spray 1c | | 5.58 |
| Spray 1d | | 5.84 |
| Spray 1e | | 6.03 |
| Spray 1f | | 0.35 |
| Spray 3a | 4:45 AM | 5.19 |
| Spray 3b | | 5.52 |
| Spray 3c | | 5.26 |
| Spray 3d | | 3.37 |
| Spray 3e | | 5.34 |
| Spray 3f | | 5.65 |
| Spray 3g | | 5.92 |
| SN-C1 | 10:30 AM | 6.64 |

Legend
SRP – Sand Recycling Pond (Source water)
Noz – From nozzle (Source water)
Run – Runoff from spray ice mound
Spray – Sample from spray before it hits the ground
SN – Frozen constituent of spray
BR – Liquid constituent of spray

A5.2 February 4 & 5, 2007 Sample Collection Data

| Source Water | | |
|---|---|---|
| Sample ID | Time | EC (mS) |
| SRP A | 1:00 PM | 7.6 |
| SRP B | | 7.47 |
| Nozzle 1 | 8:00 PM | 8.34 |
| Nozzle 2 | 10:45 PM | 8.29 |

| Spray Water (Liquid) | | |
|---|---|---|
| Sample ID | Time | EC (mS) |
| Spray Water A | 10:45 PM | 10.73 |

| Spray Water (Frozen Constituent) | | |
|---|---|---|
| Sample ID | Time | EC (mS) |
| Spray Slush A | 8:00 PM | 7.12 |
| SA | | 6.89 |
| SB | 10:45 PM | 7.56 |
| SC | | 7.13 |

| Run-off | | |
|---|---|---|
| Sample ID | Time | EC (mS) |
| Run A | 3:45 PM | 10.19 |
| Run B | | 10.45 |
| Runoff-w | 8:00 PM | 10.92 |
| Runoff Pile | 9:00 PM | 9.04 |
| Runoff E | | 10.01 |
| Runoff E2 | 10:45 PM | 11.49 |
| Runoff F | | 12.13 |
| Runoff A | 2:30 AM | 11.45 |
| Runoff B | | 12.15 |

Legend
SRP – Sand Recycling Pond (Source water)
Nozzle – From nozzle (Source water)
Run – Runoff from spray ice mound
Runoff – Runoff from spray ice mound
Spray (Water or Slush) – Sample from spray before it hits the ground
S – Frozen constituent of spray

# APPENDIX 6 - Spray Freeze Field Layout

## A6.1 Spray Freeze Observations

The spray freeze system began at the sand recycling pond. The screen and hole for the intake line are shown in Figure A6.1. The hose, pump and nozzle are shown in operation in Figure A6.2 and the fire fighting nozzle and monitor used in the second spray freeze trial is shown in Figure A6.3. The LIDAR image of spray freeze pile #1 is revealed in figure A6.4.

