University of Alberta

Freeze Separation of Saline Oil Sands Mine Waste Water

by

Nicholas Beier ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Geoenvironmental Engineering

Department of Civil and Environmental Engineering

Edmonton, Alberta

Spring 2006

Your file Votre référence
ISBN: 0-494-13789-4
Our file Notre référence
ISBN: 0-494-13789-4

ABSTRACT

This study investigated the feasibility of trickle freeze separation as an alternative treatment method for saline oil sands mine waste water. Using a specially designed flume housed in a cold room, several experiments were conducted at various ambient temperatures, salt concentrations and mass flow rates. The experiments showed the production of slush and subsequent erosion hindered the trickle freeze separation process. Melting actually proved to be more effective at concentrating salts than the freezing process. More than 80 % of the salts could be concentrated during melting into less than one third of the original volume. Utilizing results from the laboratory scale experiments, a pulse-trickle freeze separation system was designed for 20 million m^3/year of saline oil sands process water. The capital investment for construction of the pulse-trickle freezing system was $127 million or $6.36/$m^3$ capacity. Yearly operating costs amounted to $0.13/$m^3$ of waste water.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

^{o}C	degrees centigrade
C/Co	relative concentration
Cl	chloride
cm bis	centimeters below the ice surface
Co	initial salt concentration
CRREL	Cold Regions Research and Engineering Laboratory
CRGGRF	Cold Regions Geotechnical and Geoenvironmental Research Facility
EC	electrical conductivity
HCO_3^-	bicarbonate
HDPE	high density polyethylene
ID	inside diametre
MLSB	Mildred Lake Settling Basin
Mm^3	million cubic metres
mS	millisiemens
Na	sodium
NaCl	sodium chloride
NH_4^+	ammonium
RTD	resistance temperature device
T_A	ambient temperature
Sr	strontium

1. INTRODUCTION

1.1 Background

The research conducted in this study investigated the feasibility of trickle freeze separation as an alternative treatment method for saline oil sands mine waste water. A review of current literature demonstrated various freeze separation techniques have been used to treat several waste streams including oil sands waste water. However, trickle freeze separation had not been successfully studied as a treatment method for saline oil sands mine waste water. To explore this concept, laboratory testing was conducted to validate an existing mathematical model for trickle freeze separation of saline waste water. Based on the results from the laboratory experiments, a field scale treatment system for saline oil sands mine waste water was designed. The work conducted during this study is introduced in the following sections.

The process used to extract bitumen from oil sands can produce approximately 4 m^3 of a waste slurry mixture comprised of sand, clay, organics and process affected water for every cubic metre of oil sand (Holowenko et al., 2000). The process affected water generally has elevated salinity such as sodium (Na), chloride (Cl) and bicarbonate (HCO_3^-), trace inorganics such as bromine, strontium (Sr) and ammonium (NH_4^+), and organic acids such as naphthenic acids (MacKinnon, 2004). To satisfy the water demand for bitumen extraction, river water is imported on site and process water is recycled. Recycling reduces the quantity of import water required as well as the need to store large volumes of process affected water on site, however it results in increased total dissolved solids. The recycled water quality must meet the standards required for extraction and scaling, fouling, and corrosion are common issues with recycle water, resulting from increased inorganic and organic concentrations from continued reuse.

Currently, the process water does not undergo any desalination treatment. Rather it is stored on site in large, constructed settling basins. The process water is then reused directly from the settling basin. Desalination technology available for treatment of brackish waters can be divided into two processes: thermal methods and membrane processes. The technology used for a particular waste stream depends on the volume, composition and concentration of contaminants, quality of treated water required, availability of waste heat, and installation and operating costs. (CRC Press, 1999; Dore, 2005; Van der Bruggen and Vandecasteele, 2002; and Voutchkov, 2005).

Freeze separation is a process where dissolved solutes in aqueous solutions are concentrated during freezing. The physics of freeze separation have been utilized for treatment of several waste streams. Natural freezing has been used to produce potable water from brackish groundwater (Elmore, 1968) and to treat hog manure waste water and various industrial wastes (Willoughby, 2004; Gao, 1998). Previous spray freeze separation experiments on oil sands tailing pond water resulted in reusable water and a separate concentrated effluent thereby reducing the volume of water requiring treatment (Gao, 1998). However, ice fog produced during spray freezing may preclude use of this freeze-separation process near existing mine operations. An alternate trickle freeze separation process was investigated by Otto (2002) for treatment of salt contaminated groundwater and a mathematical model was developed for predicting the area required for complete freeze separation.

1.2 Objectives

The purpose of this research was to develop a trickle freeze separation system to treat oil sands mine waste water. The research included laboratory testing to validate the existing mathematical model for trickle freeze separation of saline solutions. Results from the laboratory experiments were then used to design a field-scale treatment system for saline oil sands mine waste water.

1.3 Methodology

A laboratory scale trickle freeze separation system was designed and constructed at the University of Alberta's Cold Regions Geotechnical and Geoenvironmental Research Facility (CRGGRF). Experimental saline solutions were trickle discharged into an inclined flume housed within a cold room and subsequently frozen. The produced ice was then slowly melted. The electrical conductivity and concentration of sodium and chloride was measured in the raw saline solution, the produced ice, and the melt runoff to determine the degree of concentration achieved during the freezing and melting processes.

Utilizing the results from the laboratory scale experiments, the design of a field scale pulse-trickle freeze separation system for 20 million cubic metres of saline oil sands process water was explored. The capital and operating costs for construction and operation of the freeze separation system for a typical mine scenario including final treatment cost per cubic meter were then estimated.

1.4 Organization of Thesis

This thesis has been written in paper format. Chapter 1 introduces the need for the study and outlines the structure of the research. Chapter 2 details the laboratory experimental design, execution, observations, and results of the tests. Application of the laboratory results to design a full scale treatment system for a typical oil sands mine is expounded in Chapter 3. Finally, Chapter 4 summarizes the results of the study and requirements for further research.

1.5 References

CRC Press. 1999. Environmental Engineers' Handbook CRCnetBASE 1999 CD-Rom. CRC Press LLC, Boca Raton, Florida.

Dore, M. 2005. Forecasting the economic costs of desalination technology. Desalination **172**: pp 207-214.

Elmore, W.W. 1968. Water purification by natural freezing. M.Sc. Thesis, Department of Chemical Engineering, University of Wyoming, Laramie, Wyoming.

Gao, W. 1998. Partial freezing by spraying as a treatment alternative of selected industrial wastes. Ph.D. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta. p. 308.

Holowenko, F.M., MacKinnon, M.D., and Fedorak, P.M. 2000. Methanogens and sulfate-reducing bacteria in oil sands fine tailings waste. Canadian Journal of Microbiology, **46**: 927-937.

MacKinnon, M. 2004. Oil sands water quality issues: properties, treatment and discharge options. In CONRAD Oilsands Water Usage Workshop, Fort McMurray, Alberta.

Otto, L. 2002. Evaluation of freeze separation as a treatment for salt-contaminated groundwater. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta. p. 167

Van der Bruggen, B. and Vandecasteele, C. 2002. Distillation vs. membrane filtration: overview of process evolutions in seawater desalination. Desalination **143**: 207-218.

Voutchkov, N. 2005. Desalination - Water for the next generation. Filtration & Separation, **42**:2. 14-25.

Willoughby, A. 2005. Freeze Separation to Treat Swine Manure. M.Sc Thesis. Department of Civil and Environmental Engineering, University of Alberta, 2005. p. 94.

2. FREEZE SEPARATION OF CONTAMINANTS FROM SALT CONTAMINATED WATER: LABORATORY EXPERIMENTS

2.1 Introduction

Mine waste water management in the Canadian oil sands industry has become a major concern due to increased production rates, cost and disturbance associated with limited storage capacity, and treatment costs for the waste water. The extraction and upgrading process for bitumen from oil sand deposits in Alberta currently requires large volumes of process water. This water demand is fulfilled by importing water and recycling/reuse of clarified process water. Reuse of the clarified water results in the steady increase of organic and inorganic contaminant concentrations in the recycle water. Conventional treatment methods to render the water reusable are very costly due to large volumes, driving a need for an alternative treatment method.

Previous spray freeze separation experiments on oil sands tailing pond water resulted in reusable water and a separate concentrated effluent thereby reducing the volume of water requiring treatment (Gao, 1998). However, ice fog produced during spray freezing may preclude use of this freeze-separation process near existing mine operations. An alternate trickle freeze separation process was investigated by Otto (2002) for treatment of salt contaminated groundwater. A mathematical model was developed for predicting the area required for complete freeze separation of salt contaminated groundwater. The current research is based on the promising results from Gao (1998) and the mathematical model developed by Otto (2002) for trickle freeze separation of brine solutions. Saline water consisting of table salt (NaCl) and tap water was used as a surrogate for mine waste water.

The purpose of this research was to investigate the feasibility of trickle freeze separation for the concentration of salts from salt contaminated water.

Research objectives include:

- Validation of the freeze separation mathematical model developed by Otto (2002);
- Investigate the influence of experimental variables and temperature on the freeze separation process; and
- Determine the degree of separation and subsequent concentration of salts during the freezing and melting processes.

2.1.1 Background on Freeze Separation

Freeze separation is a process where dissolved solutes in aqueous solutions are concentrated during freezing. It is also known as freeze concentration (EPRI, 2003), freeze desalination (Shone, 1987), freeze-thaw conditioning (Jean et al., 1999; Martel, 1989) or freeze crystallization (Heist, 1981). Freeze separation relies upon the physics of ice crystal formation. Under freezing conditions ice grows by adding water molecules to its crystal structure similar to adding bricks to a wall. These crystals cannot accommodate impurities (salts) within the structure without suffering severe internal strain. Therefore, impurities are rejected ahead of the growing crystal front. As freezing progresses, the impurity concentration increases and the freezing point decreases in the remaining unfrozen liquid. Ice and concentrated unfrozen liquid continue to form until the liquid reaches the ambient or eutectic temperature. Below the eutectic temperature, ice and a hydrohalite solid will form. The eutectic temperature for NaCl is approximately -21 °C. If a NaCl solution were cooled below -21 °C, ice and the hydrohalite solid, $NaCl \cdot 2H_2O$, would form (Grant, 2000; Horvath, 1985). The purity of the ice and degree of concentration in the reject depends on the freezing rate and how efficiently the reject is removed from the crystal front (Chalmers, 1959; Gao, 1998; Pounder, 1965). Furthermore, due to elution of impurities from ice in the early melt water, the purity of the remaining ice is enhanced (Cragin et al., 1993; Gao, 1998).

2.1.2 Previous Applications of Freeze Separation

The physics of freeze separation have been utilized for treatment of several waste streams. Desalination of sea water and brackish water using freeze separation has been studied by Elmore (1968), Fertuck (1969), Krepchin (1985), Spyker (1981), Terwilliger and Dizio (1970), and Weeks and Ackley (1982). Treatment of municipal wastewater and sludges with freeze separation has been investigated by Halde (1980), Martel (1989), Muller and Sekoulov (1992), and Parker et al., (2000). Freeze separation has also been used to treat hog manure waste water and various industrial wastes including mine tailings and acid mine water (Biggar et al, 2005; Gao, 1998; Jean at al., 1999; Shone, 1987; Stahl and Sego, 1995; Willoughby, 2005;). Research by Gao (1998) indicated 50 % rejection of impurities from oil sands waste water was possible with natural spray freezing. In addition, up to 76 % reduction of impurities from the spray ice was achieved within the initial 30 % of melt water. However, production of ice fog during spray freezing may pose a safety concern for operating mines.

Otto (2002) developed a mathematical model to predict the total length needed for complete freeze separation during natural trickle freezing of brine solutions. This freezing length was designated the *significant length*. Otto's model was intended to aid in the design of a retaining pond, specifically the dimensions, required to contain the produced ice from a trickle freezing process. The main variables for the model were flow rate, ambient temperature and initial salt concentration. Conceptually, natural trickle freezing is a process where saline water flows in thin sheets over an ice surface, successively adding thin layers to the ice mass. As the water freezes, salts are concentrated into the unfrozen water. The rejected salt water would then drain on top of the produced ice to the lowest point for collection.

The use of natural trickle freezing for treatment of salt contaminated mine waste water has not been investigated previously. The current experiment was to achieve trickle freeze separation by flowing saline water along an inclined flume housed in a cold room. Additional salt separation was expected during the melting of the produced ice.

2.1.3 Oil Sands Process Water Characteristics

The oil sands deposits of the Athabasca Basin in northern Alberta, Canada are estimated to contain 1.7 trillion barrels of bitumen. Syncrude Canada Ltd. (Syncrude), one of many companies mining these oils sands, utilizes open pit mining to extract the bitumen laden sand deposits. To separate the bitumen from the oil sands, a caustic, hot water extraction process is used. During the extraction process, up to 3 m^3 of water is used per cubic metre of oil sand. This process can produce approximately 4 m^3 of a waste slurry mixture comprised of sand, clay, organics and process affected water (Holowenko et al., 2000). The chemical composition of the process water depends on the in situ oil sand properties along with the mining and extraction processes utilized. The process affected water generally has elevated salinity such as sodium (Na), chloride (Cl) and bicarbonate (HCO_3^-), trace inorganics such as bromine, strontium (Sr) and ammonium (NH_4^+), and organic acids such as naphthenic acids (MacKinnon, 2004). In process water at Syncrude's Mildred Lake Settling Basin (MLSB), Na and Cl may be as high as 1000 mg/L and HCO_3^- up to approximately 800 mg/L (MacKinnon, 2004; Zubot, 2004).

To satisfy the water demand, Syncrude imports 40 Mm^3/y of river water and recycles 112 Mm^3/y of process water. A zero-discharge policy at Syncrude requires 141 Mm^3/y of tailings water and 40 Mm^3/y of trapped water (in sands and fine tails) to be contained on site in large ponds (MacKinnon, 2004). To sustain increasing plant production, Syncrude must ensure an adequate supply of water is provided (Zubot, 2004). Recycling of the process water helps fulfill their water demand and reduce the quantity of imported water. Recycling also reduces the need to store large volumes of process affected water on site. However, the recycled water quality must meet the standards required for extraction. Scaling, fouling, and corrosion are also common issues with recycle water. They are a result of increased inorganic and organic concentrations in the water due to continued reuse. Therefore, the process water requires treatment to meet the extraction standards and to prevent scaling, fouling and corrosion. Trickle freeze separation may provide an alternative, less expensive, treatment process to separate dissolved chemicals from the process water.

2.2 Methodology

Freezing experiments were conducted in the University of Alberta's Cold Regions Geotechnical and Geoenvironmental Research Facility (CRGGRF). This section describes the experimental setup and methods followed for the trickle freeze experiments.

2.2.1 Experimental Setup

The freeze separation system was designed as a laboratory scale system to validate Otto's (2002) analytical model and determine the influence of variables on the freezing process. Based on the results, a guide for designing a field scale treatment system for mine waste water will be developed (Chapter 3).

Freezing occurred in a specially designed flume 0.61 m wide, 0.61 m deep, 12.9 m long and "U" shaped to fit within the confines of the large cold room in the CRGGRF (Figures 2.1 and 2.2). The flume base and walls were constructed of transparent Lexan to allow for observations during freezing. The flume base slope was adjustable to approximately 0.5-0.7 % to induce gravity flow along the flume. The cold room housing the flume was capable of achieving ambient temperatures (T_A) of -30 to +2 °C, +/- 0.5 °C.

The experimental saline solution consisted of NaCl and tap water. Relationships between electrical conductivity (EC) and various concentrations (NaCl, Na, and Cl) were developed to quickly estimate concentration by measuring EC

(Appendix 1). A 1000 L plastic tank (Figure 2.3) was used for mixing and storage of the saline solution. The storage tank was housed in a separate cold room to maintain the temperature of the saline solution between 1 and 3 °C, typical of winter field conditions. Continuous or pulsed discharge of the saline solution was delivered to the flume at flow rates ranging from 0.044 to 0.140 kg/s using a 1/3 hp. electric pump and a combination of flow valves, volume and flow meters, and a pulsing timer (Figure 2.3). The saline solution was then fed to a 60 cm wide galvanized steel dispenser, suspended from the flume walls to evenly distribute the solution across the freezing flume (Figure 2.4). During the freezing process, the dispenser was manually raised as required to prevent ponding of water behind the growing ice mound. The metal dispenser also aided the removal of sensible heat during the freezing experiments. Unfrozen/melted runoff was captured in a gutter at the end of the flume (Figure 2.5). During melting, the base and walls of the flume were insulated with 0.05 m thick foam board insulation to induce 1 dimensional, downward melting, typical of field conditions.

From the collection gutter, runoff was conveyed through an insulated pipe to a flow-through cell equipped with EC and temperature probes to continuously measure EC of the collected runoff (Figure 2.6). Grab samples were also collected from the flow-through cell. Runoff then flowed into a barrel set upon a load cell (Figure 2.6). The load cell provided a measurement of incremental mass of runoff with time. Details on the calibration of the load cell can be found in Appendix 2.

Platinum resistance temperature devices (RTDs) were positioned above the water/ice surface and at various locations within the cold rooms to log temperatures during the experiments.

2.2.2 Experimental Methods

The procedures for the trickle freeze separation experiments are described below. The first step for an experiment was to mix the saline solution and cool it to about 2 °C. During this time the cold room was adjusted to the required T_A. The flume base slope was adjusted and the dispenser was set into place. Once the saline solution and cold room reached the desired temperature, an experiment was initiated. The desired flow rate and pulse rate (if required) were set and the saline solution was discharged to the dispenser. The combinations of experimental variables including pumping rate, initial salt concentration (Co) and T_A used for each of the experiments are listed in Table 2.1.

As ice built up and spread along the flume, elevation and position were recorded with time. Temperature, input flow rate, runoff flow rate and EC were recorded regularly during the experiment. Grab samples of runoff were also collected. Pumping was terminated when the desired input volume was reached or when no further freezing occurred.

After the saline solution had frozen solid, ice core samples were collected using a 10 cm diameter Cold Regions Research and Engineering Laboratory (CRREL) core barrel at various points along the flume. The cores were obtained to measure variations of the salt concentration within the ice as well as determine ice structure. The core holes were then refrozen with saline solution used for the particular experiment prior to thawing of the ice mass.

Melting was induced by increasing and then holding constant, T_A to +2 °C either in one step (Test 4/5) or by slowly increasing the temperature daily until +2 °C was reached (*i.e.* -15, -10, -5, -4, -3, -2, -1, 0, 1, 2). During melting, the cumulative runoff volume and EC were monitored regularly. Melting was terminated when the runoff EC matched that of typical tap water. Ice cores were again collected from the remaining ice to determine salt concentrations and ice structure at various points along the flume. The remaining ice was then disposed of.

Based on the preliminary results from Tests 1 through 5 (Section 2.3.1 to 2.3.6), slight modifications to the experimental method were introduced. The modifications were intended to reduce the erosion of slush ice, increase the volume of produced ice, and increase the separation efficiency. Freezing trials were conducted to optimize the flow rates and ice production. Details of the freezing trials can be found in Appendix 3. The optimum freezing method consisted of pulsed flow at 2 minutes on and 6 minutes off with a slightly higher discharge rate. Slush fences, consisting of standard vinyl coated polyester window screen, were installed in the flume to prevent the wash out of slush. Input of saline solution was also limited to approximately 150 to 170 L per freezing event based on the observations from Tests 6 and 7 (Section 2.3.7 and 2.3.8). Additional input to the flume resulted in erosion channels or would cause the slush to float to the surface, freeze solid, and force the flow under the surface. Both scenarios severely reduced heat removal and therefore are undesirable. The produced slush was permitted to freeze completely (approximately 8 hours) prior to the next freezing event. The above methods virtually eliminated erosion and subsequent channelling of the slush for the remaining Tests 8 through 10. Very little runoff was generated during freezing. Separation and concentration of salts was therefore only observed during melting of the produced ice.

2.3 Results

The following section describes the results of the laboratory cold room experiments including pumping and freezing of the saline solution, subsequent melting of the produced ice and the degree of freeze separation for each experiment. Detailed experimental observations and summaries of sample data can be found in Appendix 4. Temperature data was collected approximately every 10 to 20 seconds to monitor the thermal regime within the cold room during the pumping process. Ambient air temperatures at the ice surface and above the flume are compared in Appendix 5.

2.3.1 Freezing Test 1

Test 1 consisted of pumping a 500 mg/L (Co = 1.0 mS/cm) NaCl solution into the flume at a continuous rate of 0.16 kg/s per metre width (0.10 kg/s). The T_A was set at -30 °C. Ice growth profiles during pumping for Test 1 are contained in Figure 2.7. Summaries of salt water mass input, collected runoff mass and relative concentration (C/Co based on EC) during pumping for Test 1 are in Figure 2.8.

Once pumping into the flume was initiated, the solution began to freeze into slush consisting of vertical ice platelets distributed in a random, interlocking arrangement. The slush front advanced approximately 800 cm along the flume and stopped. Input of additional saline solution resulted in thickening of the slush layer rather than forward advancement (Figure 2.7). After approximately 250 kg of saline solution were added to the flume (40 to 45 minutes of pumping), channels eroded through the produced liquid/slush mixture from the dispenser to the gutter. The channels allowed the unfrozen liquid in the slush to drain. Initial runoff collected after 52 minutes of pumping, had C/Co (based on EC) of 1.8 (Figure 2.8). Relative concentration greater than 1 indicated freeze separation was occurring. Relative concentration dropped soon after to initial conditions of 1. Slush build up had also ceased because the ice thickness did not increase. Additionally, the runoff flow rate was equal to the salt water input flow rate (Figures 2.7 and 2.8). Freeze separation was no longer occurring therefore pumping was terminated. The total amount of ice produced during Test 1 was 244 kg. Ice cores were not collected.

2.3.2 Freezing Test 2

Test 2 consisted of pumping a 500 mg/L (Co = 1.0 mS/cm) NaCl solution into the flume over the produced ice from Test 1, at a lower continuous rate of 0.10 kg/s per metre width (0.06 kg/s). The T_A was set at -30 °C. Short circuiting and rapid drainage of the saline solution in the flume during Test 2 prevented the collection of sufficient data for analyses.

2.3.3 Freezing Test 3

The NaCl concentration was increased to 22,800 mg/L (Co = 28.8 mS/cm) for Test 3 with a continuous pumping rate of 0.14 kg/s per metre width (0.09 kg/s). Produced ice from Tests 1 and 2 was not removed from the flume prior to Test 3. The T_A was set at -30 °C. Insufficient data was collected to complete the ice growth profiles for Test 3. Summaries of salt water mass input, collected runoff mass and relative concentration (C/Co based on EC) during pumping for Test 3 are in Figure 2.9.

Freezing of the saline solution after pumping initiated was similar to Freeze Test 1. Vertical ice platelets formed, distributed in a random, interlocking arrangement. The slush front again advanced approximately 800 cm along the flume and stopped. Input of additional saline solution resulted in thickening of the slush layer rather than forward advancement. After approximately 250 kg of saline solution were added to the flume (40 to 45 minutes of pumping), channels eroded through the produced liquid/slush mixture from the dispenser to the collection gutter. The channels allowed the unfrozen liquid in the slush to drain. Initial runoff collected after 55 minutes of pumping, had C/Co of 1.2 (Figure 2.9). Relative concentration greater than 1 indicated freeze separation was again occurring. Relative concentration also dropped soon after to 1. After the channels had formed, flow was no longer in thin sheets across the entire width of the flume, but rather in narrow, deep channels (Figure 2.10). Slush build up had also ceased and the runoff flow rate was equal to the salt water input flow rate

(Figure 2.9). Pumping was then terminated. The total amount of ice produced during Test 3 was 254 kg.

White crystals were found on the ice surface and within the porous ice structure of Test 3, 12 hours after pumping was stopped (Figure 2.11). Based on the eutectic temperature for NaCl (-21 ^{o}C), the occurrence of hydrohalite crystals was reasonable for the given T_A. Figure 2.11 also depicts the arrangement of the vertical, platelet-like ice crystals. Figure 2.12 depicts the EC profile of the ice cores from Test 3. EC from the 0-2.75 cm below the ice surface (cm bis) layer was within 25 % of Co. EC was the greatest in the surface layer from 0 to 2.75 cm bis in all cores except at the 643 and 1043 cm locations. The surface layer (0-0.5 cm bis) at these points was encrusted with eutectic salt crystals contributing to a higher EC. No data was collected during the melting.

2.3.4 Freezing Test 4

Test 4 consisted of pumping a 20,000 mg/L (Co = 26.5 mS/cm) NaCl solution at a continuous rate of 0.09 kg/s per metre width (0.057 kg/s), with T_A set at -15 ^{o}C. Summaries of salt water mass input, collected runoff mass and relative concentration (C/Co based on EC) during pumping for Test 4 can be found in Figure 2.13.

During pumping for Test 4, the solution began to freeze into vertical platelet slush. The slush front advanced approximately 1040 cm along the flume within 5 min of pumping. Preferential flow paths and channeling of the produced slush lead to early runoff collection after 22 minutes. Pumping was terminated after 30 minutes when C/Co was 1. Approximately 55 L of saline water froze in the flume (Figure 2.13). Another 20 L of saline solution was added to the ice to fill in low spots and erosion channels. No ice cores were collected from Test 4.

2.3.5 Freezing Test 5

Test 5 consisted of pumping a 20,000 mg/L (Co = 26.5 mS/cm) NaCl solution over the produced ice from Test 4, at a lower continuous rate of 0.074 kg/s per metre width (0.045 kg/s) in an effort to prevent channeling and slush erosion. The T_A for Test 5 was the same as test 4, -15 °C. Summaries of salt water mass input, collected runoff mass and relative concentration (C/Co based on EC) during pumping for Test 5 can be found in Figure 2.14. Ice growth profiles during pumping for Test 5 are contained in Figure 2.15.

As pumping progressed, vertical ice platelets were again forming in the flume (Figure 2.16). The slush front advanced, without major channeling or erosion, to the collection gutter. Runoff collection began after approximately 245 L of saline solution was added to the flume (89 minutes; Figure 2.14). The C/Co of the runoff peaked at 2.1 indicating freeze concentration was occurring. Further input of saline solution did not result in significant thickening of the slush layer (Figure 2.15). The slush surface actually began to freeze solid forcing incoming saline solution below the ice surface. The sub surface flow hindered freeze separation as reflected by the drop in C/Co. After approximately 350 L of saline solution were added to the flume (136 minutes of pumping), channels eroded through the slush under the ice surface from the dispenser to the gutter (Figure 2.17). The channels allowed the unfrozen liquid in the flume to drain. This was reflected by the increase in the runoff collection rate to greater than the salt water input rate. Relative concentration also dropped to 1. Slush build up had also ceased because the ice thickness did not increase significantly (Figure 2.15). Freeze separation was no longer occurring therefore pumping was terminated. The total amount of ice produced during Test 5 was 173 kg. Unfrozen liquid was found on the ice surface 12 hours after pumping stopped. Based on the freezing point depression for NaCl, the presence of unfrozen water was reasonable for the given T_A.

Figure 2.18 depicts the EC profile of the ice cores from Test 5. EC of every core was less than 75 % of Co. The surface layer (0 to 2.8 cm bis) had a lower EC than the base layer at all locations except at the collection end of the flume. Inspection of the ice structure from the cores revealed the ice was relatively porous (Figure 2.19). The porous structure was caused by drainage of the unfrozen water after channels formed in the ice.

2.3.6 Melting Tests 4/5

Ice produced from Freezing Tests 4 and 5 (248 kg) was melted to determine the degree of NaCl removal during melting. A total of approximately 3.85 kg of NaCl was entrapped within the ice during freezing. Melting was induced by increasing and holding constant T_A in one step from -15 to 2 ^{o}C. The C/Co (EC based), melt water and salt mass (based on EC-NaCl relationship) runoff profiles for Melting Test 4/5 are contained in Figure 2.20. The left axis corresponds to the C/Co data set. The right axis corresponds to the melt water and salt mass data sets and represents the percentage collected in the runoff of the total available frozen in the flume.

Relative concentration of the initial runoff was 3.0 after 17 hours of melting, indicating salts were being flushed from the ice. After 42 hours, C/Co had reached 1.0. At this point, 66 % of the salt mass was collected in 28 % of the initial ice volume. Melting was terminated after 113 hours when runoff EC was slightly greater than tap water (C/Co = 0.03). Overall, melting resulted in flushing of 85 % of the salt mass into 66 % of the initial ice volume.

2.3.7 Freeze Test 6

Test 6 consisted of pumping a 22,800 mg/L (Co = 28.8 mS/cm) NaCl solution into the flume at a rate of 0.26 kg/s per metre width (0.16 kg/s). Pumping was pulsed for 2 minutes on and 6 minutes off. The T_A for Test 6 was -15 ^{o}C. Channeling and early drainage of the saline solution in the flume during Test 6 prevented the collection of sufficient data for a complete analysis. The flow rate for Test 6 was too high. No ice cores were collected from Test 6. Produced ice was disposed of.

2.3.8 Freeze Test 7

Test 7 consisted of pumping a 2,000 mg/L (Co = 1.90 mS/cm) NaCl solution into the flume at a lower rate of 0.22 kg/s per metre width (0.13 kg/s). Pumping was pulsed for 2 minutes on and 6 minutes off. The T_A for Test 7 was -15 °C. Summaries of salt water mass input, collected runoff mass and relative concentration (C/Co based on EC) can be found in Figure 2.21. Insufficient data was collected to construct the ice growth profiles.

After pumping was initiated, slush containing vertical ice platelets formed (Figure 2.22). Pulsing of the flow allowed more slush to develop than with continuous pumping. The slush front advanced to 1040 cm, without major channeling or erosion, in approximately 50 minutes. The advancing front began to slow leading to thickening of the slush layer. Runoff collection began after approximately 145 L of saline solution was added to the flume (71 minutes; Figure 2.21). Relative concentration of the runoff peaked at 2.4 indicating freeze concentration was occurring. EC began to drop significantly after 170 kg of saline solution were pumped into the flume (85 minutes). Further input of saline solution did not result in significant thickening of the slush layer. In fact, the saline solution drained from the slush during the off cycle. This was evident by the appearance of air bubbles under the rough ice surface (Figure 2.23). The slush surface actually began to freeze solid forcing incoming saline solution below the ice surface. The sub surface flow hindered freeze separation as reflected by the drop in C/Co. After approximately 277 kg of saline solution were added to the flume (128 minutes of pumping) C/Co dropped to 1. Freeze separation was no longer occurring therefore pumping was terminated. The total amount of ice produced during Test 7 was 135 kg. Inspection of the ice structure from the cores revealed the ice was relatively porous (Figure 2.24). The porous structure was caused by drainage of the unfrozen water between flow pulses. Produced ice was disposed of.

2.3.9 Freezing and Melting Test 8

A 3000 mg/L (Co = 4.628 mS/cm) NaCl solution was used for Test 8. Using improved placement methods, the saline solution was frozen into the flume over six freezing events. The first four layers were placed at 0.22 kg/s per metre width (0.14 kg/s) and the remaining two at 0.26 kg/s per metre width (0.16 kg/s). Pumping for each event was pulsed on for 2 minutes and then off for 6 minutes until approximately 170 L of solution had been placed. Each layer was allowed to solidify a minimum 8 to 10 hours before the next freezing event. The T_A for Test 8 was -15 °C. Ice growth profiles for each freezing event and associated placement volumes can be found in Figure 2.25. Two ice fences were also installed to reduce the erosion of slush during pumping (Figure 2.25). A total of 861 L of saline solution (2.57 kg of NaCl) was frozen into the flume. Approximately 50 L of runoff was collected during placement of layer 1. No runoff was collected during subsequent layer placement. Random, interlocking ice platelets formed in the slush during each freezing event (Figure 2.26).

A summary of the ambient air temperatures during the freezing process can be found in Figure 2.27. The defrost cycle in the cold room caused a short interval temperature spike for each RTD. The dispenser temperature spikes from -15 °C to approximately 1 °C during pumping for each of the six layers. RTDs positioned at the start and end of the flume (120 and 1040 cm) were within 1 °C of the target ambient air temperature of -15 °C. The RTD at 400 cm increased to approximately -13 °C after placement of layer 3 and remained elevated for the remainder of the experiment. A circulation fan was installed at position 400 cm to assist heat removal and prevent warming in this area. Refer to Appendix 5 for detailed plots of the temperature profiles from all the RTDs.

Figure 2.28 depicts the EC profile of the ice cores taken after all six layers were frozen. EC generally increased from the start of the flume to the collection end. Only the last two stations had EC greater than Co (up to 30 % greater). Layers 6 and 1 generally had the greatest EC compared to the other layers. Inspection of the ice cores revealed individual layers were evident (Figure 2.29). Small inclusions were also visible within the cores. These inclusions may be air voids, entrapped brine or interconnected drainage pathways.

Melting was induced by slowly increasing T_A daily to 2 ^oC as described in section 2.2.2. The C/Co (EC based), melt water, salt mass runoff profiles for Test 8 are contained in Figure 2.30. Three data sets are used to represent the salt mass runoff. One set represents the NaCl mass as determined by the EC-NaCl relationship. The remaining two sets represent the individual species Na and Cl (as determined by the EC-analytical concentration relationships) for comparison of the two different relationships. Data collection began after the first increase in temperature (*i.e.* -15 to -10 ^oC). The left axis corresponds to the C/Co data set. The right axis corresponds to the melt water and salt mass data sets and represents the percentage collected in the runoff of the total available frozen in the flume.

No melt runoff was collected until after 46 hours. C/Co of the initial runoff was 37 indicating salts were being flushed from the ice at a high concentration. It is important to note T_A did not reach 0 ^oC until 142 hours had elapsed. At which point approximately 36 % of NaCl (39 % Na and 42 % Cl) was collected after 0.8 % of the ice melted. After 271 hours, 80 % of NaCl (81 % Na and 87 % Cl) had been concentrated into 9 % of the initial volume and C/Co was reduced to 2.5. Melting was terminated after 387 hours when C/Co was 0.7 and the salt mass removal rate began to peak. Overall, melting resulted in flushing of 100 %

of the NaCl (103 % Na and 110 % Cl, based on EC relationship) mass into 22 % of the initial ice volume. Refer to Appendix 5 for the temperature profiles of the ice during melting.

Figure 2.31 depicts the EC profile from cores taken from the ice remaining after 387 hours. EC generally increased with depth in each ice core. The average EC from the core samples was 0.5 mS/cm, only slightly greater than tap water (0.34 mS/cm) indicating that majority of the salts had been removed. Inspection of the ice structure from the cores revealed the ice was very porous similar to tightly packed pea gravel (Figure 2.32). The porous structure was caused by drainage of the melting salt water.

2.3.10 Freezing and Melting Test 9

A 20,000 mg/L (Co = 26.8 mS/cm) NaCl solution was used for Test 9. Using improved placement methods, the saline solution was frozen into the flume over six freezing events. The first three layers were placed at 0.16 kg/s per metre width (0.098 kg/s) and the remaining three at 0.19 kg/s per metre width (0.12 kg/s). Pumping for each event was pulsed for 2 minutes on and 6 minutes off. Each layer was allowed to solidify a minimum 8 to 10 hours before the next freezing event. The T_A for Test 9 was -15 °C. Ice growth profiles for each freezing event and associated placement volumes can be found in Figure 2.33. An average of 161 L was placed in each layer (Layer 1 not included). Two ice fences were installed to reduce the erosion of slush during pumping (Figure 2.33). A total of 887 L of saline solution (17.74 kg of NaCl) was frozen into the flume. Runoff was collected during layer placement and is included in the melting analysis. Random, interlocking ice platelets formed in the slush during each freezing event.

A summary of the ambient air temperatures during the freezing process can be found in Figure 2.34. The defrost cycle in the cold room caused a short interval temperature spike for each RTD. The dispenser temperature spikes from -15 °C to approximately 0 °C during pumping for each of the six layers. Temperature at the start and end of the flume (120 and 1040 cm) was within 1 °C of the target ambient air temperature of -15 °C. The temperature at 400 cm increased to approximately -13 °C after layer placement and dropped to within approximately -14.5 °C prior to the next layer placement. Refer to Appendix 5 for detailed plots of the temperature profiles from all the RTDs.

Figure 2.35 depicts the EC profile of the ice cores taken after all six layers were frozen. EC was less than 75 % of Co until 920 cm and then increased up to three times Co. Layer 1 generally had the greatest EC compared to the other layers. Unfrozen liquid was encountered as a skim on the ice surface and at the base of the core holes from the dispenser to approximately 640 cm along the flume. EC of the unfrozen liquid was approximately 5 times Co. Inspection of the ice cores revealed individual layers were evident (Figure 2.36). Small inclusions were also visible within the cores. These inclusions were likely entrapped brine because the ice was wet to the touch (Figure 2.36). Coring required less effort than Test 8 therefore the ice was softer.

Melting was induced by slowly increasing T_A daily to 2 °C as described in section 2.2.2. The C/Co (EC based), melt water, salt mass runoff profiles for Test 9 are contained in Figure 2.37. Three data sets are used to represent the salt mass runoff. One set represents the NaCl mass as determined by the EC-NaCl relationship. The remaining two sets represent the individual species Na and Cl (as determined by the EC-analytical relationships) for comparison of the two different relationships. Data collection began after the first increase in temperature (*i.e.* -15 to -10 °C). The left axis corresponds to the C/Co data set. The right axis corresponds to the melt water and salt mass data sets and represents the percentage collected in the runoff of the total available frozen in the flume.

Runoff was generated during freezing, 100 hours before melting was initiated. C/Co of the initial runoff was 6.4 indicating salts were being flushed from the ice at a high concentration. It is important to note T_A did not reach 0 °C until 143 hours had elapsed, at which point approximately 48 % of NaCl (50 % Na and 51 % Cl) was collected after 10 % of the ice melted. After 250 hours, 80 % of NaCl (81 % Na and 84 % Cl) had been concentrated into 27 % of the initial volume and C/Co was reduced to 1.2. Melting was terminated after 494 hours when C/Co was 0.02 and the salt mass removal began to peak. Overall, melting resulted in flushing of 92 % of the NaCl (93 % Na and 96 % Cl) mass into 53 % of the initial ice volume. Refer to Appendix 5 for the temperature profiles of the ice during melting.

Figure 2.38 depicts the EC profile from cores taken from the ice remaining after melting. EC was generally the greatest in the surface layer. The average EC from the core samples was 0.11 mS/cm, less than tap water (0.34 mS/cm) indicating that majority of the salts had been removed. Inspection of the ice structure from the cores revealed the ice was very porous similar to Test 8 (Figure 2.39).

2.3.11 Freezing and Melting Test 10

A 500 mg/L (Co = 1.00 mS/cm) NaCl solution was used for Test 10. Using improved placement methods, the saline solution was frozen into the flume over six freezing events. The first three layers were placed at 0.23 kg/s per metre width (0.139 kg/s) and the remaining three at 0.25 kg/s per metre width (0.15 kg/s). Pumping for each event was pulsed 2 minutes on and 6 minutes off. Each layer was allowed to solidify a minimum 8 to 10 hours before the next freezing event. The T_A for Test 10 was -15 °C. Ice growth profiles for each freezing event and associated placement volumes can be found in Figure 2.40. An average of 153 L was placed in each layer. Two ice fences were installed to reduce the erosion of slush during pumping (Figure 2.40). A total of 911 L of saline solution (0.456 kg of NaCl) was frozen into the flume. Runoff was not collected during layer placement. Random, interlocking ice platelets formed in the slush during each freezing event.

A summary of the ambient air temperatures during the freezing process can be found in Figure 2.41. Data collection began at the start of pumping for layer 1 and continued until after the completion of layer 6. The defrost cycle in the cold room caused a short interval temperature spike for each RTD. The dispenser temperature spikes from -15 ^{o}C to approximately 0 ^{o}C during pumping for each of the six layers. Temperatures from the start and end of the flume (120 and 1040 cm) were within 1 ^{o}C of the target ambient air temperature of -15 ^{o}C. The temperature at 400 cm increased to approximately -12.5 ^{o}C after layer placement and dropped to within approximately -14.5 ^{o}C prior to the next layer placement. Refer to Appendix 5 for detailed plots of the temperature profiles from all the RTDs.

Figure 2.42 depicts the EC profile of the ice cores taken after all six layers were frozen. EC was the greatest in the first core (244 cm) with all layers above Co. EC of the cores generally dropped below Co except for layers 6 and 1. EC then increased above Co at the end of the flume (core 1043 cm). Inspection of the ice cores revealed individual layers were evident. Small inclusions were also visible within the cores. These inclusions may be air voids, entrapped brine or interconnected drainage pathways. Coring required more effort than Test 9 therefore the ice was hard similar to Test 8.

Melting was induced by slowly increasing T_A daily to 2 ^{o}C as described in section 2.2.2. The C/Co (EC based), melt water, salt mass runoff profiles for Test 10 are contained in Figure 2.43. Three data sets are used to represent the salt mass runoff. One set represents the NaCl mass as determined by the EC-NaCl relationship. The remaining two sets represent the individual species Na and Cl (as determined by the EC-analytical relationships) for comparison of the two different relationships. Data collection began after the first increase in temperature (*i.e.* -15 to -10 °C). The left axis corresponds to the C/Co data set. The right axis corresponds to the melt water and salt mass data sets and represents the percentage collected in the runoff of the total available frozen in the flume.

No melt runoff was collected until after 117 hours passed. C/Co of the initial runoff was 102 indicating salts were being flushed from the ice at a high concentration. The T_A did not reach 0 °C until 145 hours had elapsed, at which point approximately 9.5 % of NaCl (8.5 % Na and 8.9 % Cl) was collected after 0.06 % of the ice melted. After 350 hours, 80 % of NaCl (74 % Na and 76 % Cl) had been concentrated into 8 % of the initial volume and C/Co was reduced to 2.3. Melting was terminated after 386 hours due to expiration of laboratory access. C/Co was reduced to 1.89 and the salt mass removal had not yet peaked. Overall, melting resulted in flushing of 86 % of the NaCl (82 % Na and 84 % Cl) mass into 11 % of the initial ice volume. Refer to Appendix 5 for the temperature profiles of the ice during melting. No anomalies were encountered during melting.