## A6.2 Figures

Figure A6.1 Intake Screen, Hose and Ice Hole

Figure A6.1 Spray Freeze Field Trial #2 – Hose, Pump and Nozzle in Operation

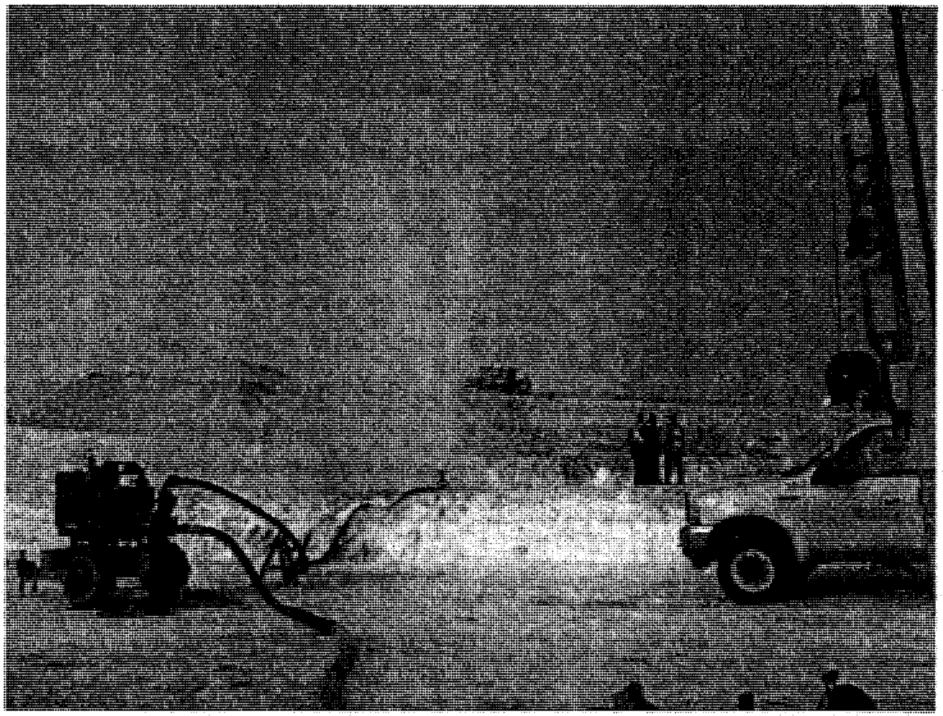


Figure A6.3 Spray Freeze Field Trial #2 – Nozzle and Monitor

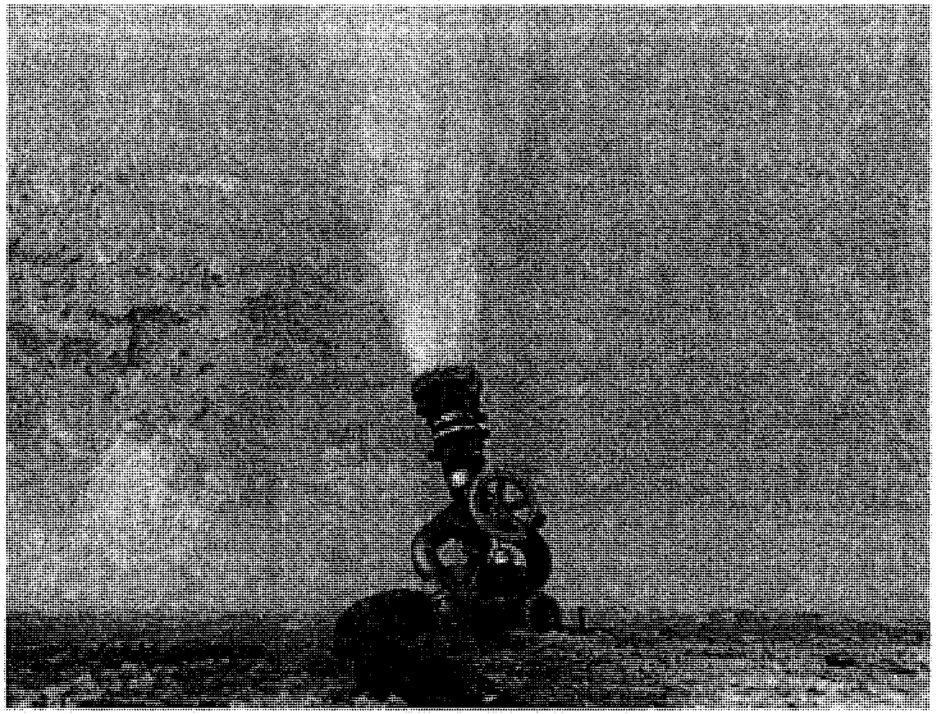
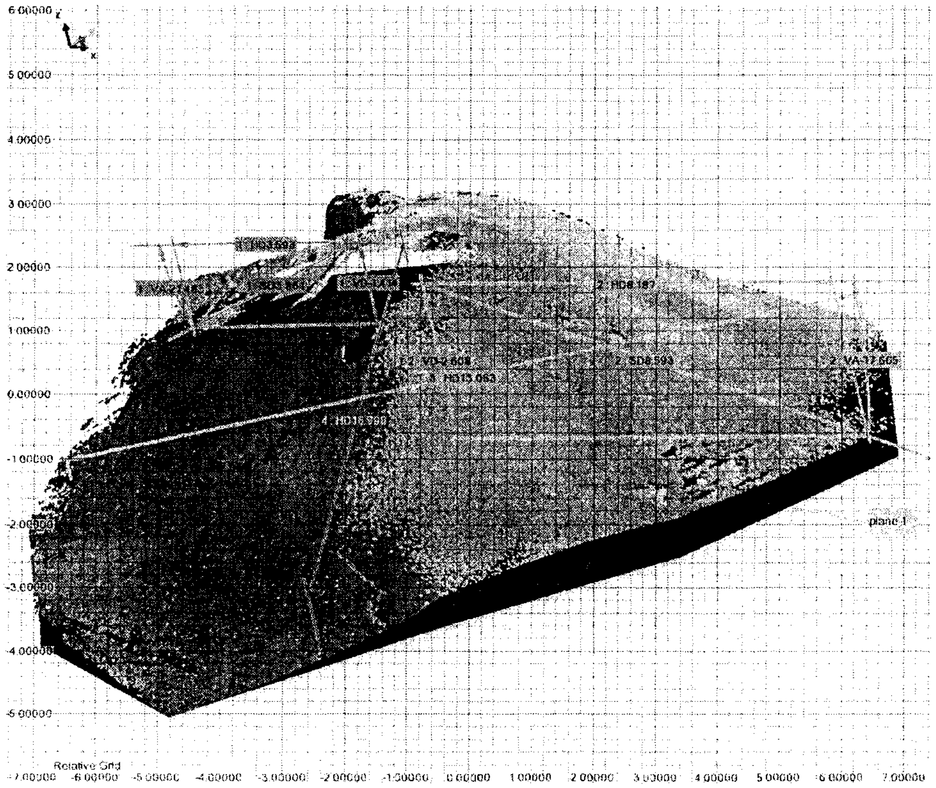


Figure A6.4 LIDAR Image – Spray Ice Mound #1



## APPENDIX 7 - Spray Ice Core Data

### A7.1 Spray Ice Core Data – EC Readings and Melt Rates

Figure A7.1 to A7.3 show the Electro-conductivity readings for the three ice cores with depth. spray ice core #1 is shown in Figure A7.1 and was sprayed on January 14 and 15, 2008 and the core obtained on January 5, 2008. Figure A7.2 shows spray ice core #2 which was also sprayed on February 4, 2008 and the core was obtained right after spraying at 2:30 am on February 5, 2008. Figure A7.3 shows spray ice core #3 was and also sprayed on February 4, 2008, the core was collected on February 13, 2008. There is no visible relationship between EC and depth.

The slow melting of the cores produced samples with EC readings shown in Figures A7.4 to A7.6.

The melting rate for core #2 and core #3 which were not shown in Chapter 5 are displayed in Figures A7.7 and A7.8.