Figure 2.44 depicts the EC profile from cores taken from the ice remaining after melting. EC generally increased with depth in each ice core. The average EC from the core samples was 0.3 mS/cm, only slightly less than tap water (0.34 mS/cm) indicating that majority of the salts had been removed. Inspection of the ice structure from the cores revealed the ice was slightly porous and comparatively solid (Figure 2.45). The porous structure was caused by drainage of the melting salt water.

2.3.12 Mass Balance

To ensure the salt concentration and volume measurements were accurate, a mass balance was performed at the completion of melting for Tests 8, 9, and 10.

Salt mass was calculated by multiplying the volume of ice, runoff or remaining ice after melting with the associated salt concentration calculated by the EC-NaCl relationship. The concentration of the remaining ice was based on the average calculated concentration taken from melted ice cores. The mass balance calculations were also completed on individual species Na and Cl using the respective relationships. Concentrations of Na and Cl in the remaining ice cores were based on the actual laboratory analyses. If measurements and calculations were reasonable, the mass of salt in the original produced ice should equal the sum of the salt mass in the runoff and ice remaining after melting. Table 2.2 summarizes the mass balance analyses. In most cases the mass balance was within 15%. The Cl mass balance was within 21 % for Test 8.

2.4 Discussion

The final freeze/thaw process was very effective at separating and concentrating the salts into a smaller volume. The volumes of the purified water and concentrated runoff and associated NaCl concentrations for Tests 8 through 10 after 80 % NaCl removal and at the end of each experiment, are summarized in Tables 2.3 and 2.4, respectively. In Test 8 (Co = 3,000 mg/L), 785 L of purified ice (91 %) had a NaCl concentration of 720 mg/L (24 % of Co) after 80 % removal. At thaw termination, all of the NaCl was removed leaving 673 L of purified ice (78 %). In Test 9 (Co = 20,000 mg/L), 644 L of purified ice (73 %) had a NaCl concentration of 5530 mg/L (28 % of Co) after 80 % removal. At thaw termination, NaCl concentration was reduced to 3550 mg/L (17 % of Co) in 416 L of purified ice (47 %). In Test 10 (Co = 500 mg/L), 840 L of purified ice (92 %) had a NaCl concentration of 110 mg/L (22 % of Co) after 80 % removal. At thaw termination, NaCl concentration was reduced to 77 mg/L (15 % of Co) in 810 L of purified ice (89 %). Removal efficiencies are expected to be greater in the field because thawing in the field is generally slower than in the laboratory (Gao, 1998).

The freezing mechanism during the laboratory experiments was considerably different from the expected conceptual model based on Otto's (2002) work. Instead of freezing as thin, successive, solid layers, the saline solution only partially froze as slush. The slush, comprised of vertical platelet ice crystals, grew from the ice base as the saline solution cooled. The platelets then reached the water-air surface within minutes of formation. The development of vertical platelet slush was similar to the slush produced in ground icing experiments conducted by Schohl and Ettema (1986). They studied the growth of ground icings called Naleds in refrigerated flume experiments, comparable to the present set up. Otto's (2002) model assumed the ice crystals would not grow throughout the entire flow field, but rather only on the frozen surface below the liquid surface. He also assumed the flowing fluid would only contain brine and travel as laminar flow across the ice surface. Due to the presence of slush ice, flow actually occurred through the porous ice. The density and viscosity of the flowing fluid also changed due to the concentration of salts as the water froze and is not accounted for in Otto's (2002) model. Additionally, as the voids in the slush decreased, flow was retarded forcing the upstream thickness to increase, increasing the head behind the leading edge of the slush. This build up of head subsequently lead to breakthrough, erosion, and channeling in the slush as seen in Tests 1 through 7. With flow in narrow, deep channels, heat removal and consequently ice production was significantly reduced. Therefore, the actual flow rate that could maintain a stable flow field or the *significant length* for a given set of variables as described in Otto's (2002) model could not be reproduced.

Brine drainage during melting proved to be more efficient at concentrating salts than the freezing process. This was partially due to the problems encountered with the freezing process, and the fact that melting was conducted much slower than freezing. Furthermore, as the slush mixture cooled, the brine became more concentrated, which then developed vertical channels through the underlying ice permitting vertical drainage to the base of the ice mass. Evidence of unfrozen concentrate at the base of the ice was found in Test 9 during coring.

Redistribution and concentration of salts to the ice grain boundary is likely the reason for production of eutectic salt crystals and unfrozen liquid found on the ice surface for Tests 3, 5, and 9.

The initial salt concentration of the saline solution did not significantly affect the ice production rate in the tests conducted. The daily ice production rates for Tests 8 (3000 mg/L) and 9 (20,000 mg/L) were 845 and 790 L/day per m width (with a flow path of 12 m), respectively. An order of magnitude difference in concentration resulted in only 7 % difference in the daily production rate, at an ambient temperature of -15 °C. The production rate is expected to drop at warmer temperatures and increase for colder temperatures. The change in ice production rate as a function of temperature was not determined in this study. The production rate is not likely to increase with an increase in flow rate, because erosion and channeling will likely occur with increased flow rate. Pilot scale, field tests could be used to optimize ice production rates based on the ambient conditions, where the objective is to freeze the maximum volume possible during the winter months.

Initial salt concentration did affect the timing of runoff. When the initial concentration was 20,000 mg/L (Test 9) at -15°C, the concentrated brine drained more readily at temperatures less than 0°C than when Co was 3,000 mg/L (Test 8).

The ice production rate may also have been affected by the flume geometry. Erosion channels may have been prematurely initiated due to the flume shape. During the experiments, the flow front advanced just beyond the bend in the flume and stopped. The bend may have slowed the flow enough to allow more heat removal and increase the density of the slush. Flow would then be retarded, leading to thickening of the slush, the build up of head, and eventually development of erosion channels. If the front had not stopped just beyond the bend, more saline solution may have been added to the flume before the critical slush thickness was reached and channelling started.

The salt mass balance calculated on the final three successful experiments did not have complete closure. More than 100 % recovery was calculated for NaCl, Na, and Cl for Test 8 which is theoretically not possible, so is likely due to measurement and calculation errors. Mass and volume measurements were based on grab samples collected during melting leading to averaging of the actual values between measurements. Additionally, due to low concentrations in the final runoff and in the remaining ice cores, small analytical errors may lead to larger errors in the mass calculations. In Test 9, 92 % of the NaCl was recovered. Leaks in the flume joints may have contributed to the loss of mass in addition to the measurement errors. The low concentrations in Test 10 may have contributed to the error in the mass balance. In all tests, the majority of the species were within 10 % recovery, therefore, measurements of EC and volume as well as calculations of salt concentration were reasonably accurate.

2.4.1 Limitations of Test Method

The final freeze/thaw method proved to be quite effective at concentrating salts into small volumes in a laboratory scale setting. There are some inherent issues with scaling up the process to the field. Emulating the layer placement will be crucial. The requirement to use pulse flow may be an artifact of the narrow, U-shaped flume geometry. Wide, unobstructed flow paths in the field may allow for continuous flow until the critical slush thickness is reached. Dispensing the saline solution in thin layers is also vital to prevent channeling and short circuiting. The use of ice fences to reduce slush erosion may be required at the field level. Ultimately, the goal is to place and freeze as much saline solution as possible during the winter months. Due to the potential for runoff during freezing conditions, the collection system will require appropriate design measures to combat freezing. Climate will also affect the success of the process. Insufficient freezing conditions from warm winters reduce the volume of saline solution that can be frozen. Snow fall may also affect the freezing process. Snow cover insulates the ice, decreasing the heat removal to the atmosphere thereby reducing the freezing rate (Ashton, 1980). The above issues will be addressed in the following chapter on the design of a field scale treatment system.

2.5 Summary and Conclusions

Oil sand mine operators facing increased production rates, cost and disturbance associated with limited storage capacity and high treatment costs for waste water are looking to alternative methods to reduce costs. The research was designed to investigate the feasibility of trickle freeze separation for the concentration of salts from salt contaminated water. Research objectives included validating a freeze separation mathematical model, investigating the influence of the variables on freezing, and determining the degree of salt separation achieved during the freeze separation process. All of the objectives in the study were met leading to the following conclusions:

- The laboratory experiments have shown that the freezing process assumptions Otto (2002) used in developing his model for trickle freeze separation did not agree with the experimental observations. The observed mechanism of freezing was quite different therefore Otto's (2002) model is invalid for trickle freeze separation of saline water in this fashion.

- Initial salt concentration of the saline solution did not significantly affect the ice production rate. The daily ice production rates for 3000 mg/L and 20000 mg/L NaCl solutions were 845 and 790 L/day per m width (with a flow path of 12 m), respectively.

- Production of slush and subsequent channeling hindered the freeze separation process. Melting actually proved to be more effective at concentrating salts than the freezing process.

- Satisfactory removal of salt was achieved after melting of the produced ice. For source waters with 3000 mg/L (NaCl) or less, 80 % removal of salts was possible after 9 % of the produced ice melted. For source waters with higher concentrations (20,000 mg/L), 80 % removal was possible after 27 % of the produced ice melted.

Freeze separation can offer many advantages for separation of salts over conventional treatment methods. Freezing requires approximately 15 % of the energy needed to evaporate the same mass of water, and the local climate can be used for freezing and thawing. Existing mine structures such as ponds may be utilized for storage and ice containment. By producing a small amount of highly concentrated brine solution from a large, diluted source, freeze separation reduces the volume of waste water requiring further treatment. The purified melt water may also be reused in the extraction and upgrading process, reducing the demand for fresh, imported water. Pulse-trickle freeze separation can provide an environmentally sustainable treatment alternative for the oil sands escalating waste water volumes.

2.6 Figures

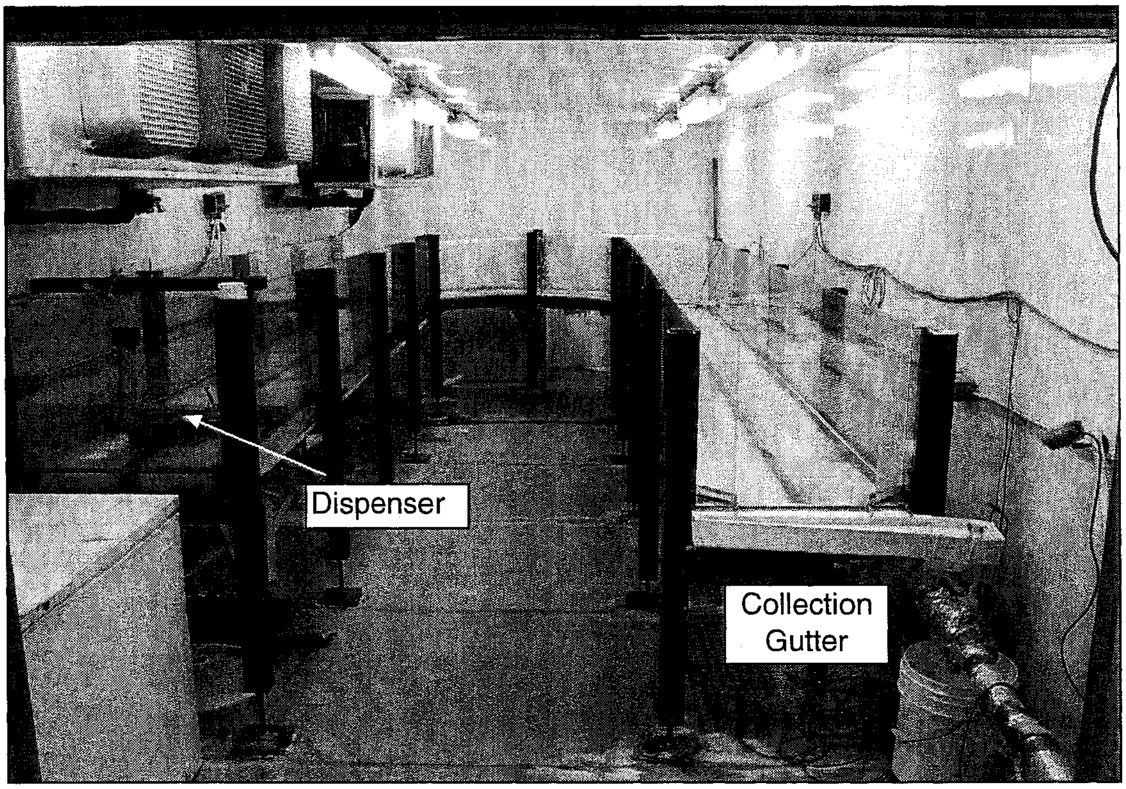


Figure 2.1 Freezing flume in the cold room.

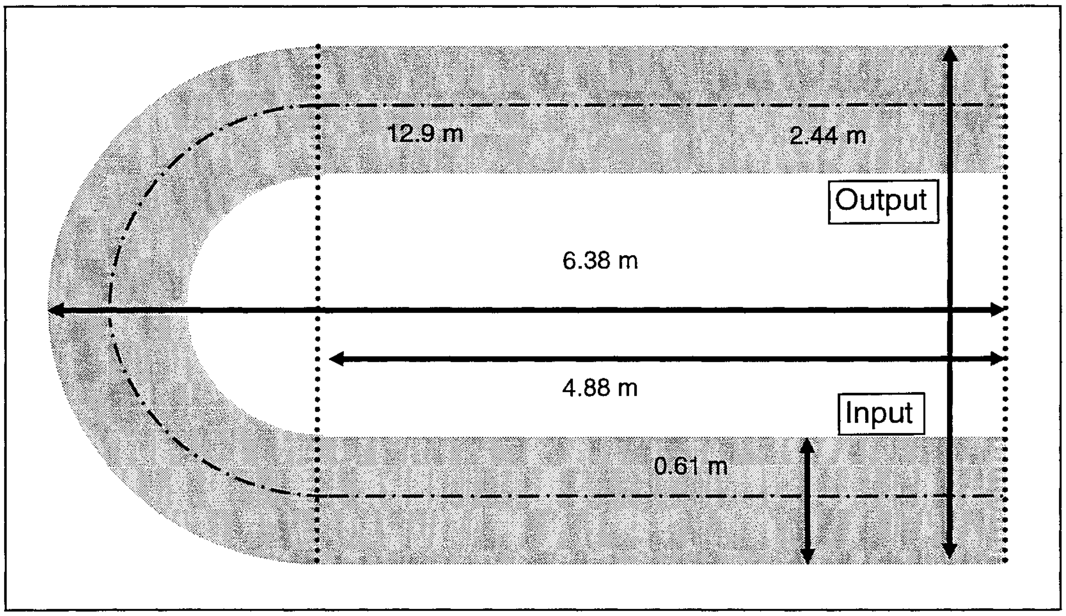


Figure 2.2 Plan view of the freezing flume.

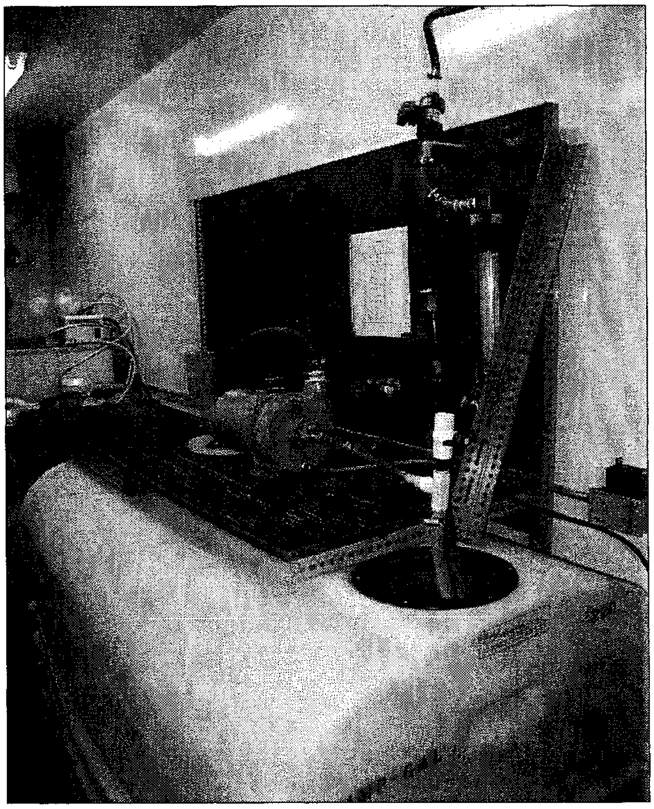


Figure 2.3 Saline storage tank and pumping system.

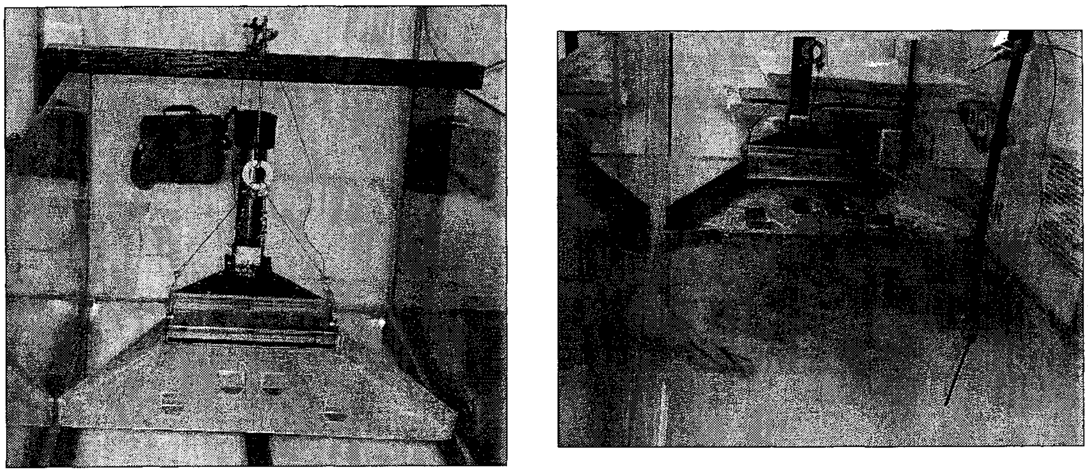


Figure 2.4 Saline solution dispenser shown prior to and during pumping into the flume.

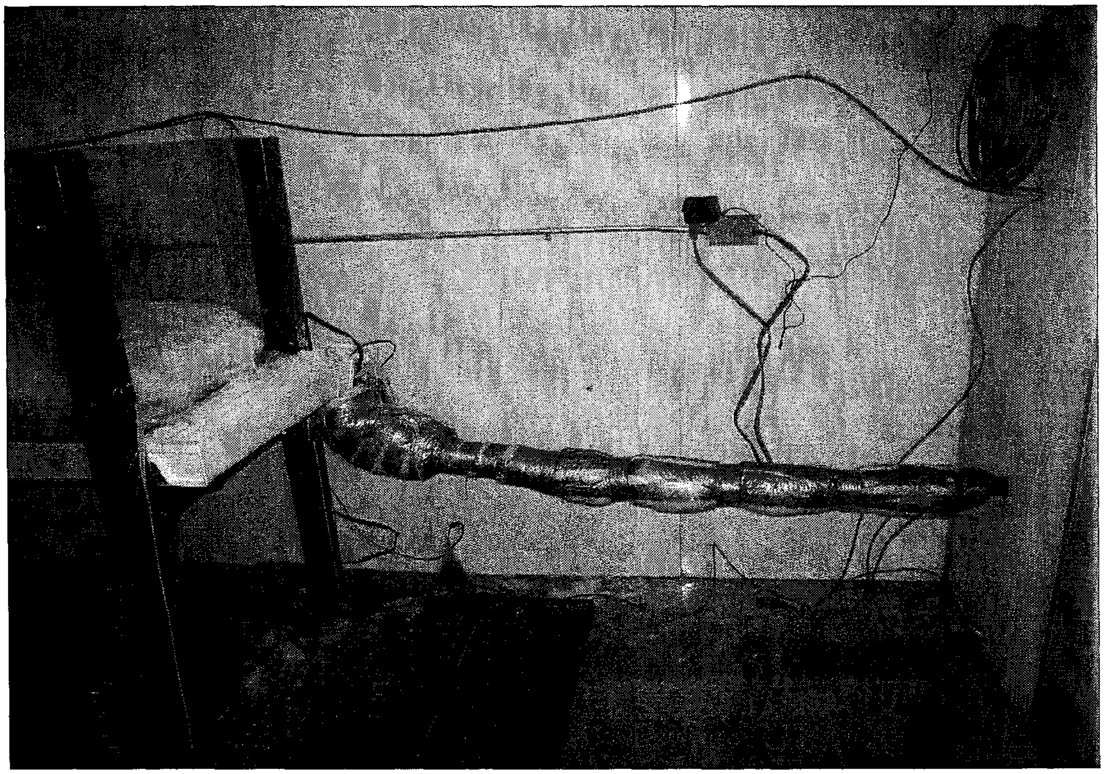
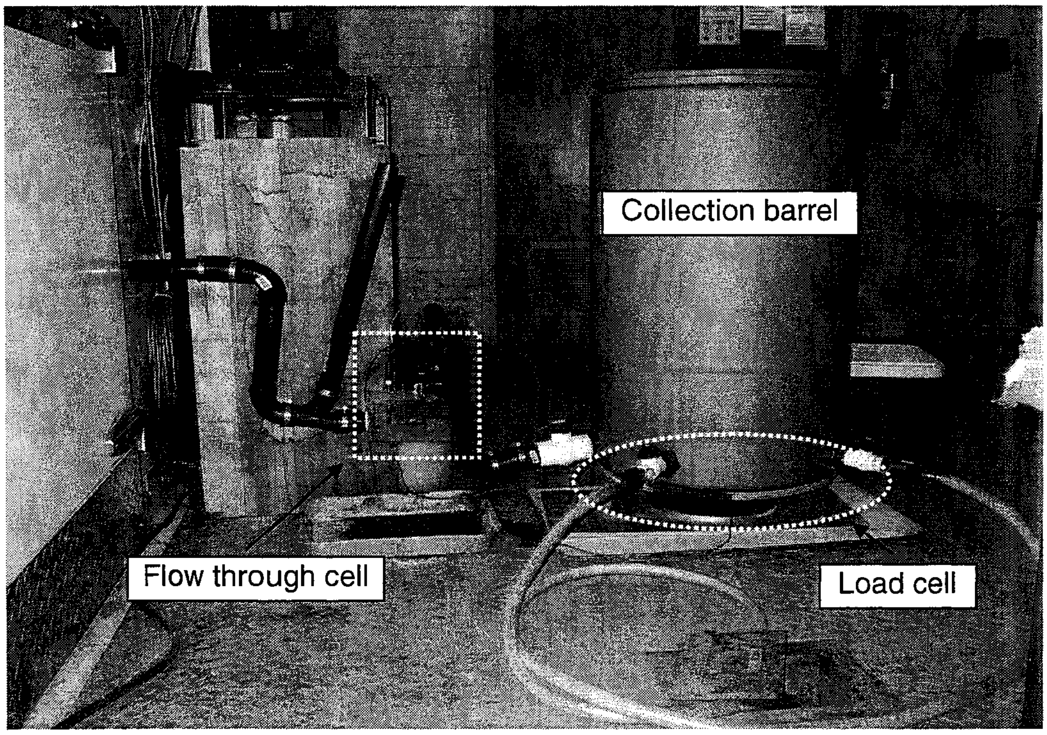


Figure 2.5 Collection gutter and insultated pipe to convey runoff out of the cold room.



Figrue 2.6 Flow through cell and collection barrel .

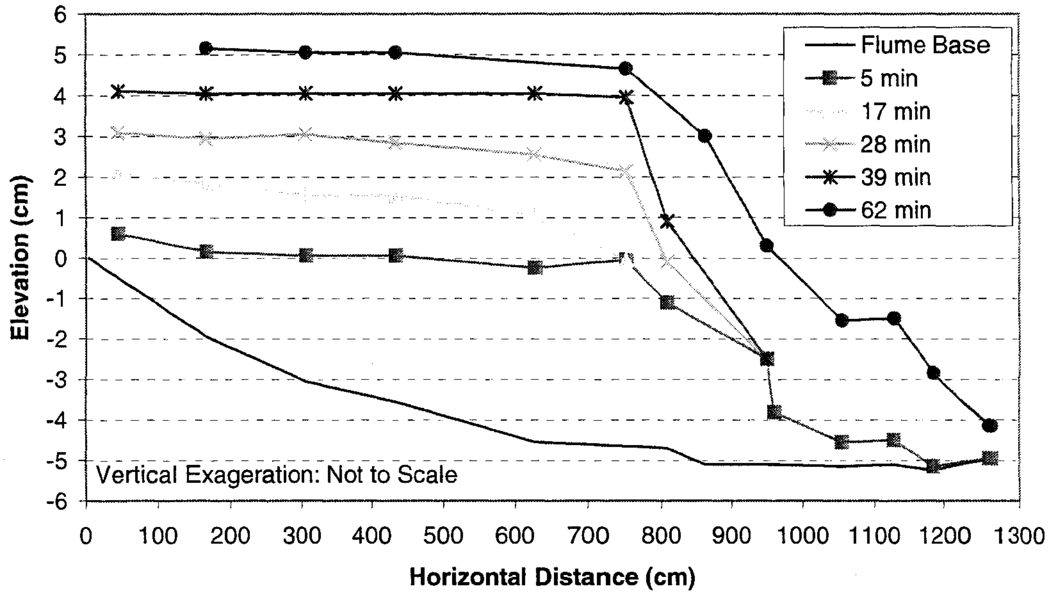


Figure 2.7 Ice growth profile during pumping (0.16 kg/s m) for freezing Test 1 (500 mg/L NaCl) at -30 °C ambient temperature.

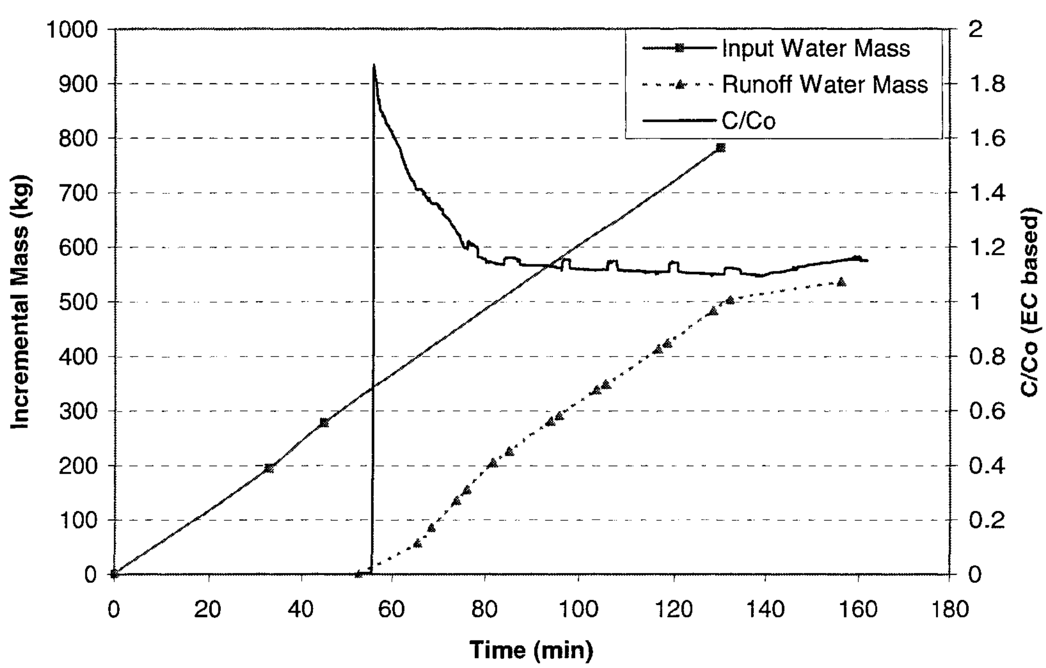


Figure 2.8 Summary of salt water mass input, runoff water mass collection and relative concentration (C/Co) during pumping (0.16 kg/s m) for Test 1 (500 mg/L NaCl).

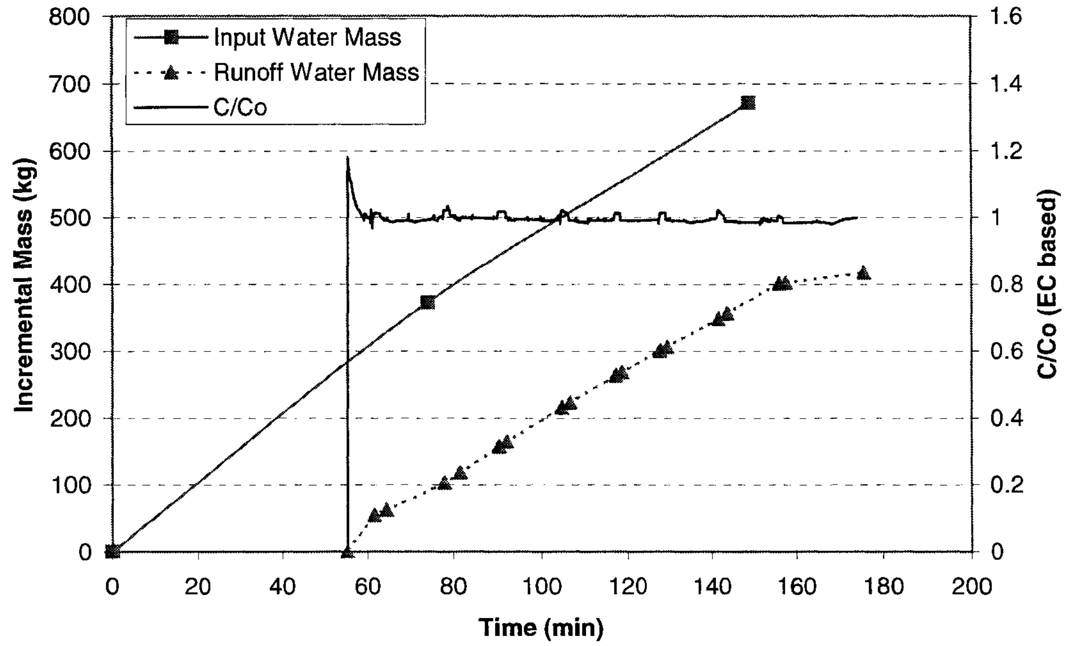
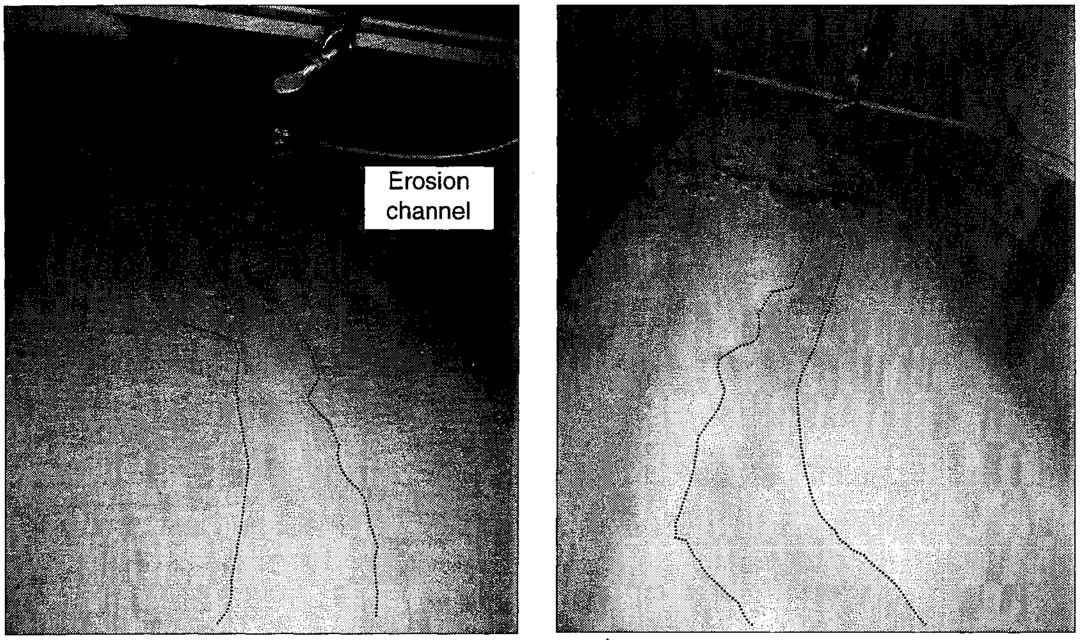


Figure 2.9 Summary of salt water mass input, runoff water mass collection and relative concentration (C/Co) during pumping (0.14 kg/s m) for Test 3 (22800 mg/L NaCl).



a. b.

Figure 2.10 Erosion channels formed in the produced ice from during Test 3 (looking up gradient along the flume from 950 cm to 750 cm).
a. Initial channel development
b. Channel near completeion of test

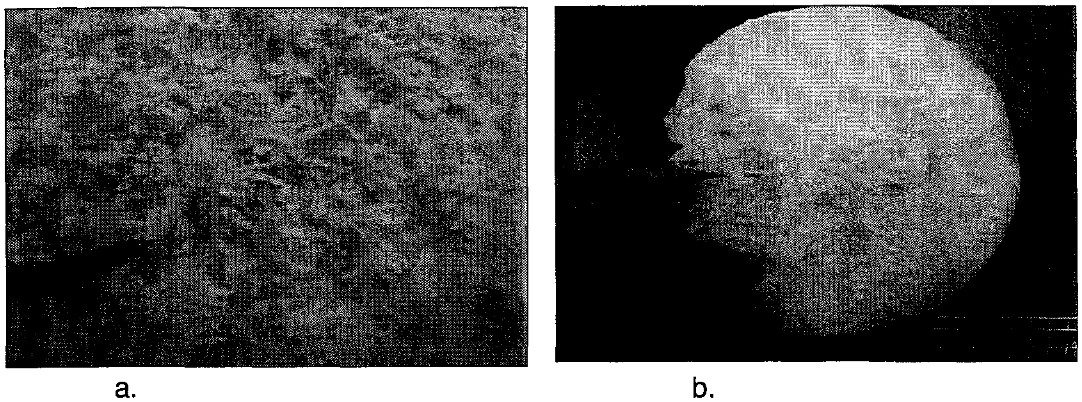


Figure 2.11 a. White hydrohalite crystals found on the final ice surface of Test 3 (-30 °C), 12 hours after completion;
b. White hydrohalite crystals found within the porous ice core from Test 3. Also note the orientation of the platelet arrangement of the ice crystals.

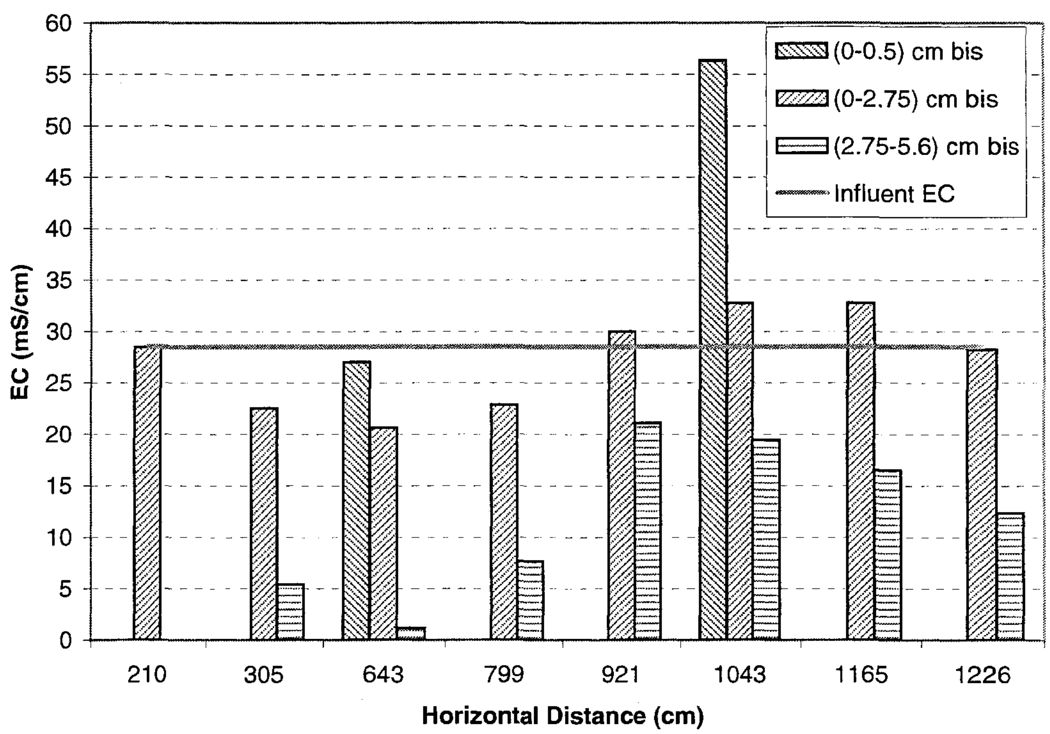


Figure 2.12 Ice core electrical conductivity profile from produced ice for Test 3. Depth intervals are in cm below the ice surface (cm bis).

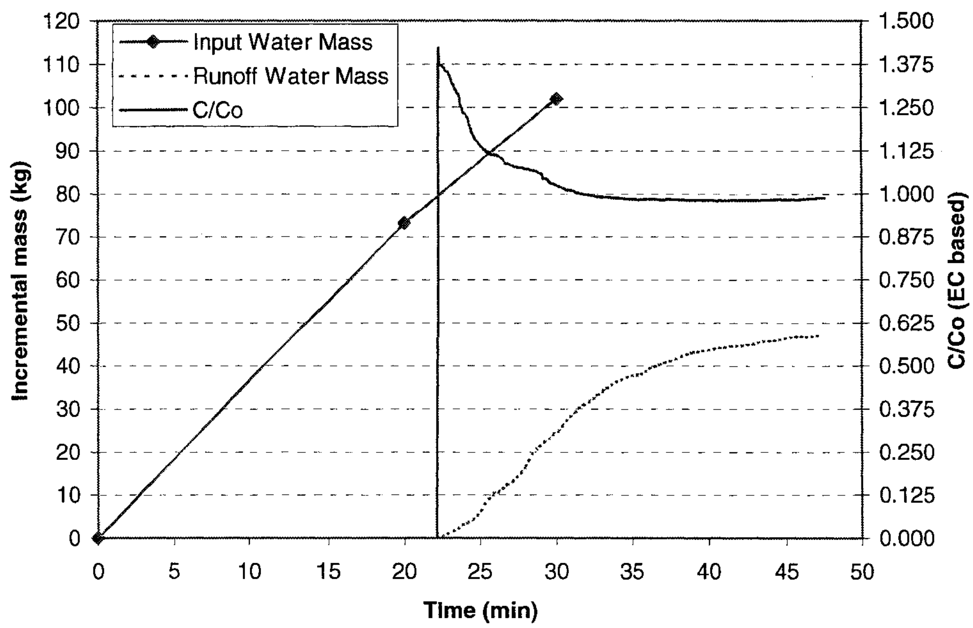


Figure 2.13 Summary of salt water mass input, runoff water mass collection and relative concentration (C/Co) during pumping (0.09 kg/s m) for Test 4 (20000 mg/L NaCl).

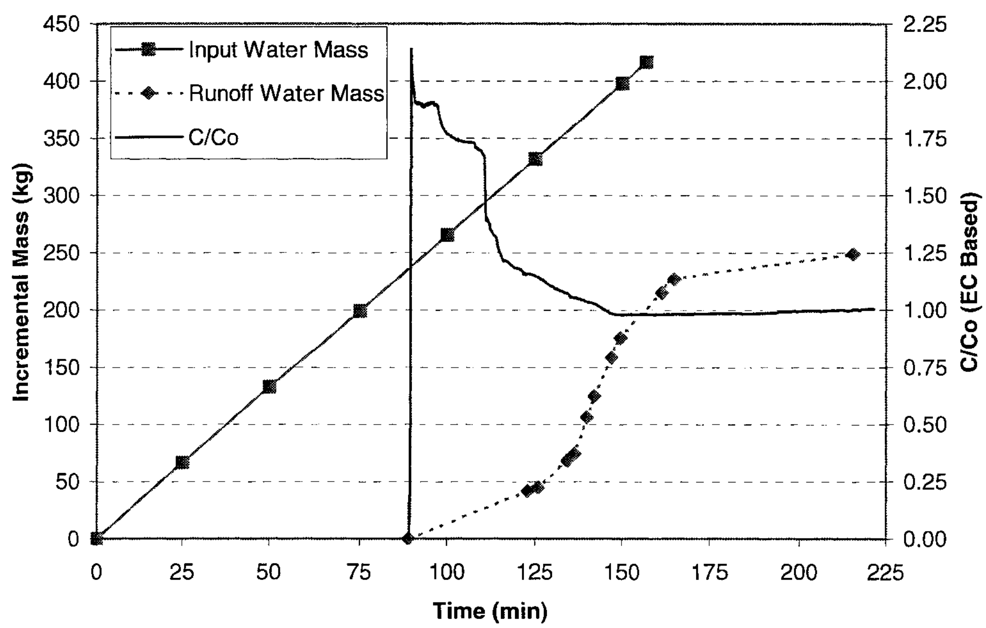


Figure 2.14 Summary of salt water mass input, runoff water mass collection and relative concentration (C/Co) during pumping (0.074 kg/s m) for Test 5 (20000 mg/L NaCl).

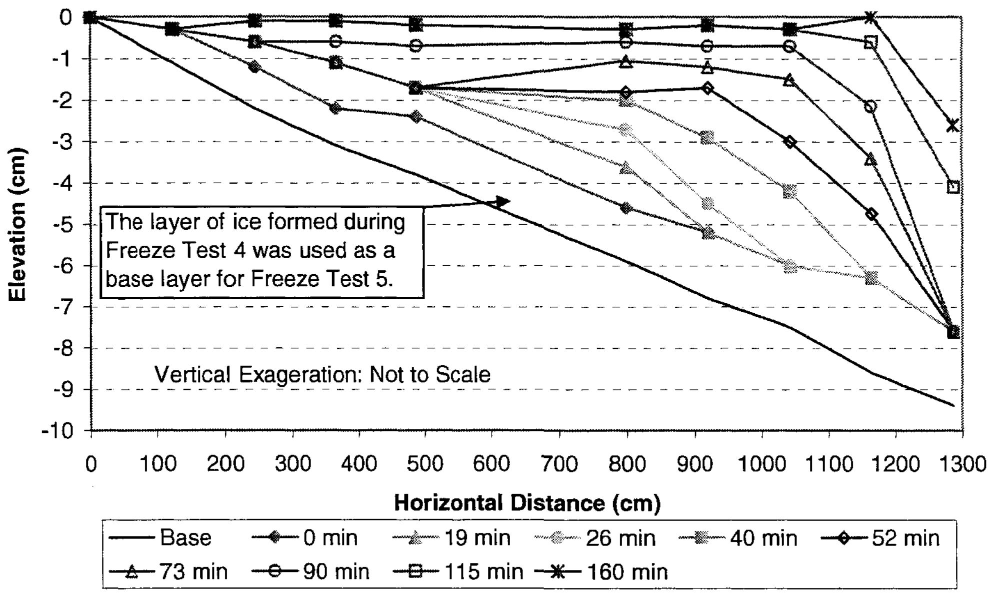


Figure 2.15 Ice growth profile during pumping (0.074 kg/s m) for freezing Test 5 (20000 mg/L NaCl) at -15 °C ambient temperature.