## A7.2 Figures

Figure A7.1 Spray Ice core #1 – Electro-conductivity vs. Depth

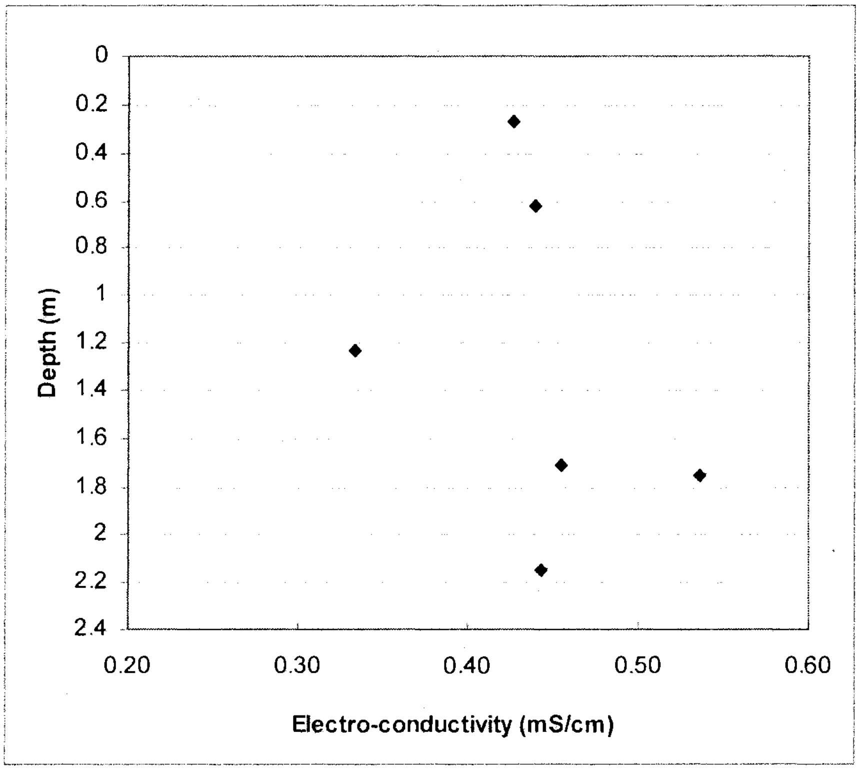


Figure A7.2 Spray Ice Core #2 – Electro-conductivity vs. Depth

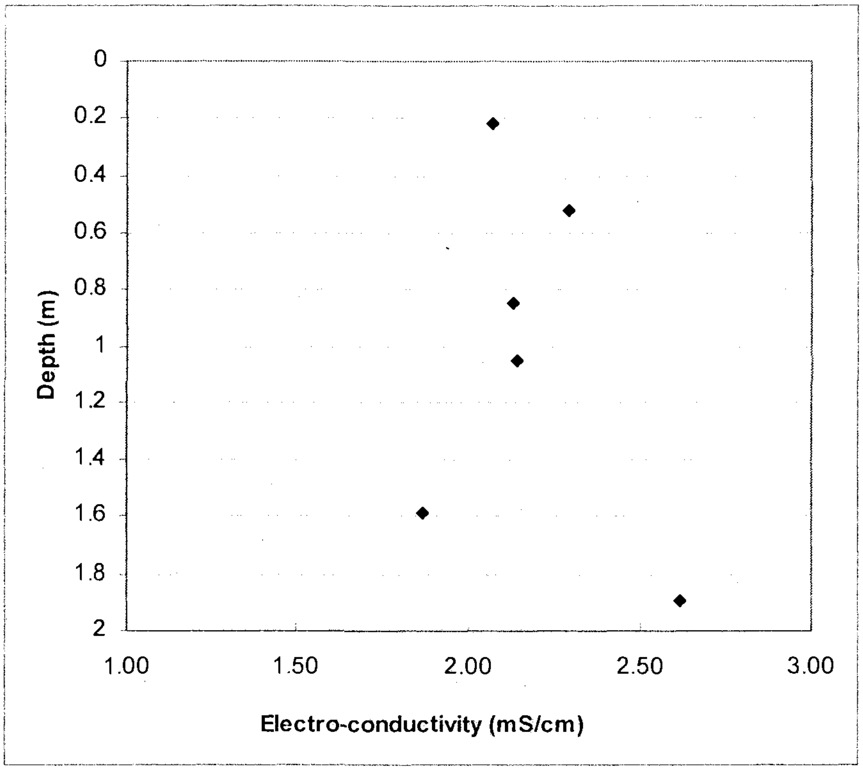


Figure A7.2 Spray Ice Core #3 – Electro-conductivity vs. Depth