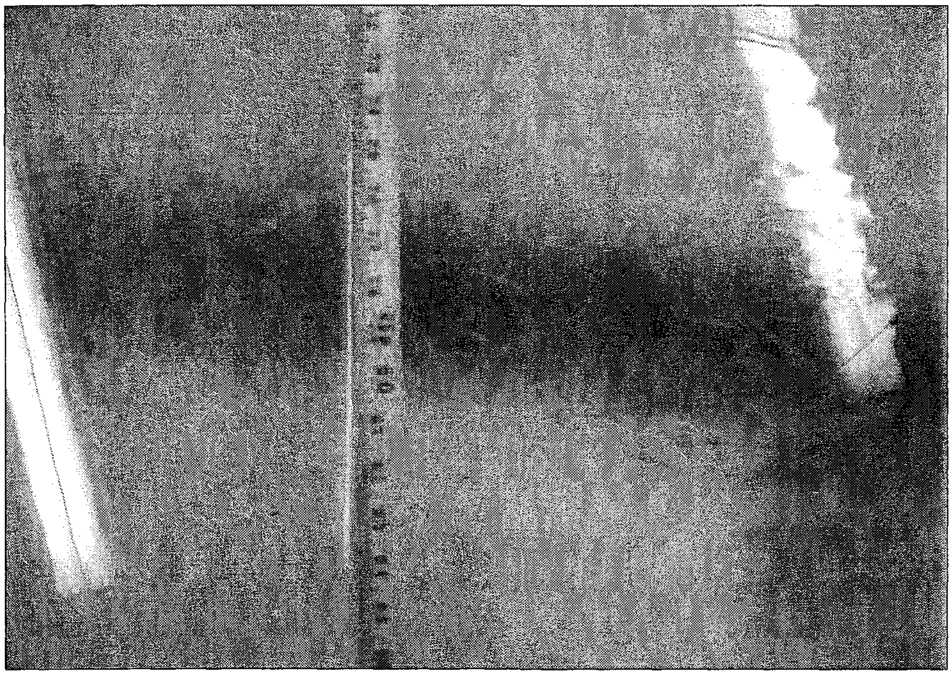


Figure 2.16 Vertical platelet ice crystals forming in the saline slush/water mixture during pumping for Test 5.

Figure 2.17 Erosion channels forming under the prodcued ice during Test 5 (looking upgradient along the flume from 850 cm to 750 cm).

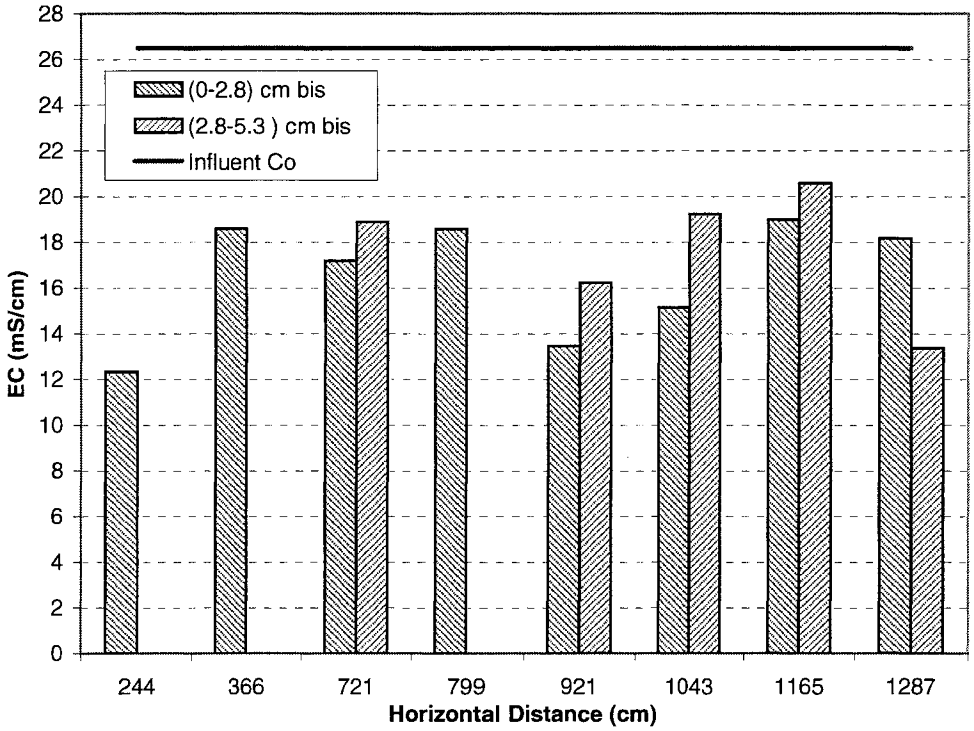


Figure 2.18 Ice core electrical conductivity profile from produced ice for Test 5. Depth intervals are in cm below the ice surface (cm bis).

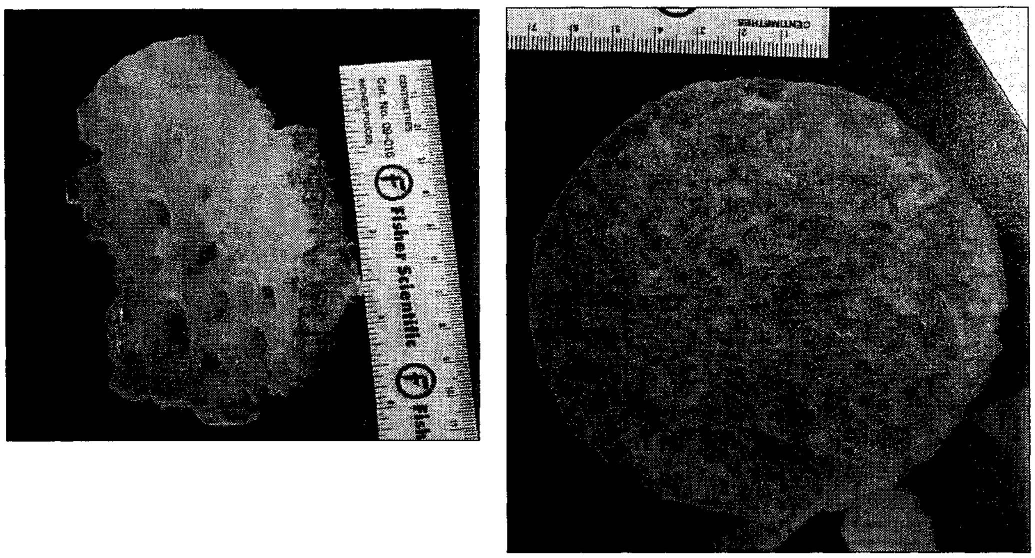


Figure 2.19 Ice cores from Test 5 depicting the porous nature of the ice.

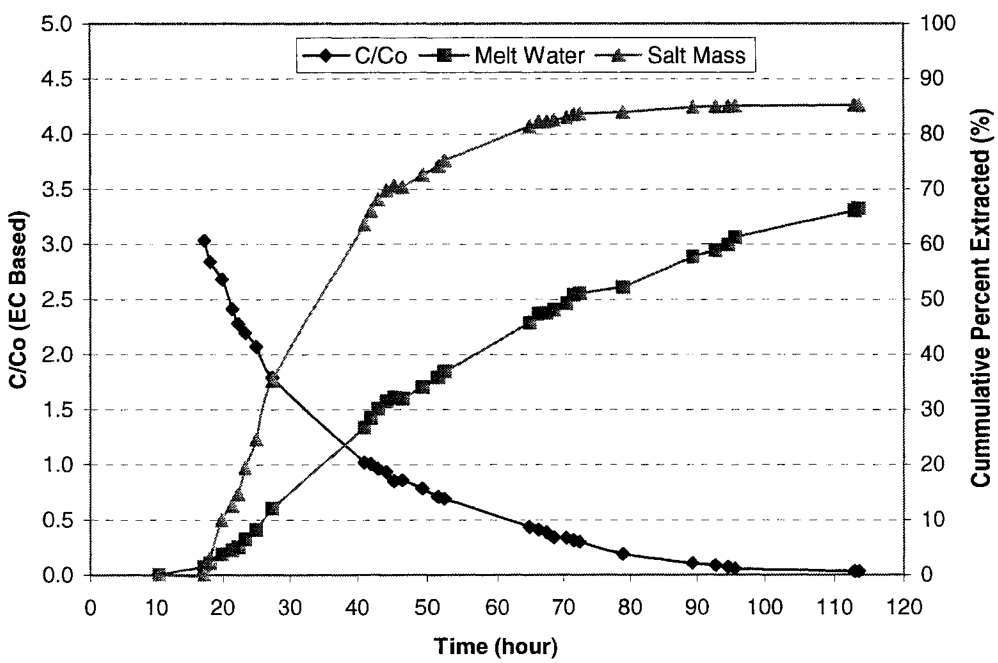


Figure 2.20 Cummulatvie percent extracted of sodium chloride and melt water, and relative concentration (C/Co) during melting for Test 4/5 ice (20000 mg/L NaCl).

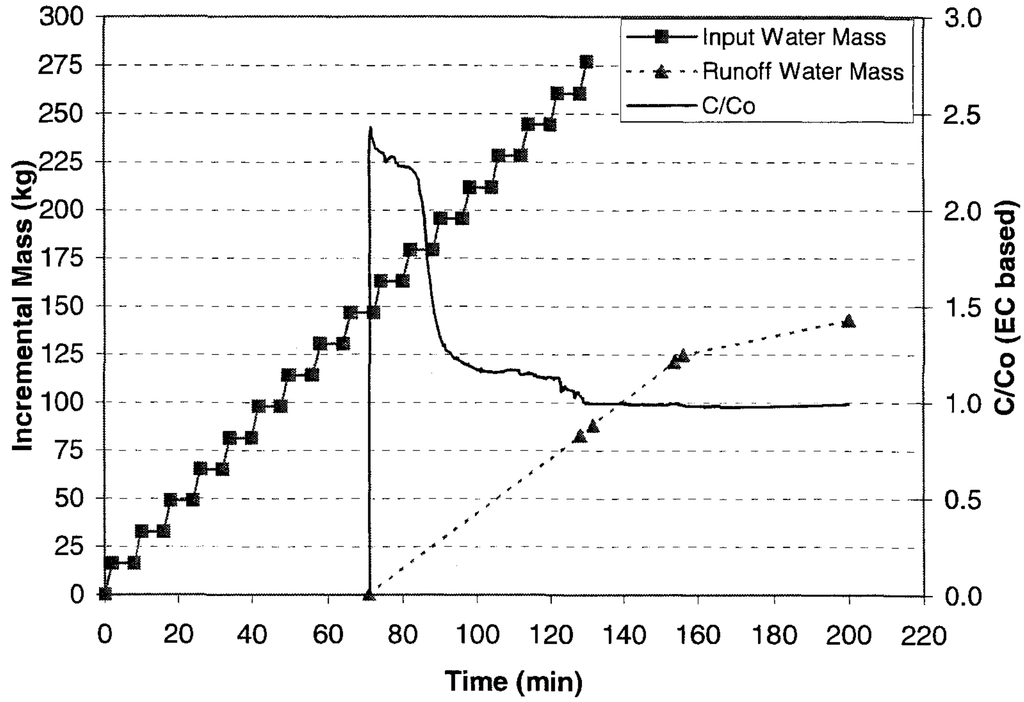


Figure 2.21 Summary of salt water mass input, runoff water mass collection and relative concentration (C/Co) during pulsed pumping (0.22 kg/s m) for Test 7 (2000 mg/L NaCl).

Figure 2.22 Vertical platelet ice crystals forming in the saline slush/water mixture during pumping of Test 7.

Figure 2.23 Plan view of saline solution draining from the slush and ice evident by the air bubbles forming under the ice surface.

Figure 2.24 Ice core from Test 7 depicting the porous nature of the ice.

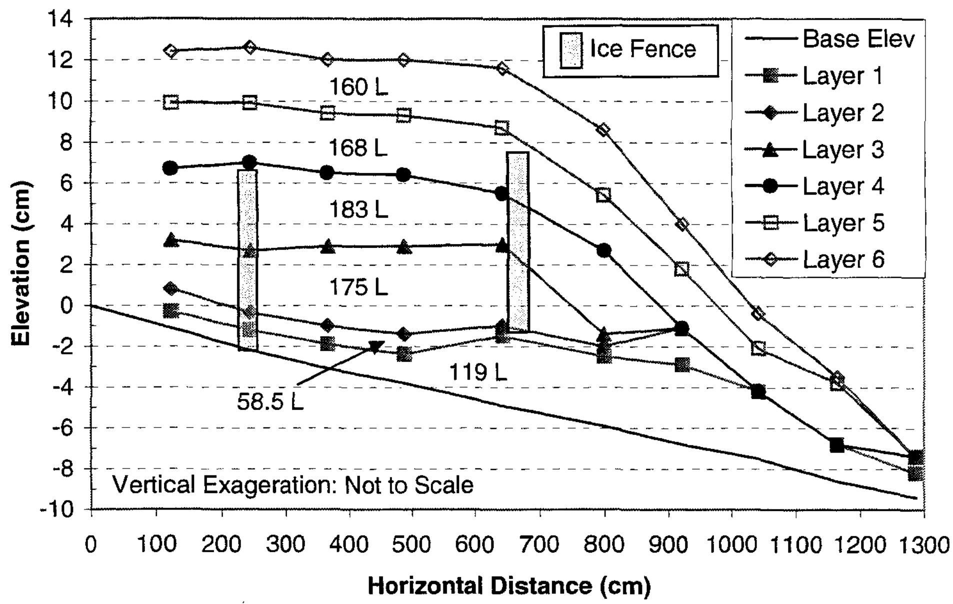


Figure 2.25 Summary of volume frozen and associated ice elevation for each freezing event in Test 8 (3000 mg/L).

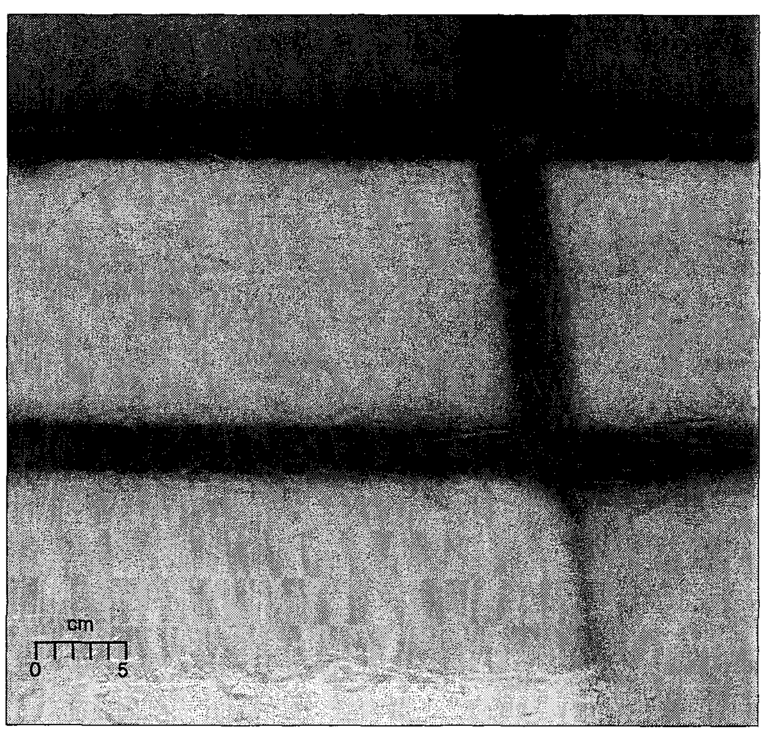


Figure 2.26 Vertical ice platelets forming in the slush during layer placement for Test 8 (3000 mg/L).

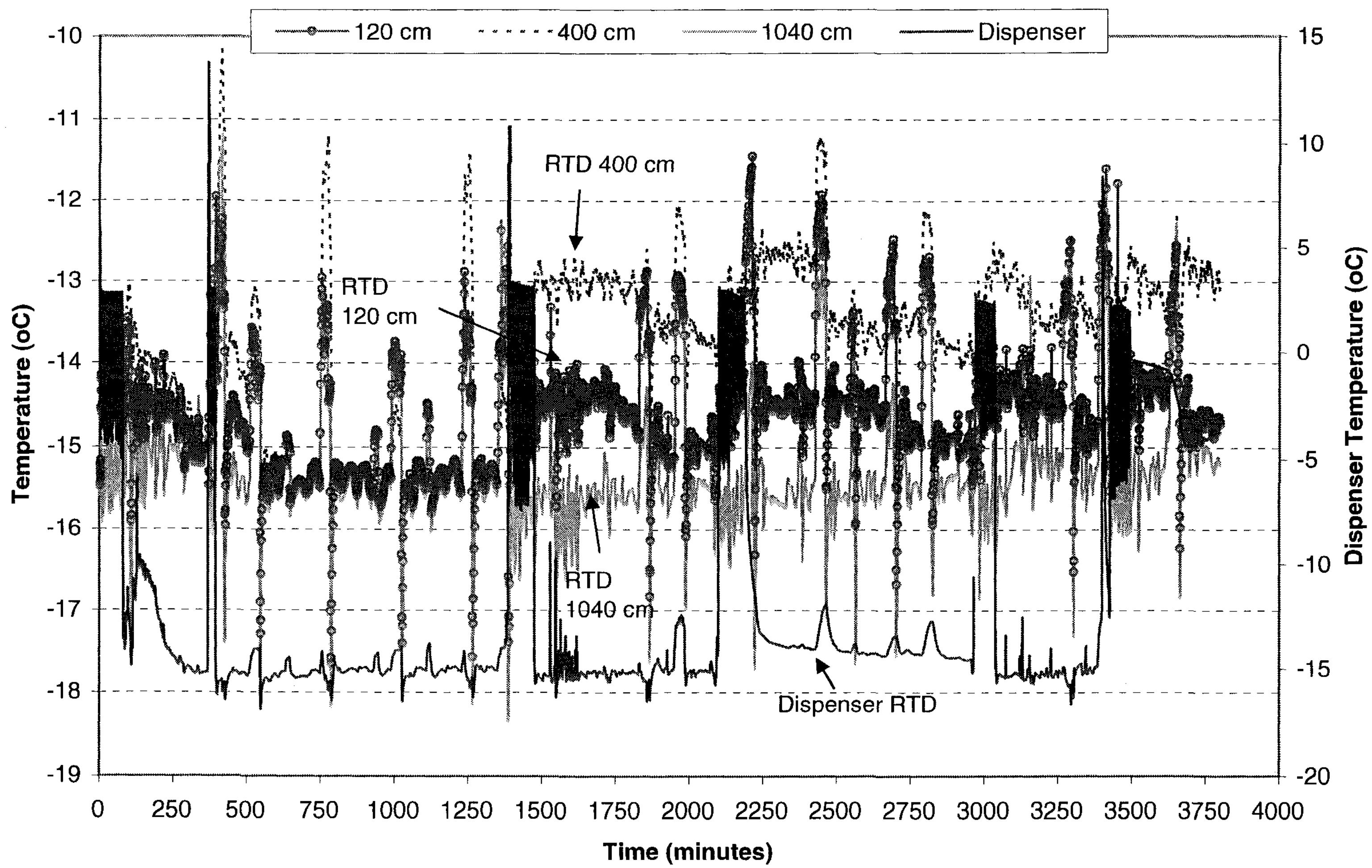


Figure 2.27 Flume temperatures during freezing for Freeze Test 8.

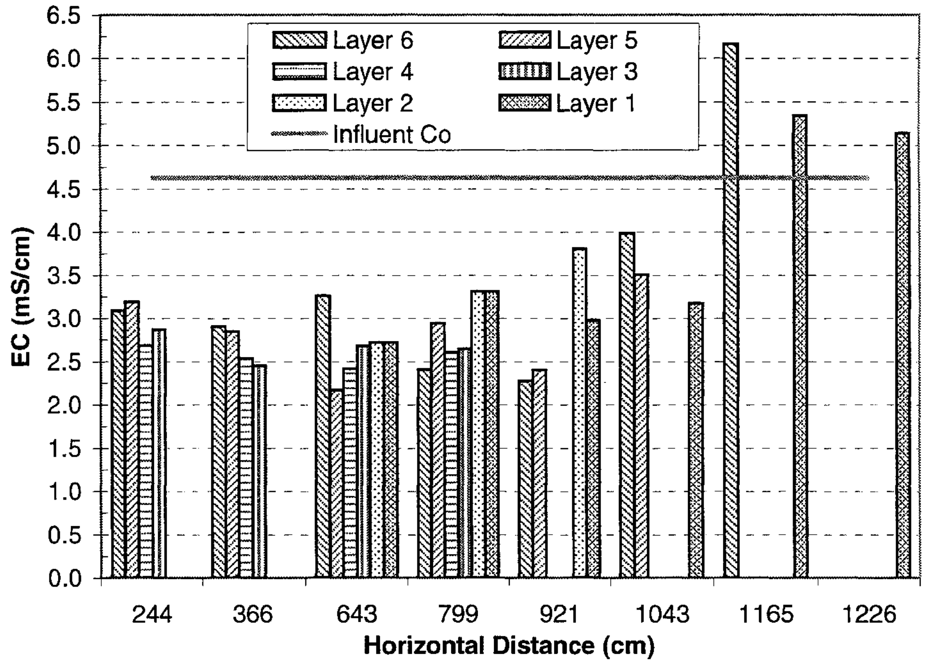
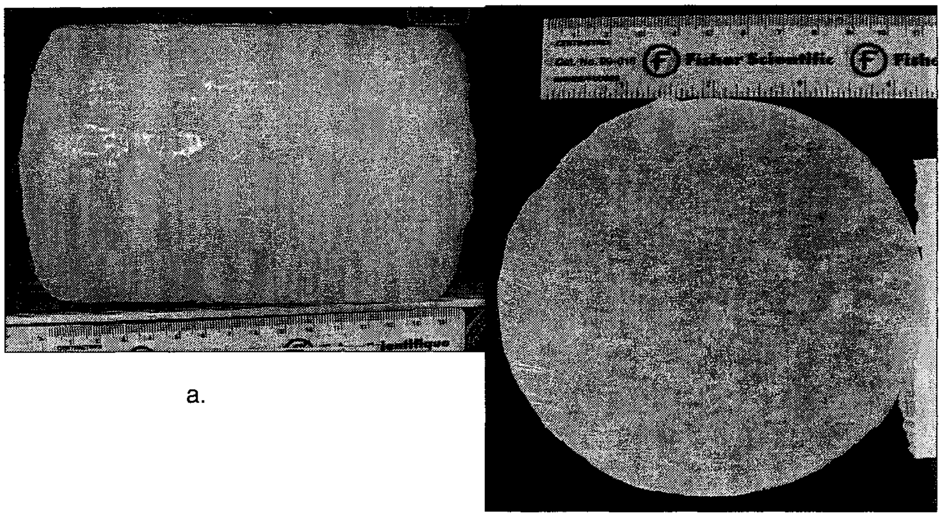


Figure 2.28 Ice core electrical conductivity profile from produced ice prior to thaw for Test 8 (3000 mg/L). Depth intervals correspond to placement layers.



a.

b.

Figure 2.29 a. Side profile of an ice core (799 cm) from Test 8. Note the individual layers that are evident.
b. Small inclusions trapped within the ice core.

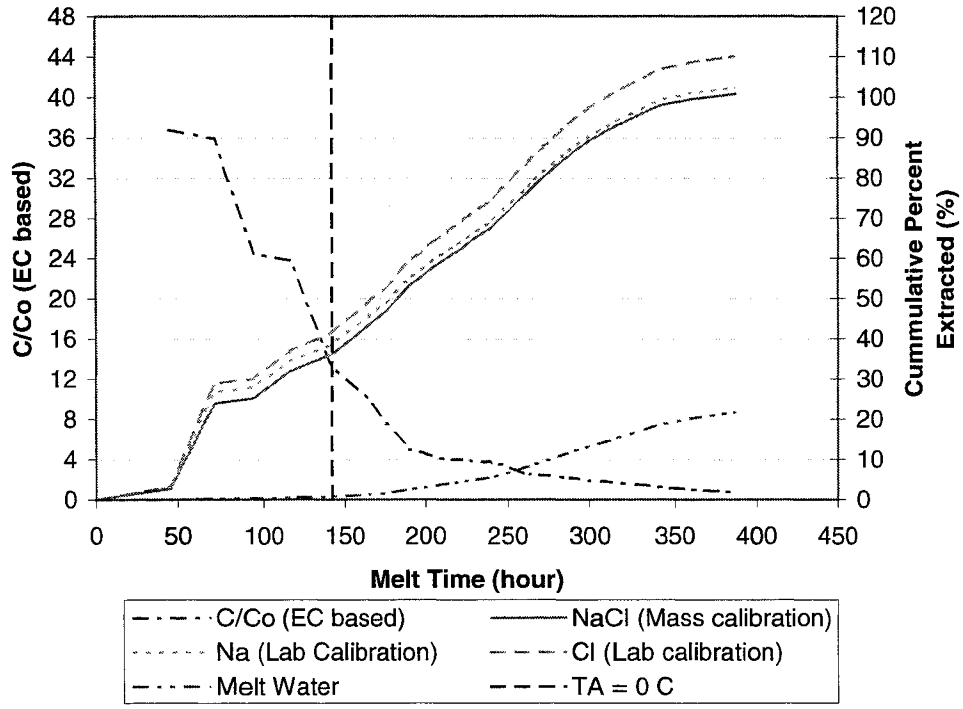


Figure 2.30 Cummulative percent removed of sodium chloride and melt water and relative concentration (C/Co) during melting of Test 8 ice (3000 mg/L NaCl).

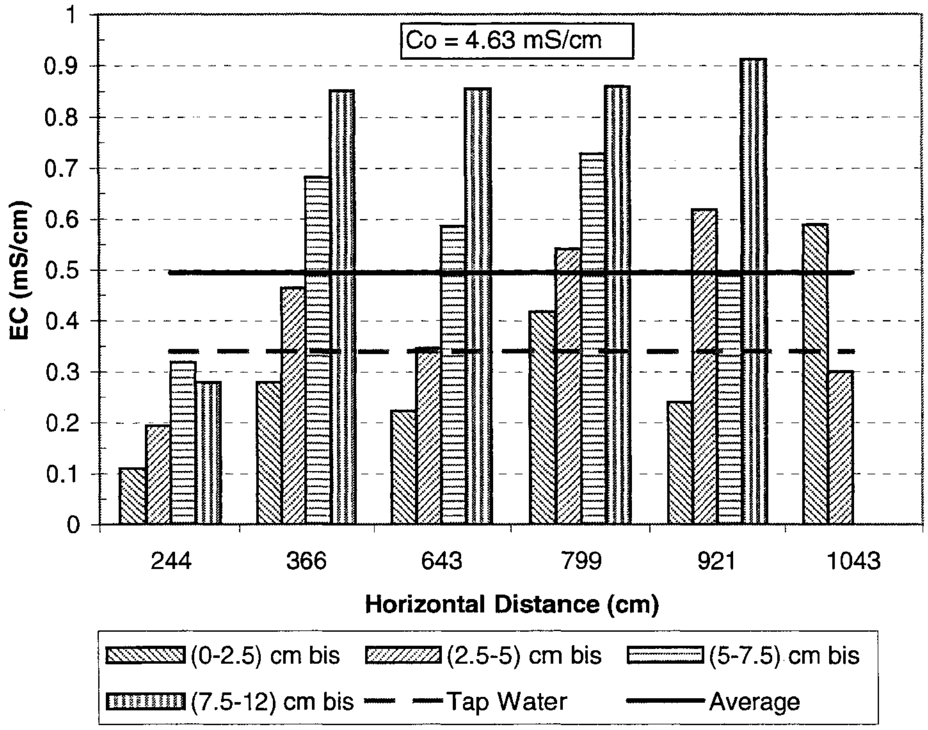
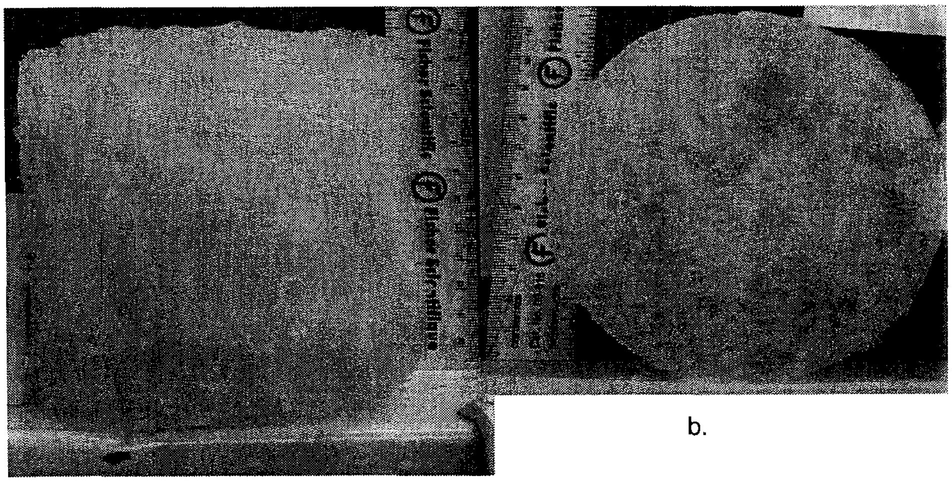


Figure 2.31 Ice core electrical conductivity profile from ice remaining after termination of melting for Test 8. Depth intervals are in cm below the ice surface (cm bis).



a.

b.

Figure 2.32 a. Side profile of an ice core (243 cm) taken after termination of melting from Test 8.
b. Porous structure of the ice core.

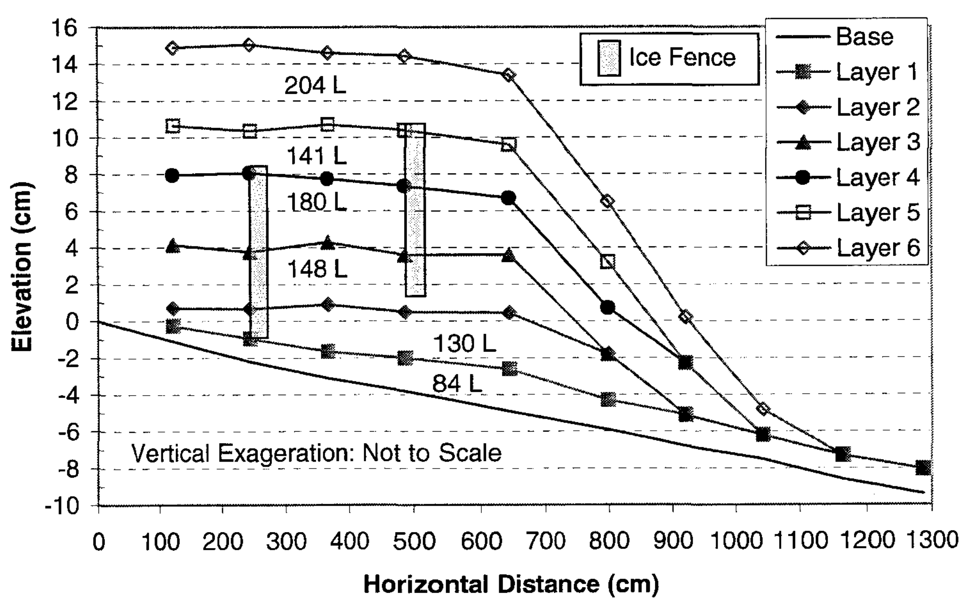


Figure 2.33 Summary of volume frozen and associated ice elevation for each freezing event in Test 9 (20000 mg/L).

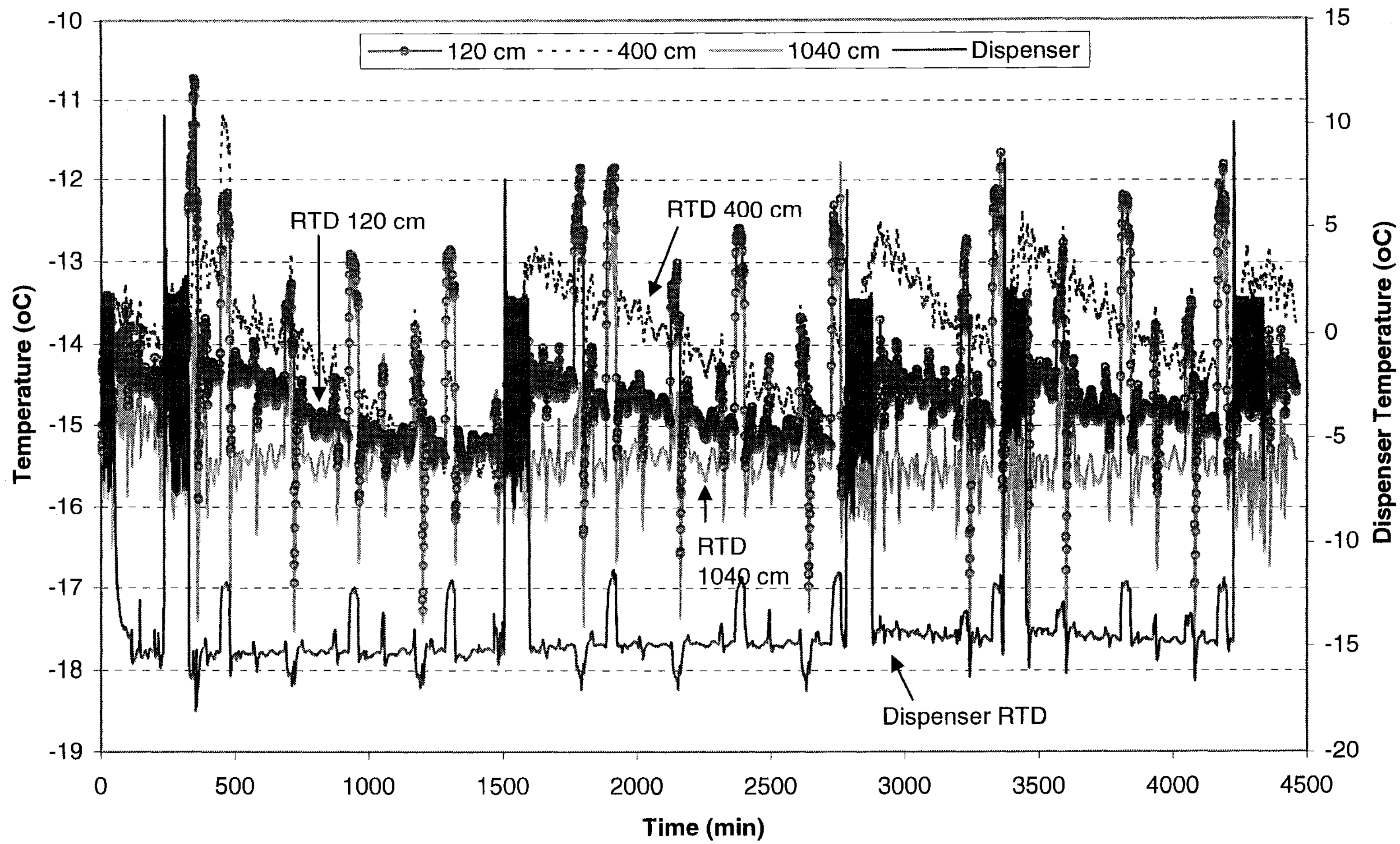


Figure 2.34 Flume temperatures during freezing for Freeze Test 9.

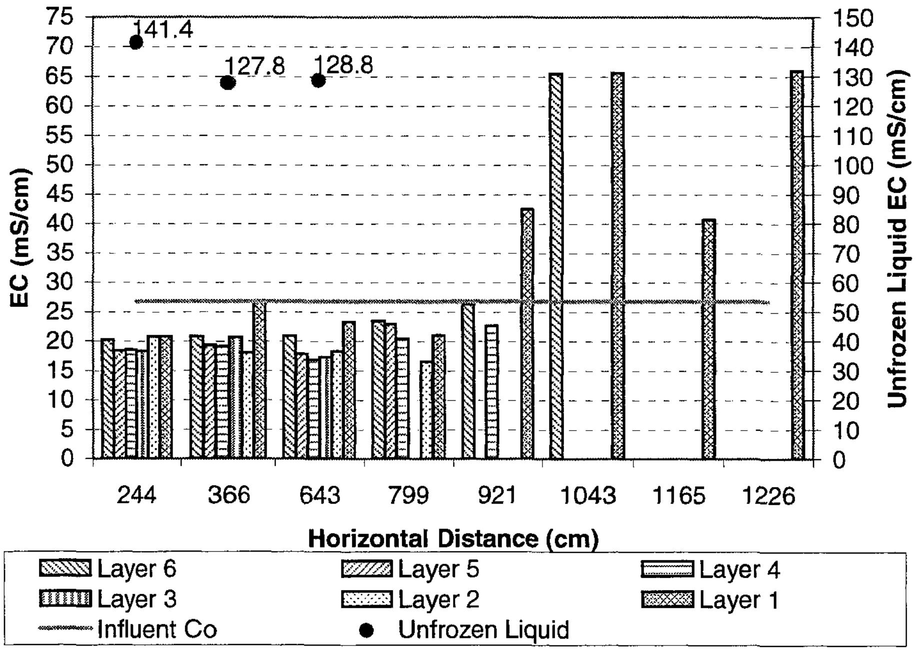
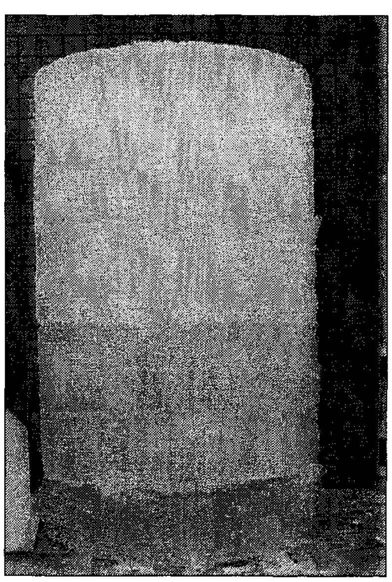
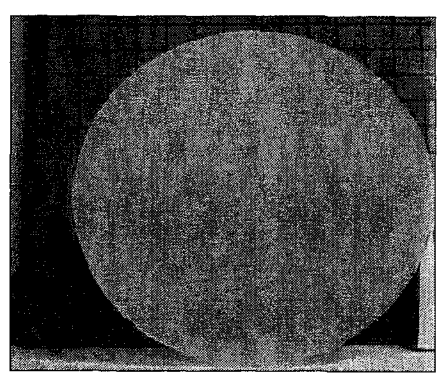


Figure 2.35 Ice core electrical conductivity profile from produced ice for Test 9 (20000 mg/L). Depth intervals correspond to placement layers.



a.



b.

Figure 2.36 a. Side profile of an ice core (1043 cm) from Test 9. Note the individual layers that are evident.
b. Small inclusions trapped within the ice core.

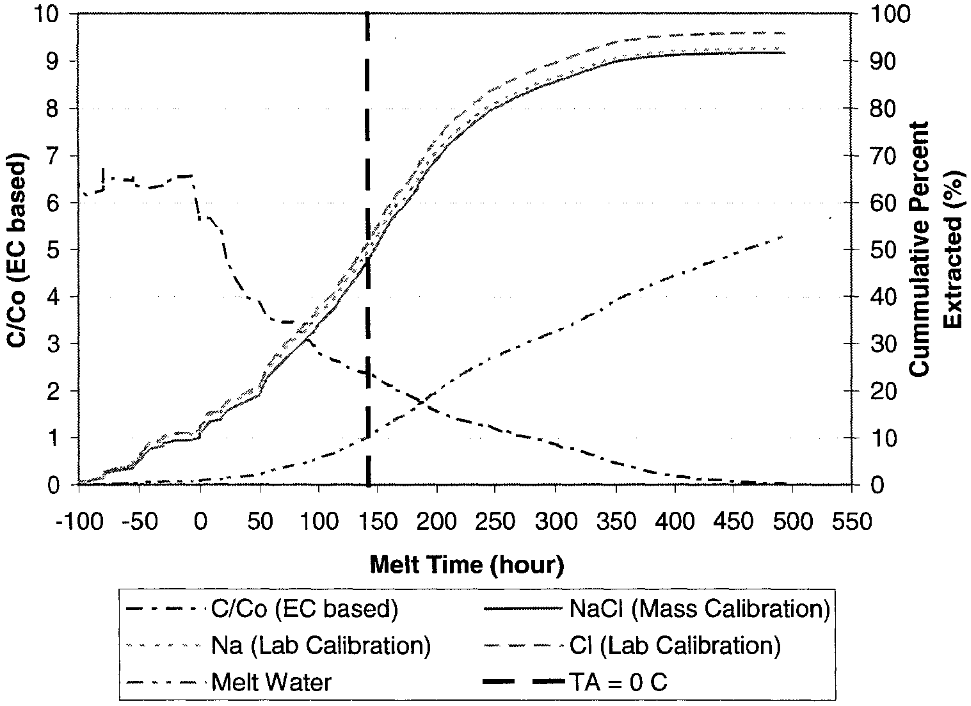


Figure 2.37 Cummulative percent removed of sodium chloride, melt water, and relative concentration (C/Co) during melting of Test 9 ice (20000 mg/L NaCl).