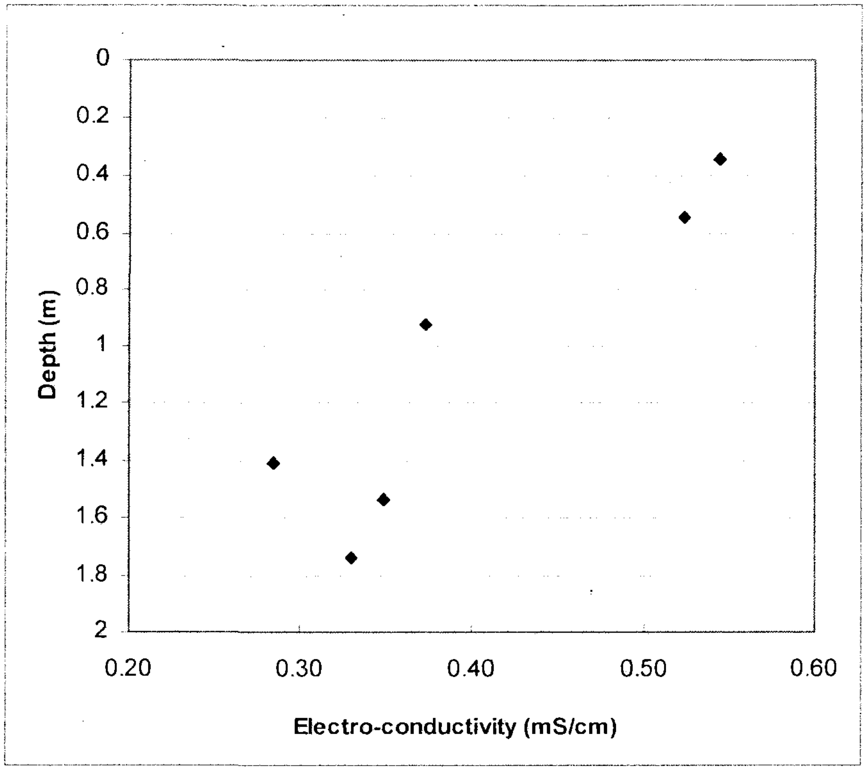
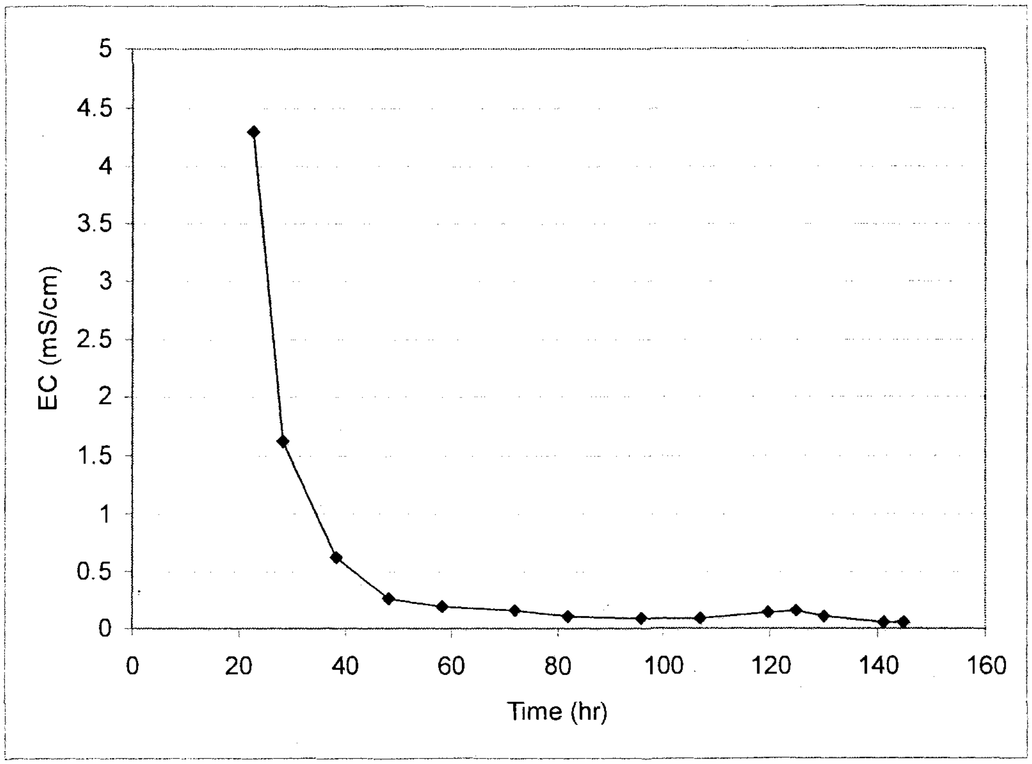
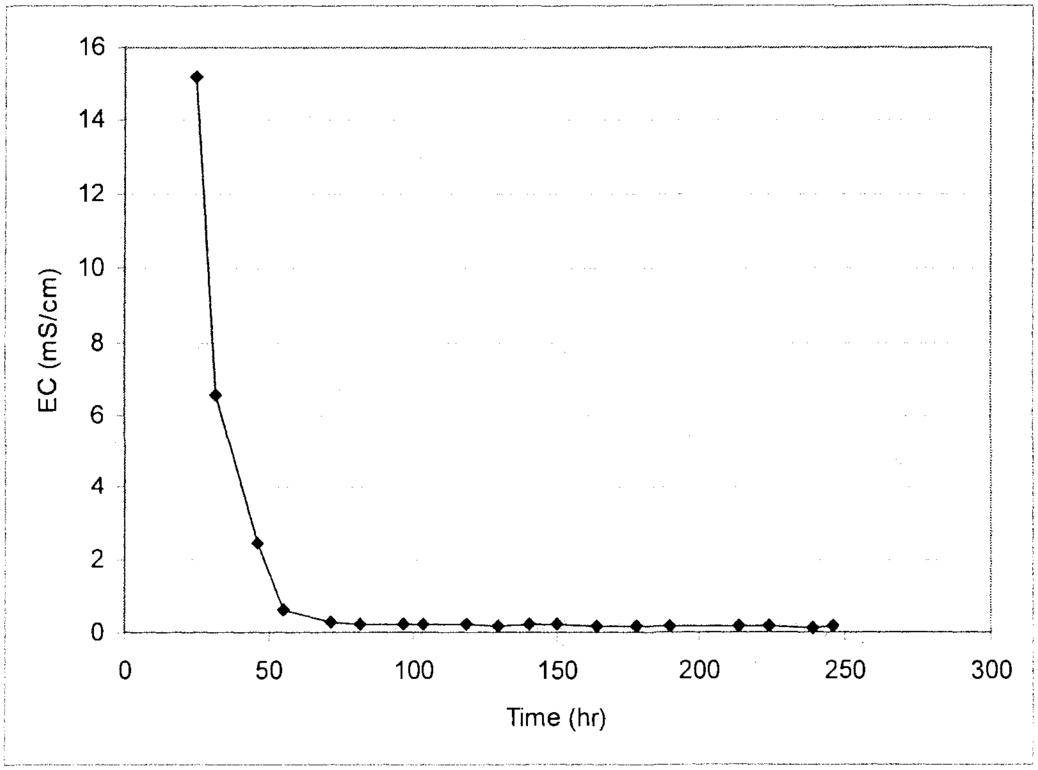


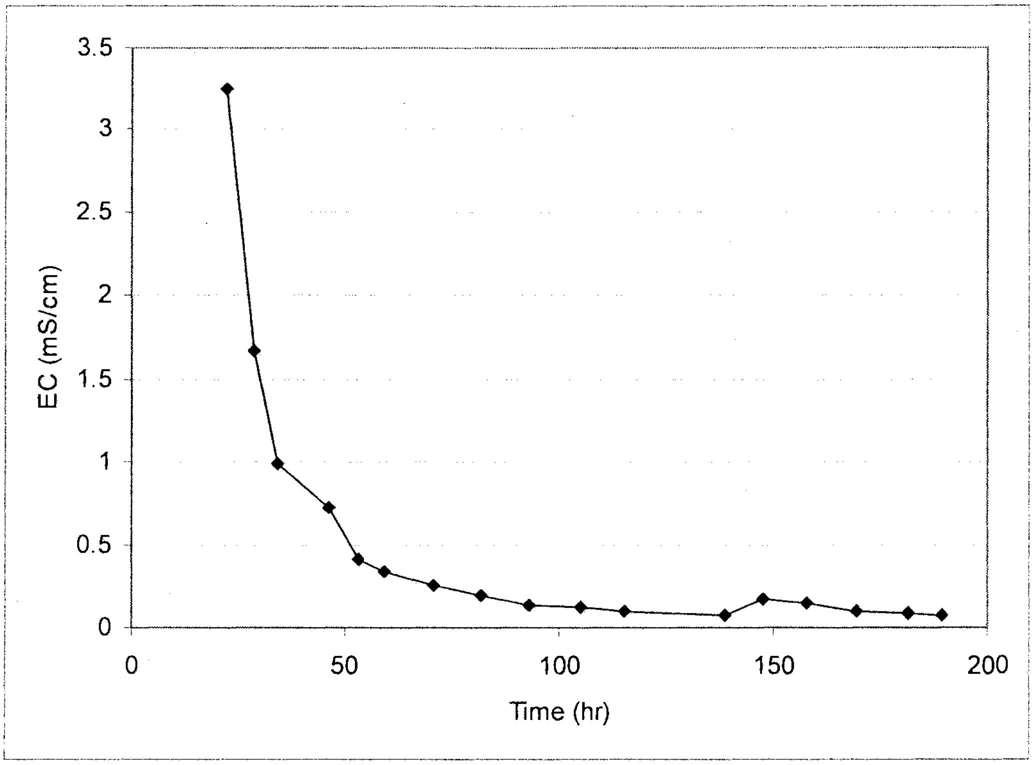
Figure A7.4 Spray Ice Core #1 – Change in EC of Melt Water with Time