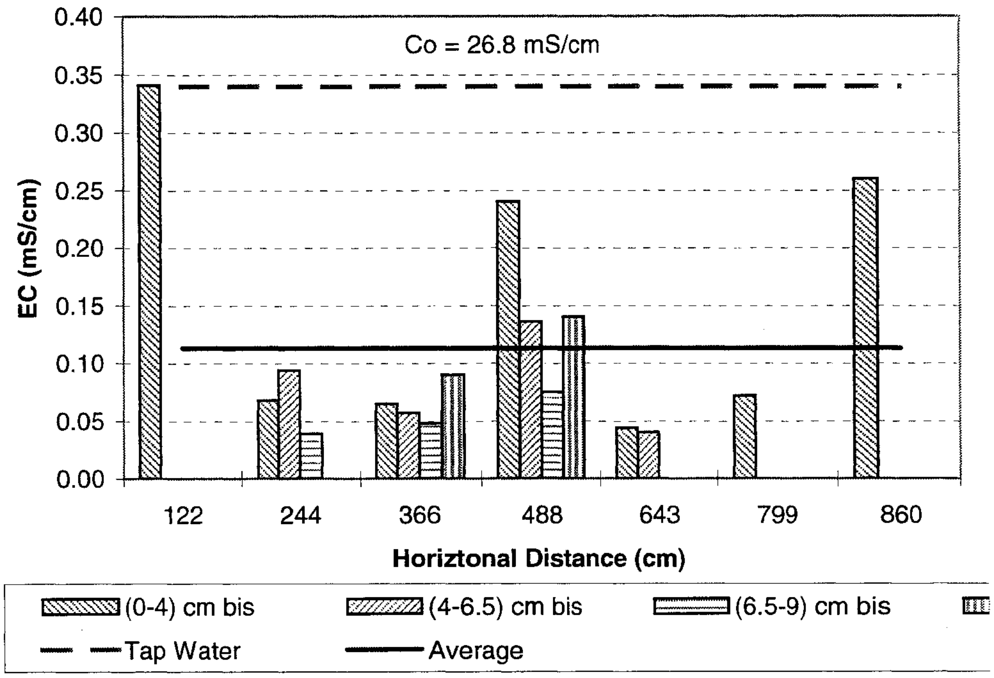
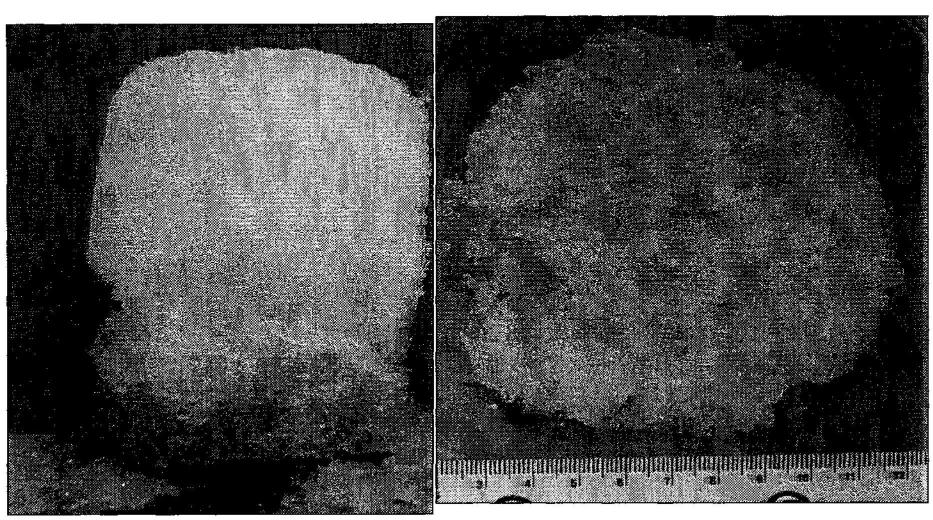


Figure 2.38 Ice core electrical conductivity profile from ice remaining after termination of melting for Test 9. Depth intervals are in cm below the ice surface (cm bis).



a. b.

Figure2.39 a. Side profile of an ice core (366 cm) taken after melting from Test 9.
b. Porous structure of the ice core.

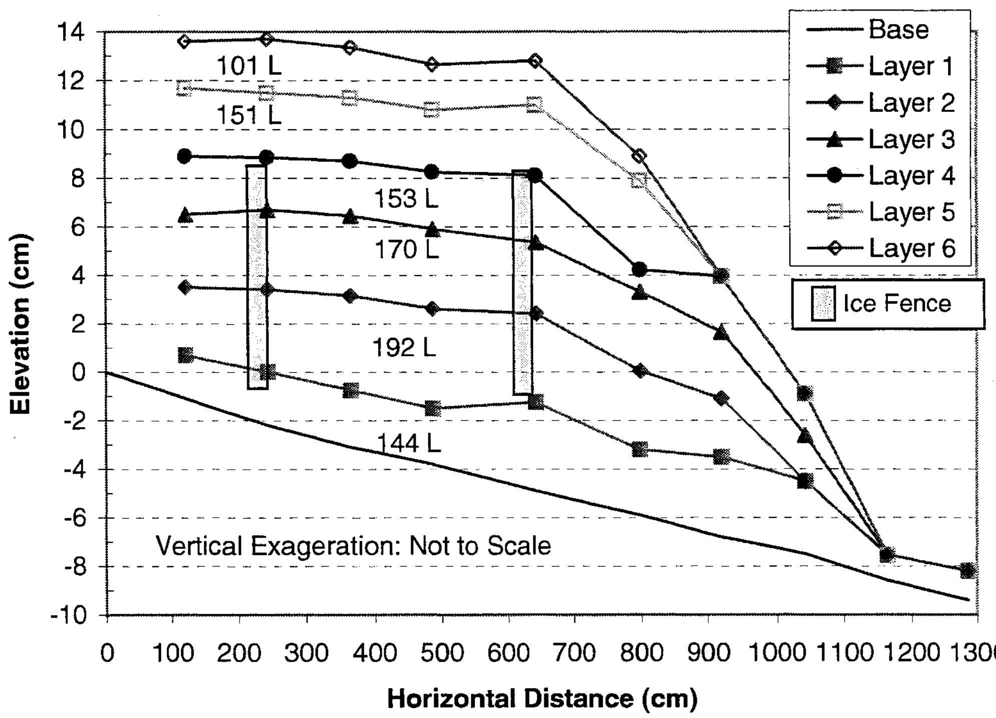


Figure 2.40 Summary of volume frozen and associated ice elevation for each freezing event in Test 10 (500 mg/L).

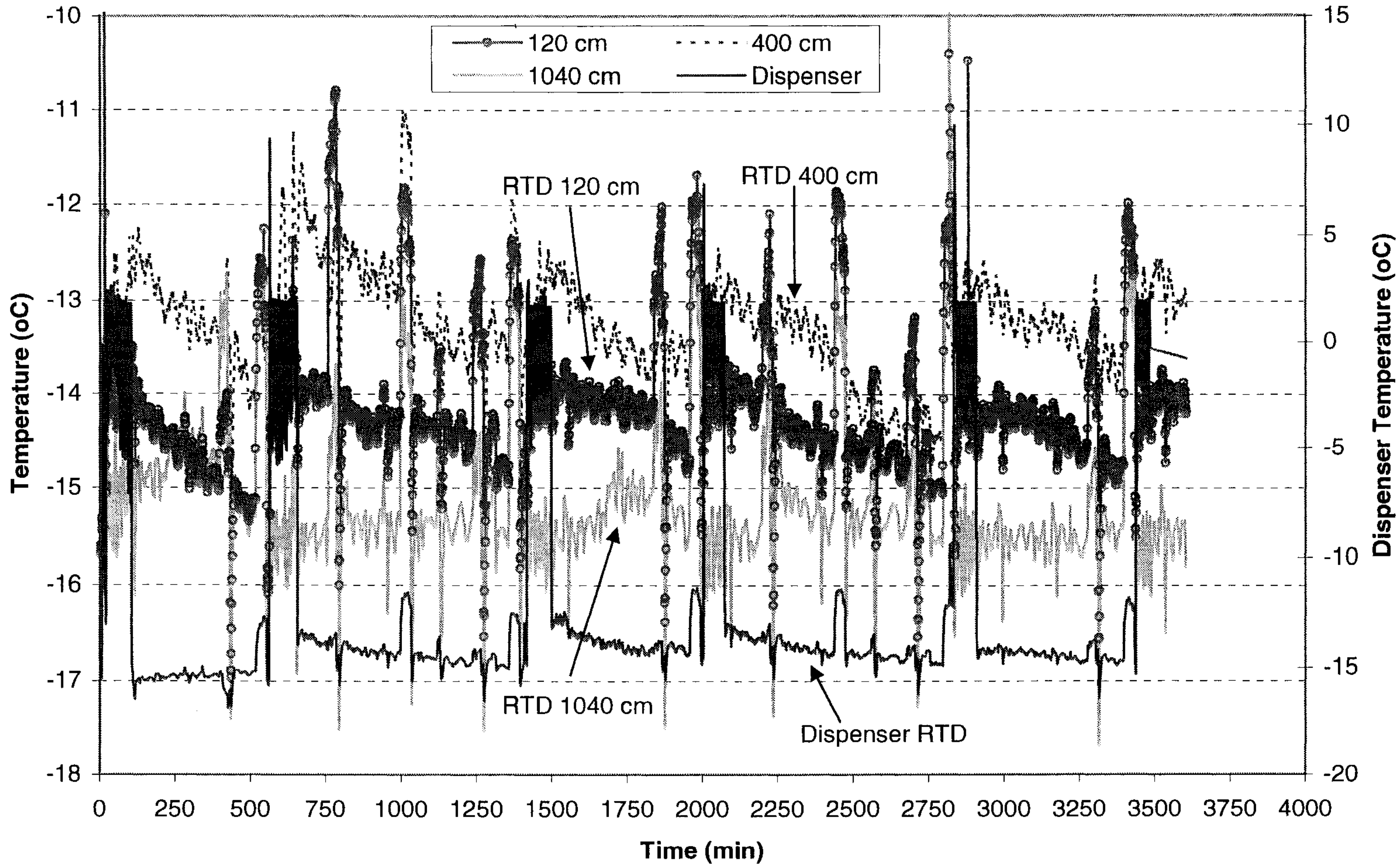


Figure 2.41 Flume temperatures during freezing for Freeze Test 10.

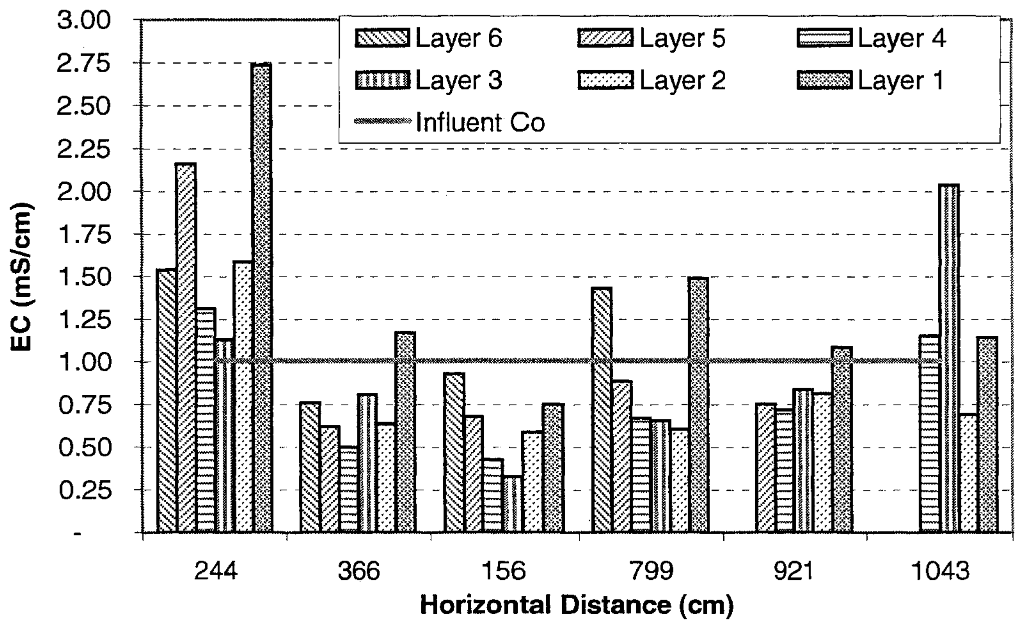


Figure 2.42 Ice core electrical conductivity profile from produced ice for Test 10 (500 mg/L). Depth intervals correspond to placement layers.

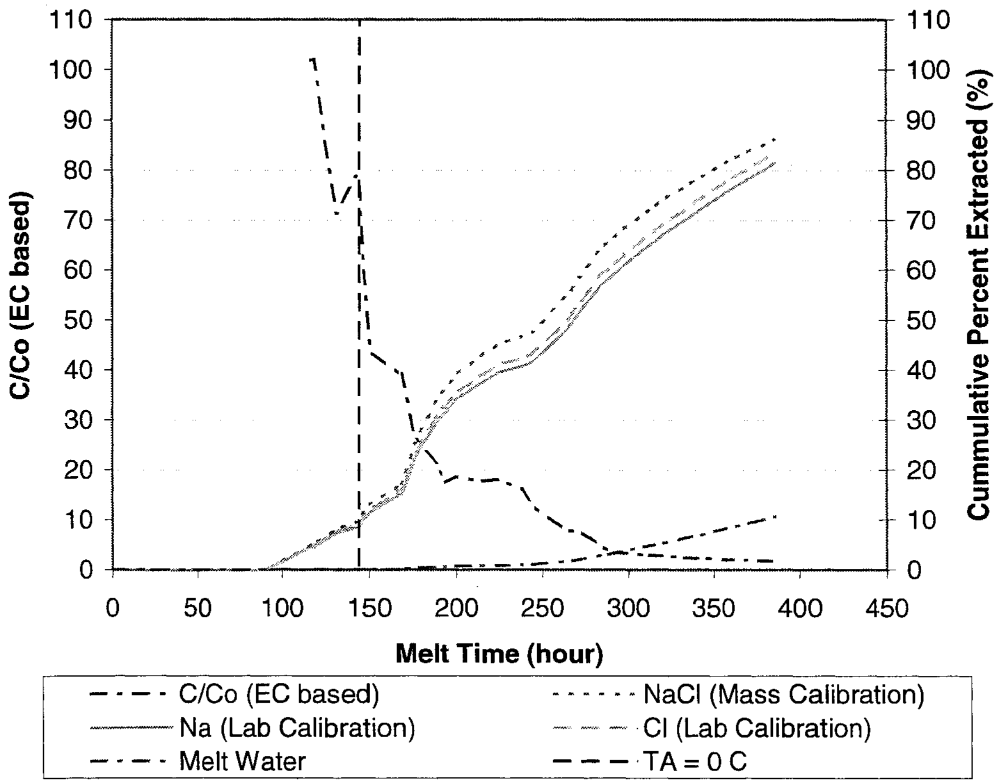


Figure 2.43 Cummulative percent removed of sodium chloride, melt water, and relative concentration (C/Co) during melting of Test 10 ice (500 mg/L NaCl).

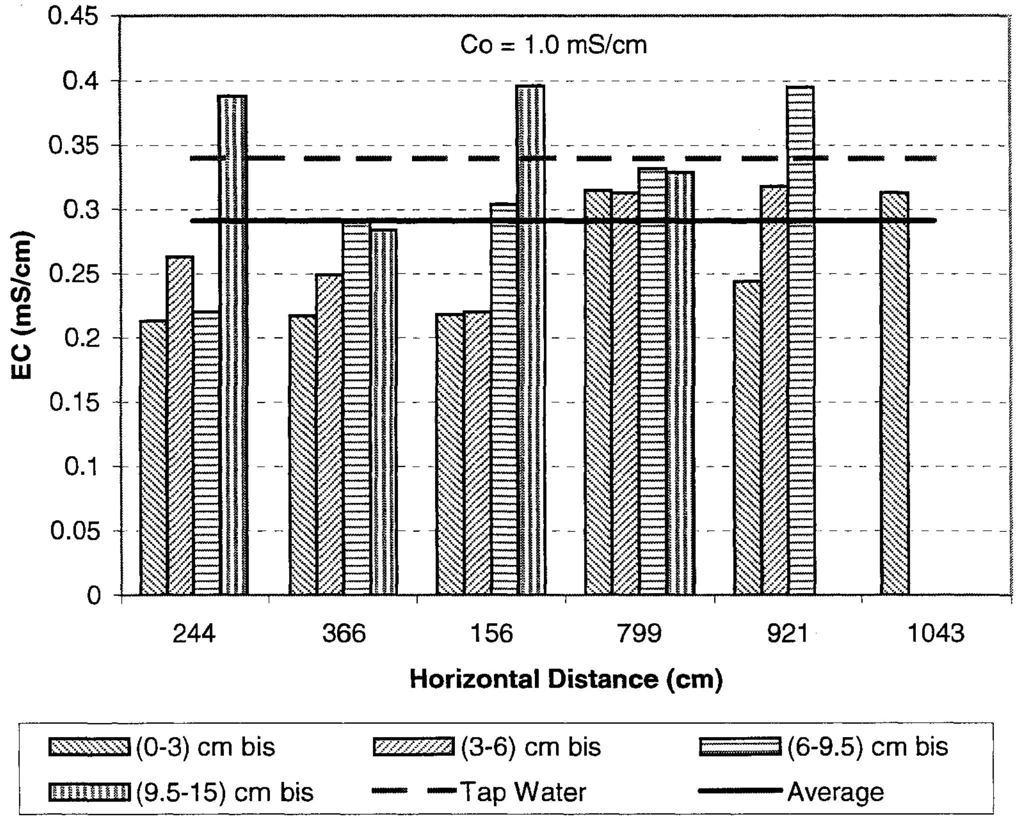


Figure 2.44 Ice core electrical conductivity profile from ice remaining after termination of melting for Test 10. Depth intervals are in cm below the ice surface (cm bis).

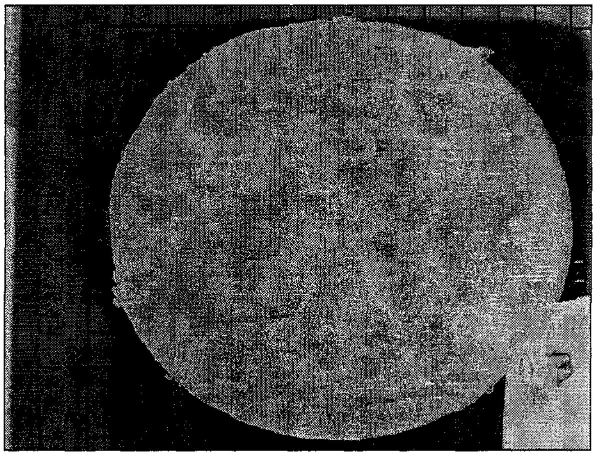


Figure 2.45 Slighlty porous ice taken from ice remaining after melting from Test 10 (core 244 cm).

2.7 Tables

Table 2.1 Experimental variable combinations used in the freezing experiments.

Test Number	Input Salt Concentration	Ambient Temperature	Mass Flow Rates
	Co (mg/L [mS/cm]*)	T_A (°C)	kg/(s m width)
Test 1	500 [1.00]	-30	0.16
Test 2	500 [1.00]	-30	0.10
Test 3	22800 [28.8]	-30	0.14
Test 4	20000 [26.5]	-15	0.09
Test 5	20000 [26.5]	-15	0.074
Test 6	22800 [28.8]	-15	0.26**
Test 7	2000 [1.90]	-15	0.22**
Test 8	3000 [4.63]	-15	0.23 to 0.26**
Test 9	20000 [26.8]	-15	0.16 to 0.19**
Test 10	500 [1.00]	-15	0.23 to 0.25**

* measured at ~2 °C

** flow rate during 2 minute on-cycle. Flow was pulsed at intervals of 6 min off and 2 min on

Table 2.2 Calculated mass balance of salts for Tests 8, 9, and 10.

Test Number	Species	Mass			% Difference
		Produced ice (g)	Runoff (g)	Remaining ice (g)	
Test 8 3000 mg/L	NaCl	2570	2591	76	4
	Na	960	980	90	11
	Cl	1250	1374	142	21
Test 9 20000 mg/L	NaCl*	17740	16260	0	-8
	Na	6580	6100	9	-7
	Cl	8980	8630	12	-4
Test 10 500 mg/L	NaCl*	456	393	0	-14
	Na	189	154	41	3
	Cl	257	215	57	6

* remaining ice mass is 0 because average ice core concentration was less than tap water

Figure 2.3 Water balance at 80 % NaCl removal

Test	Species	Co*	Runoff		Purified Ice		
			Volume	Average Concentration**	Volume		Average Concentration***
		(mg/L)	(L)	(mg/L)	(L)	%	(mg/L)
8	NaCl	3000	76	26370	785	91	720
	Na	1190	76	9970	785	91	250
	Cl	1570	76	14080	785	91	230
9	NaCl	20000	243	58350	644	73	5530
	Na	7500	243	24980	644	73	1930
	Cl	10320	243	31110	644	73	2210
10	NaCl	500	71	5130	840	92	110
	Na	210	71	1960	840	92	60
	Cl	280	71	275	840	92	75

* Co for NaCl is based on mass of table salt, Na and Cl are based on laboratory analyses

** Average concentration based on cummulative salt mass/runoff volume

*** Concentration based on (input mass - runoff cummulative mass)/ remaining purified ice volume

Figure 2.4 Water balance at thaw termination

Test	Species	Co*	Runoff		Purified Ice		
			Volume	Average Concentration**	Volume		Average Concentration***
		(mg/L)	(L)	(mg/L)	(L)	%	(mg/L)
8	NaCl	3000	188	13650	673	78	0
	Na	1190	188	5090	673	78	134
	Cl	1570	188	6630	673	78	211
9	NaCl	20000	471	34530	416	47	3550
	Na	7500	471	12960	416	47	20
	Cl	10320	471	18320	416	47	30
10	NaCl	500	101	3890	810	89	77
	Na	210	101	1525	810	89	50
	Cl	280	101	2130	810	89	72

* Co for NaCl is based on mass of table salt, Na and Cl are based on laboratory analyses

** Concentration based on cummulative salt mass/runoff volume

*** NaCl concentration based on (input mass - runoff cummulative mass)/ remaining purified ice volume, Na and Cl concentration based on lab analyses

2.8 References

Ashton, G.D. 1980. Freshwater Ice Growth, Motion, and Decay. In Dynamics of Snow and Ice Masses. *Edited by* S.C. Colbeck. Academic Press, Harcourt Brace Javanovich, New York. pp. 261-304.