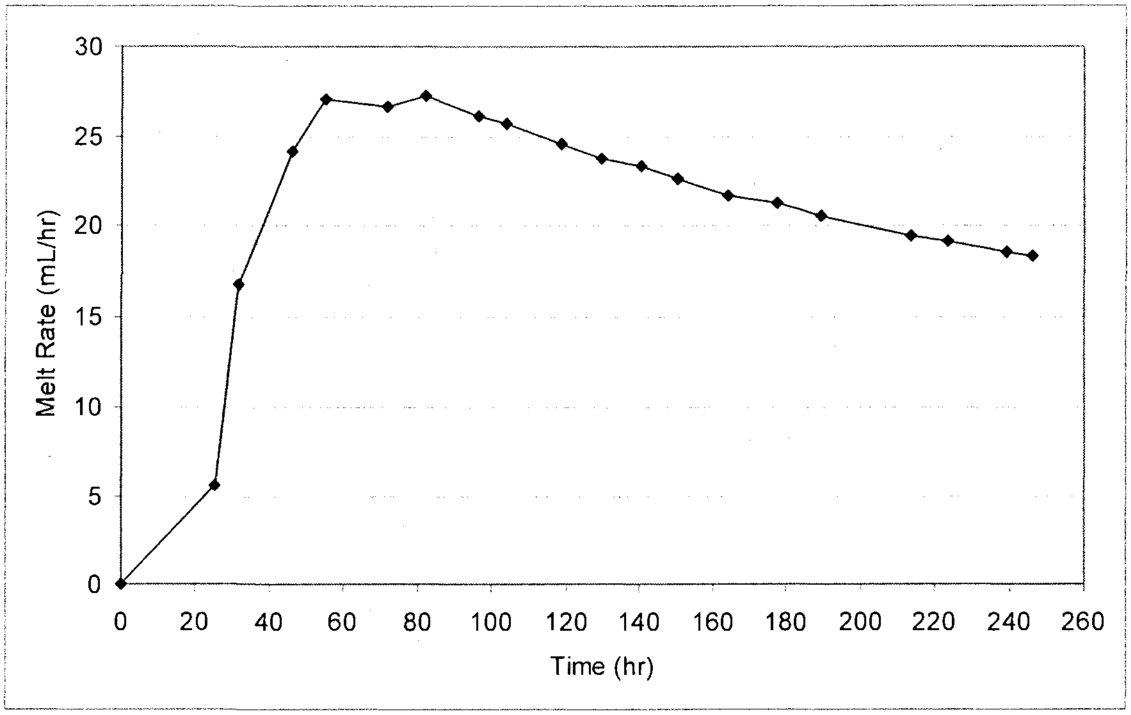
A7.5 Spray Ice Core #2 – Change in EC of Melt Water with Time



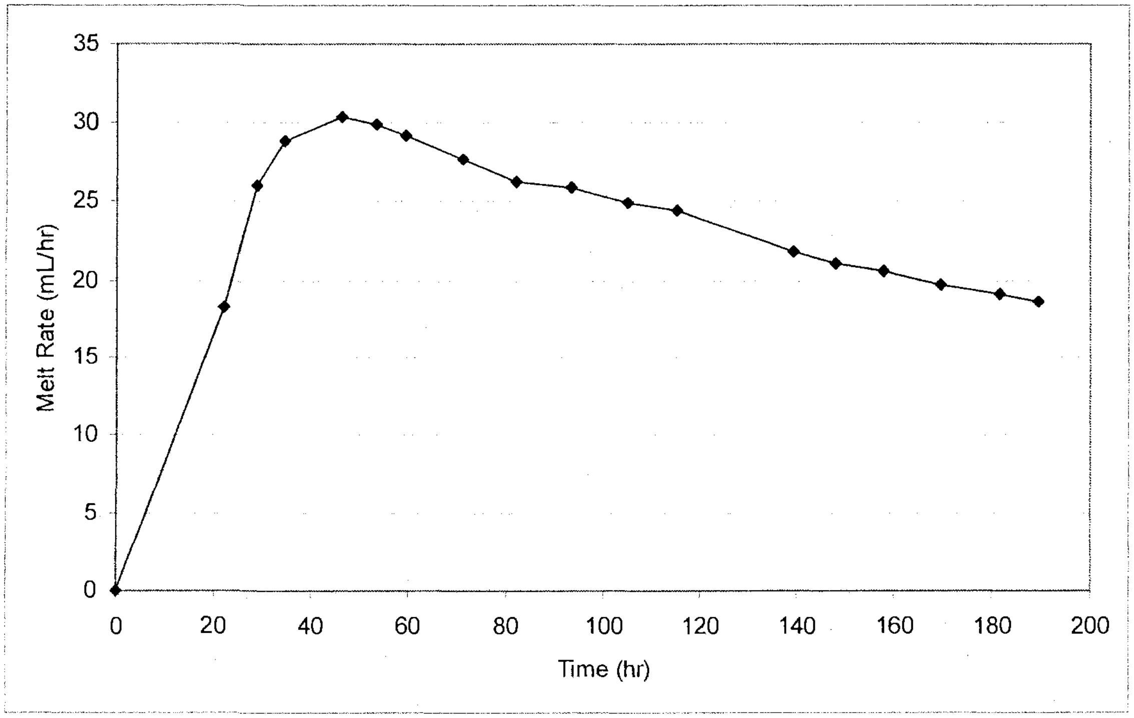
### A7.6 Spray Ice Core #3 – Change in EC of Melt Water with Time



### A7.7 Spray Ice Core # 2 – Change in Melt Rate with Time



### A7.8 Spray Ice Core # 3 – Change in Melt Rate with Time



# APPENDIX 8 - Freeze Point Depression Test

## A8.1 Freeze Point Depression Methodology

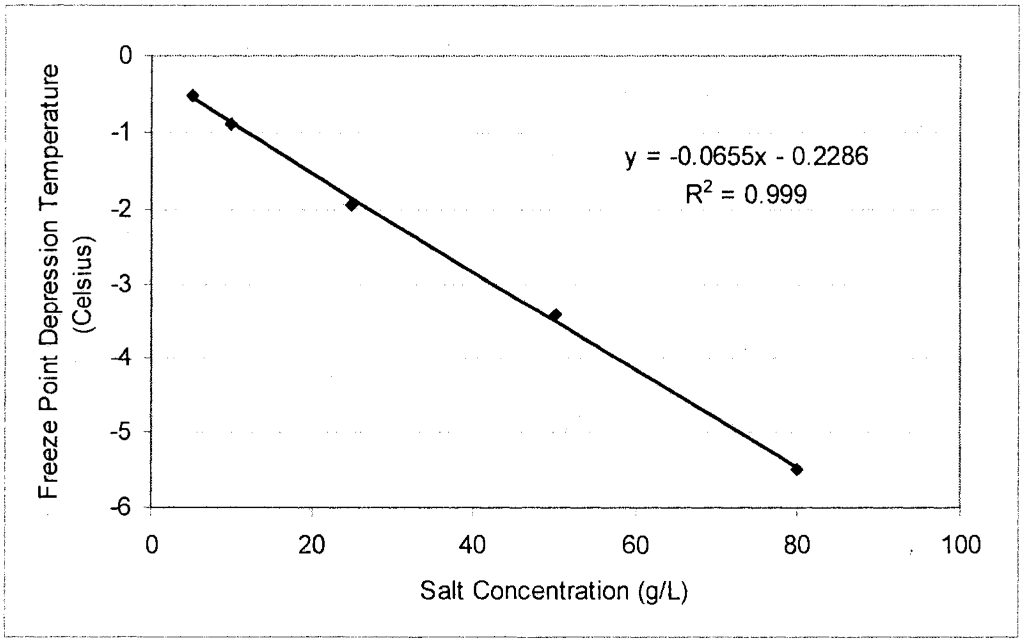
Freeze point depression tests were performed in order to confirm the effect of salts on the freezing point of the brine-saturated road sand. A total of 6 samples were frozen and the test was run in accordance with ASTM standard D 5918, the recommended method to obtain freezing-point depression. Six sand samples were placed in glass vials and brine of different concentrations was added ranging between 5 and 80 g/L road salt. The sand samples were generally saturated with the brine and the moisture contents ranged between approximately 18 and 24%. The samples were then place one by one in an ethylene glycol bath in which the temperature was controlled. Thermistors were placed within the samples to monitor the change in temperature as the samples froze. As super cooling of the sample took place the temperature dropped to below the freezing point, or to the freezing point depression, which is evident as the low point in the graph which was then recorded for each sample.

## A8.2 Freeze Point Depression Results

The road sand used in this experiment had a low fines content and usually the temperature at which water in soil begins to freeze, decreases with an increasing amount of fine grained particles (ASTM D 5918, 2001). The results of this experiment confirmed that the freezing point of the given concentrations was similar to that shown on the NaCl-$H_2O$ binary phase diagram and are shown in Figure 4.8. The relationship was generally linear and the graph below demonstrates this. The 40 g/L sample was omitted from the graph because it seemed to be erroneous and did not configure with the results of the other samples. The lowest freezing point was found for the 80 g/L sample which was -5.5 °C.

## A8.3 Figures

Figure A8.1 Freeze Point Depression of Sand-Brine mixtures



## A8.4 References

ASTM Standards D 5918 – Appendix. 2001. Recommended Method to Obtain the Freezing Point Depression.

# APPENDIX 9 - Ablation of the Snow Pile by Water Jet

## A9.1 Background

The purpose of this experiment was to:

1) Carry out a small scale experimental operation demonstrating the impact of water jets on the melting rate of the Poundmaker snow pile.
2) Evaluate the effectiveness, feasibility and economic viability of this method as an alternative to the current melting practice (using a cat/loader to "stir" up the snow pile to induce melting).

The University of Alberta and Sand Recycling Ltd. conducted a small scale study to investigate the ablation of the Poundmaker snow pile using water jets. Studies have shown that water may be used to melt ice through the use of jets (Gilpin, 1973-74) (Gilpin & Lipsett, 1978). When high pressure jets are used, ablation may occur largely due to mechanical forces or "wearing down" of the snow or ice pile. However, Gilpin, 1973-74, found that at lower water pressure (approximately 100 psi or lower) the mechanical action of the jet is minimal and the removal of ice is primarily produced by melting.

In construction engineering, high pressure water jets are used for a variety of applications including sewer channelling and pipe cleaning and extremely high pressure applications such as hydro-demolition or the jet cutting of metals, rocks, glass and ceramics (Womber, 1998). The jets used in these applications are commonly required to produce water jets at velocities greater than 700 m/s and extremely high pressures near 200,000 kPa (29,000 psi). Generally, very small nozzles with diameters less than 5 mm are required to produce velocities and pressures of this magnitude.

## A9.2 Experimental Method

The experiment was conducted on May 15, 2008 and the ambient air temperature was approximately 21°C, with very strong winds at 35 km/hr prevailing from the Northwest. The temperature of the water in the settling pond ranged between 6 and 9 °C. In order to conserve water, it was proposed to pump water from the existing settling pond to the face of the snow pile.

The set-up consisted of one small 23 hp portable fire pump stationed near the pond and a screen was attached to the end of the suction line to prevent debris from entering the system. The pump discharged water through a 1.5" hose to a handheld, 1.5" turbojet nozzle located near the face of the pile, approximately 50 metres away from the pump. Pumping began at approximately 10:30 am and continued for approximately 2.5 hours until 1:00 pm.

### A9.3 Results

Since the pond temperatures were generally quite low, very little heat was available for melting and ablation of the pile had to be done through force. The snow pack was very dirty and brown in colour with a very high density which was estimated to be approximately 0.8 to 0.9 kg/m$^3$, where pure ice has a density of approximately 0.917 kg/m$^3$ (Lock, 1990). The pressures obtained at the nozzle were much lower than the required values for ablation due to erosion. During the first half hour of the experiment the flow rate through the nozzle was 60 gpm (3.79 x 10$^{-3}$ m$^3$/s) and the pressure at the nozzle was 50 psi (345 kPa), using the 1.5" (38.1 mm) nozzle. After about 20 minutes, the flow rate was decreased to 45 gpm (2.83 x 10$^{-3}$ m$^3$/s) to create a corresponding increase in pressure to 90 psi (620 kPa). After one hour, less than 0.5 cubic metres of ice had been removed.

At 12:00 pm, after 1.5 hours of spraying, a 0.5" (12.7 mm) bore nozzle was used to replace the larger nozzle on the end of the hose in an attempt to narrow the spray and increase the pressure produced at the tip. Using this nozzle, a pressure of 110 psi (758 kPa) was produced with a flow rate of 78 gpm (4.92 x 10$^{-3}$ m$^3$/s) and a velocity of 39 m/s. The rate of ablation increased slightly with this increase in pressure; however it was evident that a much higher pressure and velocity at the nozzle would be required to produce a notable impact on the snow pile. After 2.5 hours of spraying, approximately 1 to 2 cubic metres of ice had been removed. Figure 6.5 shows a photo of the experimental spraying process.

### A9.4 Conclusions

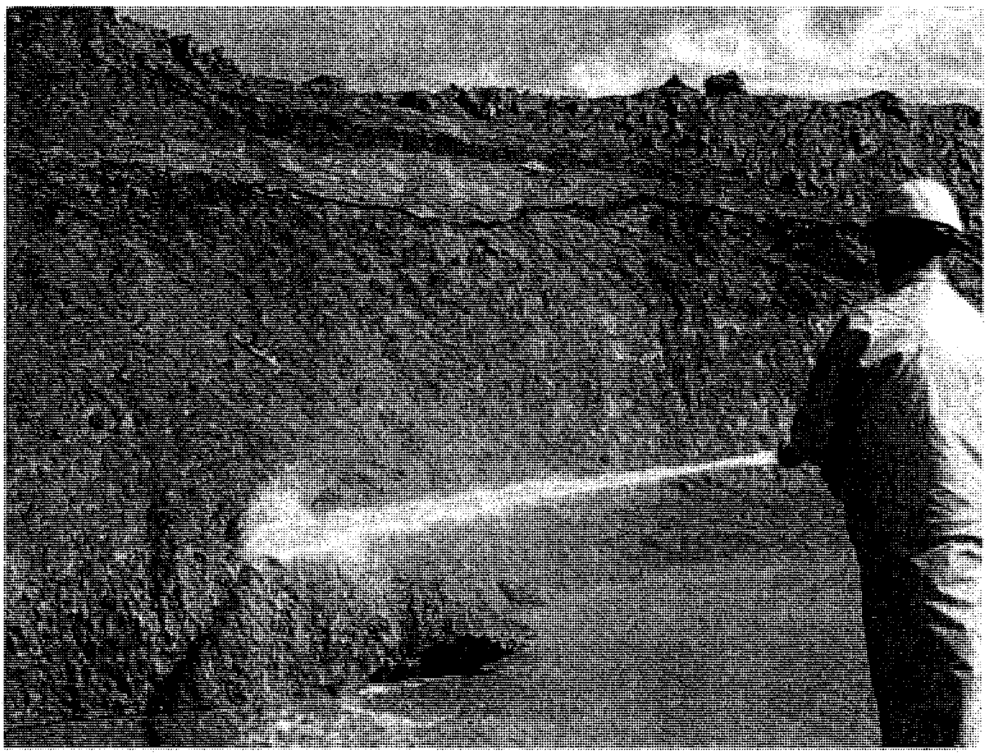
The results of this experiment confirmed that with water of low temperature (between 6 and 9 °C), little to no melting will occur and ablation of compact snow must be done by force using pressures much higher than 100 psi (689 kPa) at the nozzle. Further work would need to be done to determine the required pressures, but it is estimated that pressures greater than 200 psi (1,379 kPa) at the nozzle would be necessary to make any sort of visible impact on the compacted snow. The use of jets to mechanically ablate the snow at the snow storage facility may not be practical for a variety of reasons including:

- Extremely high pressures are required to produce any sort of ablation with the given water temperatures.
- To produce the required pressures very large pumps and operating systems will be required, increasing the cost.
- There may be site access and mobility issues with such large equipment.
- If high pressures along with large flow rates are not possible, cutting of the pile may occur rather than homogeneous erosion.
- Heating the water may greatly increase the success of the operation when high pressures cannot be obtained, but the high costs of this may make this an unviable option.

If further work is to be done in this area, thought must be given to the practicality of the large pressures required and the costs, feasibility and site access issues related to the use of the systems necessary to produce these pressures. In regards to the City of Edmonton snow storage facilities, the small scale experiment done here has shown that presently mechanical ablation of a large snow pile using water jets is not practical or efficient.

## A9.5 Figures

Figure A9.1 Water Jet Ablation Experiment



## A9.6 References

Gilpin, R.R. 1973-74. The Ablation of Ice by a Water Jet, Transaction of the Canadian Society of Mechanical Engineers, Vol. 2, 91-92.

Gilpin, R.R. & Lipsett, A.W. 1978. Impingement melting: Experiment and Numerical Simulation. Proceeding of 6th International Heat Transfer Conference, Hemisphere, Washington. Vol. 3, pp 43-47.

Womber, A. 1998. Water Jet Applications in Construction Engineering: Introductional Aspects of Water Jet technology in the Construction Industry. A.A. Balkema, Rotterdam, Netherlands, 3-15.

# APPENDIX 10 -City of Edmonton Pond Water Data

## Figure A10.1 General Water Parameters

| **Test Parameter Methodology**<br>APHA 4500H<br>**"General Water Parameters" Detection Limit**<br>0.1<br>**Units Sewers Use Bylaw, No. 9675,**<br>**Schedule C Discharge Limits (2007)**<br>6.0-9.0 | | | | pH Conductivity<br>APHA 2510B<br>0.2<br>N/A | Electrical Total<br>EPA 200.7<br>0.02<br>µS/cm at 25<br>1.0 | Phosphorus Dissolved<br>APHA 4500Cl-E<br>1<br>mg/L<br>N/A | Chloride Total Suspended<br>APHA 2540D<br>3<br>mg/L<br>N/A | Solids Biochemical Solids<br>Biochemical<br>2<br>mg/L<br>50 | BOD 5 Day Chemical Oxygen Demand<br>APHA 5220D<br>5<br>mg/L<br>100 | COD Membrane Filtration<br>APHA 9222D<br>1<br>mg/L<br>1000 | Fecal Coliforms<br>CFU/100 mL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | Date | Site ID | Lot ID | | | | | | | | |
| Poundmaker Snow Facility (1 | 12/04/2007 | 2 | 495025 | 7.9 | 11200 | 0.03 | 1680 | 11 | 10 | 170 | <1 |
| Poundmaker Snow Facility (1 | 26/04/2007 | 2 | 499424 | 7.9 | 11800 | 0.03 | 3850 | 17 | 10 | 84 | 2 |
| Poundmaker Snow Facility (1 | 01/05/2007 | 2 | 50077 | 7.9 | 10900 | 0.06 | 3820 | 16 | 16 | 79 | 2 |
| Poundmaker Snow Facility (1 | 11/05/2007 | 2 | 504698 | 7.7 | 7920 | 0.07 | 2780 | 26 | 10 | 65 | <1 |
| Poundmaker Snow Facility (1 | 15/05/2007 | 2 | 505706 | 7.8 | 6500 | 0.07 | 2180 | 44 | 9 | 58 | 3 |
| Poundmaker Snow Facility (1 | 23/05/2007 | 2 | 508683 | 8.1 | 4300 | <0.02 | 1220 | 10 | 4 | 42 | 4 |
| Poundmaker Snow Facility (1 | 29/05/2007 | 2 | 510771 | 8 | 3180 | 0.18 | 892 | 4460 | 4 | 25 | 3 |
| Poundmaker Snow Facility (1 | 05/06/2007 | 2 | 513764 | 8.1 | 1690 | 0.11 | 419 | 46 | 2 | 29 | 59 |
| Poundmaker Snow Facility (1 | 13/06/2007 | 2 | 517483 | 8.1 | 1300 | 0.06 | 230 | 28 | <2 | 13 | 4 |
| Poundmaker Snow Facility (1 | 21/06/2007 | 2 | 521094 | 8.1 | 1140 | 0.09 | 182 | 38 | 2 | 23 | 100 |
| Poundmaker Snow Facility (1 | 27/06/2007 | 2 | 523268 | 8.1 | 910 | 0.13 | 120 | 101 | <2 | 17 | <1 |
| Poundmaker Snow Facility (1 | 05/07/2007 | 2 | 526471 | 8.2 | 600 | 0.52 | 65 | 336 | <2 | 22 | 14 |
| Poundmaker Snow Facility (1 | 13/07/2007 | 2 | 529759 | 8.2 | 530 | **1.53** | 53 | 2710 | 6 | **226** | **1400** |
| Poundmaker Snow Facility (1 | 18/07/2007 | 2 | 531511 | 8 | 427 | **3.61** | 47 | 3780 | 2 | **300** | 140 |
| Poundmaker Snow Facility (1 | 24/07/2007 | 2 | 533601 | 8.1 | 335 | **3.82** | 36 | 14300 | 8 | 93 | 170 |
| Poundmaker Snow Facility (1 | 30/07/2007 | 2 | 535942 | 8.1 | 274 | **3** | 27 | 7960 | 6 | **399** | 30 |
| Poundmaker Snow Facility (1 | 13/08/2007 | 2 | 541147 | 8.1 | 437 | **5.52** | 50 | 15100 | 12 | **1350** | 140 |

# Figure A10.2 Organic Parameters

| **2007 Storage Site Meltwater Analytical Report**<br>Test Parameter Methodology | | | | Oil and Grease | Benzene | Toluene | Ethylbenzene (m,p,o) | Total Xylenes | Phenol |
|---|---|---|---|---|---|---|---|---|---|
| **"Organic Parameters"** | | | | APHA 5520 | USEPA 5030/8260 | USEPA 5030/8260 | USEPA 5030/8260 | USEPA 5030/8260 | APHA 5530 |
| Detection Limit | | | | 1 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.001 |
| Units | | | | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L |
| Sewers Use Bylaw No. 9675,<br>Schedule C Discharge Limits (2007) | | | | 15 | 0.37 | 0.039 | 0.039 | 0.5 | 0.005 |
| **Sample Description** | **Sampled Date** | **Site Id** | **Lot ID** | | | | | | |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 04/12/2007 | 2 | 495025 | <1 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.007 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 04/26/2007 | 2 | 499424 | <1 | <0.0005 | <0.0005 | <0.0005 | 0.0017 | 0.013 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 05/01/2007 | 2 | 50077 | <1 | <0.0005 | 0.0006 | <0.0005 | 0.0034 | 0.011 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 05/11/2007 | 2 | 504698 | <1 | <0.0005 | 0.0009 | <0.0005 | 0.0057 | 0.035 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 05/15/2007 | 2 | 505706 | <1 | <0.0005 | 0.0007 | <0.0005 | 0.0050 | 0.006 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 05/23/2007 | 2 | 508683 | 1 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.003 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 05/29/2007 | 2 | 510771 | <1 | <0.0005 | <0.0005 | <0.0005 | 0.0015 | 0.002 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 06/05/2007 | 2 | 513764 | 1 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.008 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 06/13/2007 | 2 | 517483 | 1 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.005 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 06/21/2007 | 2 | 521094 | <1 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.003 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 06/27/2007 | 2 | 523268 | <1 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | N/A |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 07/05/2007 | 2 | 526471 | 2 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.003 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 07/13/2007 | 2 | 529759 | 3 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.004 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 07/18/2007 | 2 | 531511 | 3 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.007 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 07/24/2007 | 2 | 533601 | 3 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.008 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 07/30/2007 | 2 | 535942 | 4 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.008 |
| Poundmaker Snow Facility (186 Street - 107 Avenue) | 08/13/2007 | 2 | 541147 | 9 | <0.0005 | <0.0005 | <0.0005 | <0.0005 | 0.010 |