Biggar, K.W., Donahue, R., Sego, D.C., Johnson, M., and Birch, S. 2005. Spray freezing decontamination of tailings water at the Colomac Mine. Cold Regions Science and Technology, **42**: 106-119.

Chalmers, B. 1959. How water freezes. Scientific American, **200**: 114-122.

Cragin, J.H., Hewitt, A.D., and Colbeck, S.C. 1993. Elution of Ions from Melting Snow: Chromatographic Versus Metamorphic Mechanisms. US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory (CRREL), Report 93-8.

Electrical Power Research Institute (EPRI). 2003. Mechanical Freeze/Thaw and Freeze Concentration of Water and Wastewater Residuals. EPRI Technical Report 1009236.

Elmore, W.W. 1968. Water purification by natural freezing. M.Sc. Thesis, Department of Chemical Engineering, University of Wyoming, Laramie, Wyoming.

Fertuck, L. 1968. Water purification by freezing in reservoirs, work done during the season 1968-1969. 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. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta. p. 308.

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

Halde, R. 1980. Concentration of impurities by progressive freezing. Water Research, **14**: 575-580.

Heist, J.A. 1980. Freeze crystallization applications for wastewater recycle and reuse. *In* Water - 1980. *Edited by* G.F. Bennet. American Institute of Chemical Engineers Symposium Series, pp. 259-272.

Holowenko, F.M., MacKinnon, M.D., and Fedorak, P.M. 2000. Methanogens and sulfate-reducing bacteria in oil sands fine tailings waste. Canadian Journal of Microbiology, **46**: 927-937.

Horvath, A.L. 1985. Handbook of aqueous electrolyte solutions, physical propeties, estimation and correlation methods. Ellis Horwood limited, Chichester, England.

Jean, D., Lee, D., and Wu, J. 1999. Separation of oily sludge by freezing and thawing. Water Research, **33**:7, 1756-1759.

Krepchin, I.P. 1985. Fresh water from the sea. High Technology, **September**: 64-65.

MacKinnon, M. 2004. Oil sands water quality issues: properties, treatment and discharge options. In CONRAD Oilsands Water Usage Workshop, Fort McMurray, Alberta.

Martel, C.J. 1989. Development and design of sludge freezing beds. American Society for Civil Engineering Journal of Environmental Engineering, **115**:4, 799-808.

Muller, M. and Sekoulov, I. 1992. Wastewater reuse by freeze concentration with a falling film reactor. Water Science Technology, **29**:7-8, 1475-1482.

Otto, L. 2002. Evaluation of freeze separation as a treatment for salt-contaminated groundwater. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta. p. 167

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. 1965. The physics of ice. Pergamon Press, London, England.

Robinson, R.A. and Stokes, R.H. 1959. Electrolyte Solutions, the measurement and interpretation of conductance, chemical potential and diffusion in solutions of simple electrolytes. Butterworths Scientific Publications, London, England.

Schohl, G.A. and Ettema, R. 1986. Theory and laboratory observations of naled ice growth. Journal of Glaciology, **32**:111, 168-177.

Shone, R.D. 1987. The freeze desalination of mine waters. Journal of the South African Institute of Mining and Metallurgy, **87**:4, 107-112.

Spyker, J.W. 1981. Desalination of brackish water by spray freezing progress report 1979-1980. Saskatchewan Research Council Technical Report No. 126, SRC Publication No. E-835-1-B-81, June 1981.

Stahl, R.P. and Sego, D.C. 1995. Freeze-thaw dewatering and structural enhancement of fine coal tails. American Society of Civil Engineers, Journal of Cold Regions Engineering, **9**:3, 135-151.

Terwilliger, J. and Dizio, S. 1970. Salt rejection phenomena in the freezing of saline solutions. Chemical Engineering Science, **25**: 1331-1349.

Weeks, W.F. and Ackley, S.F. 1982. The growth, structure, and properties of sea ice. US Army Cold Regions Research and Engineering Laboratory Monograph 82-1.

Willoughby, A. 2005. Freeze Separation to Treat Swine Manure. M.Sc Thesis. Department of Civil and Environmental Engineering, University of Alberta, 2005. p. 94.

Zubot, W. 2004. Management of multiple tailings ponds. In CONRAD Oilsands Water Usage Workshop, Fort McMurray, Alberta.

3. DESIGN OF A FIELD SCALE PULSE-TRICKLE FREEZE SEPARATION SYSTEM FOR SALT CONTAMINATED WATER

3.1 Introduction

Oil sands mine operators in northern Alberta utilize open pit mining to extract bitumen laden sand deposits. To extract the bitumen from these sand deposits, a large volume of water is required. To satisfy the water demand for extraction, mine operators import river water and recycle process water. Due to continued reuse of the process water, inorganic and organic concentrations in the water have increased leading to scaling, fouling, and corrosion. The mines are currently storing the process water on site in large basins or old mine pits. Little treatment is conducted to remove the inorganics from the water. High costs of conventional treatment to render the water reusable have led to the need for the development of an alternate cost effective treatment system. Natural pulse-trickle freeze separation may provide an alternative treatment process to reduce the salinity in the process water.

Laboratory scale testing of natural pulse-trickle freeze separation on saline solutions was conducted at the University of Alberta's Cold Regions Geotechnical and Geoenvironmental Research Facility (CRGGRF). The laboratory scale studies were able to concentrate the majority of the salts into less than a third of the original volume. By producing a small amount of highly concentrated brine solution from a large, diluted source, freeze separation reduces the volume of waste water requiring further treatment. The purified melt water may also be reused in the extraction and upgrading process, reducing the demand for fresh, imported water. Utilizing the results from the laboratory scale experiments, the design and cost of a field scale pulse-trickle freeze separation system for saline oil sands process water will be explored. Research objectives include:

- Design a pulse-trickle freeze separation treatment system for 20 million cubic metres of typical oil sands mine process water

- Estimate the capital and operating costs for construction and operation of the freeze separation system for a typical mine scenario including final treatment cost per cubic meter

3.1.1 Desalination Technologies

Desalination technology for treatment of brackish waters can be divided into two processes: thermal methods and membrane processes. Thermal technologies include distillation and freeze separation. Membrane processes include reverse osmosis (RO), electro dialysis, and ion-exchange. The technology used for a particular waste stream depends on the volume, composition and concentration of contaminants, quality of treated water required, availability of waste heat, and installation and operating costs. (CRC Press, 1999; Dore, 2005; Van der Bruggen and Vandecasteele, 2002; and Voutchkov, 2005;). Pretreatment is usually required for membrane processes. Corrosion and scaling are common issues for thermal processes. A detailed description of each technology is beyond the scope of this research.

Management (storage and release) of oil sand process water is governed under the mine's operating license. Process water from Syncrude Canada Ltd. (Syncrude) can not be released from site. Currently, the process water does not undergo any desalination treatment. Rather it is stored on site in large, constructed settling basins such as the Mildred Lake settling basin (MLSB). The process water is reused directly from the settling basin.

3.1.2 Freeze Separation for Treatment of Mine Waste Water

Based on the freeze separation process discussed in chapter 2, a pulse-trickle freeze separation system was designed to treat brackish oil sands mine wastewater. The field scale system was designed to simulate the pumping method utilized in the laboratory experiments. Waste water is pumped into a containment cell through a series of vertical risers during the winter season. To emmulate the pumping and pulsing rate, waste water discharge will cycle through several zones within many containment cells. The waste water will flow away from the riser in thin layers, freezing over time. Ice build up will continue as long as temperatures permit. In the spring, melt water will be collected with concentrated brine from the initial melt conveyed to a secondary treatment system or to another containment cell for storage. The remaining, purified melt water can be recycled back to the oil sands extraction process for reuse. Details on the design and operational procedures are discussed in sections 3.2 and 3.3.

3.2 System design

Due to the large scale of the freeze separation treatment system a modular design, consisting of several small freezing cells, was chosen. The modular design permits use of a freezing cell as soon as it is constructed. Therefore, treatment of waste water may commence during the first winter if construction takes more than one season to complete. Future expansion is also simplified with a modular design. The location and layout of the freezing cells will depend on the specific mine operations and progression, operating license, applicable environmental regulations, and availability of materials and equipment.

The size and number of freezing cells will depend on the volume of water requiring treatment, requirements for freeboard, and annual precipitation. The current design was based on treating 20 million m^3 (M m^3) of waste water per year. Results from the laboratory scale freeze separation experiments were used to predict the behavior of the waste water during freeze and thaw. The laboratory scale results should effectively simulate the behavior due to similarity in the results with oil sands waste water freeze separation experiments conducted by Gao (1998). Electrical conductivity (EC) and total dissolved solid concentrations from Freeze Test 8 are similar to pond water concentrations in MLSB at Syncrude (MacKinnon, 2004). Therefore MLSB pond water will be the target waste water. The design calls for waste water feeding directly from MLSB to the freezing cells. The following sections summarize the design for the freezing pits, including the waste water placement system and the collection system. Design calculations and assumptions are detailed in Appendix 6.

3.2.1 Freezing Cells

To treat 20 M m^3 in one season, sixteen freezing cells were used. Figures 3.1 and 3.2 show plan and cross section views of the freezing cells. Based on freeze/thaw research on oil sands fine tails, the maximum thickness of ice produced each year is governed by the thawing season. The estimated thickness of ice that can be melted in one year is 4.5 m (Dawson, Sego, and Pollock, 1999; Martel, 1989). Using a rectangular volume and accounting for 9 % expansion upon freezing, the base of one freezing cell (top of the sand drainage layer) is 550 by 550 m. The edges of the cell and an additional 0.4 m depth are required to contain precipitation. The berms are 5.9 m high from the base of the collection layer. The berm crest is 4 m wide to allow access to all of the cells.

The freezing cells were designed with a compacted clay liner. After scarifying and compacting, it is expected that the native material will meet the requirements for a competent clay barrier (Landcare, 1996). If the native soil is not satisfactory, an alternate liner, such as a geomembrane, may be required. The capital cost will be much greater if competent clay is not available.

3.2.2 Waste Water Placement

The waste water placement system was designed to emmulate the pumping scheme utilized in the laboratory scale experiments. Waste water is pulse-pumped into the freezing cell for one hour, three times a day. Figures 3.3 through 3.5 illustrate the freezing pit layout and piping design. Details on the pumping strategy are discussed in section 3.3.

Waste water is pumped from MLSB to a central station were it is dispersed to the freezing cells. To prevent freezing, the main feed line from MLSB is buried under the berms. There are four separate pumping zones in each of the sixteen freezing cells. One pump is utilized for each zone. The pumps and valves are housed in a heated shed atop the berms between adjacent freezing cells. A schematic of the pump and valve layout is illustrated in Figure 3.4. Pumping zones from adjacent freezing cells share the use of a single pump. Each pumping zone consists of five high density polyethelene (HDPE) header pipes supplying the freezing cell. To reduce freezing and traffic damage to the header pipes, the pipes enter the freezing cell below the gravel base layer. Five, 200 mm diameter HDPE riser pipes extend vertically from the header pipe (Figure 3.5). Each riser will supply a 50 m by 50 m area. Waste water will spill out of the riser pipes and fall to the ground. The flow rate at each riser will be controlled by a valve atop the riser. Exposure of the water to the atmosphere while falling aides in the removal of sensible heat from the water. A ring of straw bails or a geotextile fence at the base of each riser will force a plunge pool. The plunge pool will remove kinetic energy from the water and allow laminar flow across the ice surface, away from the riser (Figure 3.6).

To prevent freezing of the header pipes and risers after completion of a pulse cycle, a reverse pumping cycle will be initiated. Water pumped out of the lines will be directed back to the main feeder system.

3.2.3 Collection System

The effluent collection system was designed to capture runoff using a gravel drainage layer and full flowing pipes under atmospheric pressure. Thawing rates were estimated based on results from the laboratory scale freezing experiments and from Willoughby (2005). Calculations of the maximum and minimum thaw rates for the concentrated brine and treated water are found in Appendix 6. The maximum thaw rate for the concentrated brine (0.080 m^3/s) governed the design of the collection system. Figure 3.7 illustrates a plan view of the collection system piping for one freezing cell. Each freezing cell has four collection zones. Each zone has a base grade of 1 % from the centre of the freezing cell to the corner. The gravel drainage layer covering the entire freezing cell base allows melt water to drain to the collection piping at the low corner. The gravel layer consists of 0.3 m thick, 20 mm crushed gravel (Figure 3.2). Each collection zone also has eight single slotted 150 mm (inside diameter, ID) PVC pipes buried at the base of the gravel layer (1 % grade). The slotted PVC pipes capture the melt water and convey it to two, 250 mm ID, solid, PVC header pipes at the corner of the freezing cell.

The melt water flows from the header pipes by gravity to the collection sump buried under the berms. The base of the collection sump is buried 9 m from the berm crest. One sump may collect melt from up to four collection zones depending on its location within the freezing field. Sumps located at the edges of the freezing field have only one or two collection zones. Sumps located inside the freezing field capture melt from four collections zones. Figure 3.8 shows a schematic of the collection system for two adjacent freezing cells. Pumps used to supply the freezing zones can also empty the sumps. Level actuators in the sumps start the pumps when the fluid level is 1m high. Two pumps are required for sumps with four collection zones. Only one pump is required for sumps with two or less collection zones (Appendix 6). The suction lines from the sump to the pump house are buried to prevent freezing. The collection sump was designed with an entry hatch and ladder to access the valves and level actuator. Melt water is conveyed from the sumps to the main feed line at the pump house and finally to a central station outside of the freezing field. The initial 22 % of the melt would be concentrated brine and the remaining 78 % would be purified water. Concentrated brine will be transferred from the central station for further treatment or storage. Treated water can be transferred from the central station to the processing plant for reuse. Details on the collection system operation will be discussed in section 3.3.

3.3 System Operation

Operation of the thin layered freezing system will commence during the winter months of November and run through March. An average of 150 days is expected for the freezing cycle. A schematic of the freeze separation system for one freezing cell can be found in Figure 3.9. Prior to freezing the waste water, the collection sump isolation valve will be closed. Waste water placement should only occur when the following two conditions are met: the minimum daily temperature is less than –10 °C and the maximum daily temperature is no greater than -5 °C (freezing point of ~80,000 mg/L NaCl solution) (Willoughby, 2005). Waste water pumping will continue through the winter until the maximum ice depth is achieved or the above conditions are no longer met. The pumping scheme is outlined in Appendix 7.

Melt water collection will begin in early spring. The collection sump isolation valve should be opened after the freezing cycle is complete. Due to the freezing point depression of the melt water, collection may commence when ambient temperatures are below 0 °C. The initial melt water shall be directed to a secondary treatment process or to a storage pond until EC of the melt decreases below the raw waste water EC of approximately 5.0 mS/cm. Based on the laboratory experiments, once the melt EC decreased to the input EC, majority of the salts were removed. The fate of the concentrated brine is beyond the scope of this research and will not be discussed further. Measurement of the melt water EC should be continuously monitored to determine when the EC reaches initial conditions. The EC from the concentrated brine and purified water is expected to range from 5 to 200 mS/cm and 0 to 5 mS/cm, respectively. Purified water can be directed back to the mine processing plant for reuse. Completion of melting is expected by the end of September. Approximately one month is available for repairs and maintenance before the freezing cycle recommences. Repositioning of the plunge pool ring (bails or geotextile) may also be required. Any precipitation collected in the cells can be directed to the processing plant. The collection sump isolation valve shall remain open until the freezing cycle is initiated.

3.4 Results

The laboratory scale freezing experiments demonstrated the capability of natural thin layered freezing to separate salts from saline waste water resulting in concentrated brine and purified melt water. Gao (1998) also demonstrated freeze separation has the ability to treat oil sands mine waste water at a field pilot scale. Results from a full scale pulse-trickle freeze separation system are expected to be comparable to the laboratory and pilot scale experiments. It is expected that the majority of the salts will be concentrated into approximately 22 % of the initial water volume, leaving 78 % of the water relatively purified.

Expected results from a full scale pulse-trickle freeze separation system for 20 M m^3 of saline water (3000 mg/L NaCl) are contained in Table 3.1. The results are contingent on the source water concentration, the number of actual thawing days, the rate of thaw, and the amount of snowfall accumulation. Approximately 4.4 M m^3 of concentrated brine (13,600 mg/L) containing 60,000 tonnes of NaCl would be produced and 15.6 M m^3 of relatively pure melt water (<100 mg/L NaCl).

3.5 Construction and Operating Costs

Costs for the pulse-trickle freeze separation system were based on construction and operation of a new system. Utilization of existing infrastructure (generators, pumps, etc.) would decrease the treatment costs. Construction costs for the new treatment system are summarized in Table 3.2. Cost data was obtained from RS Means environmental remediation, mechanical, and heavy construction cost data series (Martin, 2002; Mossman, 2002; and Spencer, 2004) as well as local suppliers and professionals. Costs are subject to change depending on season and availability of labour and materials.

Capital costs for construction of the treatment system include, but are not limited to: earthwork for preparation of the freezing cells, compaction and placement of the clay liner and drainage layer in the freezing cell, purchase and installation of pumps, piping and related infrastructure. Recurring expenses such as repairs, maintenance, and professional oversight were not included. The total capital investment for construction of the pulse-trickle freeze separation system amounted to \$127,200,000 or \$6.36/m^3 capacity. Distribution of the initial cost over 10 years at 7 % interest rate was calculated to be \$0.91/m^3, or \$0.60/m^3 over 20 years (Madwar and Tarazi, 2002; Appendix 8). The most significant component of the cost was the earthwork to construct the freezing cell, particularly the gravel drainage layer. Significant cost reductions can be realized if a cheaper source of gravel is found. If competent clay is not available for the engineered clay liner, an alternative geomembrane system may be required, driving the construction costs up.

Employing natural freezing and thawing process has limited the yearly operating costs for the freeze separation system to energy required for pumping and man hours for operation and maintenance. The annual operating cost for the pulse-trickle freeze system was estimated to be \$2,547,000 or \$0.13/m^3 (Table 3.3). Yearly maintenance was estimated at 5 % of the mechanical and electrical systems capital cost (pumps, valves, and generators).

Comparison of costs with existing desalination plants can be complicated. Costs are determined by many factors such as location, plant capacity, pretreatment required, effluent quality and site related costs for land to name a few (Mielke, 1999). Madwar and Tarazi (2002) reported RO costs of \$0.56/m^3, for treatment of 10,000 m^3 of brackish water per day. Costs include capital investment distributed over 20 years at 7 % interest, as well as energy, operation and maintenance costs. In comparison, the pulse-trickle freeze system could treat 5.5 times the volume for $0.73/m^3, more expensive than the unit costs for RO, unless the RO unit costs increase with greater capacity. Dore (2004) reported RO costs for desalination of 1400 m^3/day were in the range of $0.59 to 0.83/m^3 with the capital investment distributed over 30 years at 8 %. The pulse-trickle freeze system could treat 40 times the volume for the approximately the same price, $0.69/m^3. These costs are similar to those reported by Buros (2000). Production costs for desalination of brackish water with capacities of 4000 to 40000 m^3/day were $0.30 to $0.71/m^3 (1999 Canadian dollars, including capitol recovery). Larger desalination plants may still be lower than the pulse-trickle freeze system even if economies of scale do not reduce the costs for greater capacities.

3.6 Discussion

Pulse-trickle freeze separation has been proven at the laboratory scale for its ability to separate large volumes of brackish water into relatively pure water and concentrated brine. This specific technology has not yet been proven at the field level. It is expected field scale results will be similar to the laboratory experiments', but field testing is required before pulse-trickle freezing can be considered a viable treatment alternative for oil sands process water. Field testing will help confirm and/or determine several operating parameters and techniques. Waste water placement rates need to be determined at various ambient temperatures other than -15 °C to optimize the freezing rates. Several placement techniques should be tested other the proposed central fountain discharge to determine the most efficient method. An efficient method would be one that reduces the adverse impacts of channeling of the base ice layers and maximizes the ice production. The current design assumed that slush screens, to prevent channeling during water placement, were not required. Slush screens may only have been needed in the flume tests due to the laterally confined setup. Channels that form in the field can meander across a larger area and therefore may be less detrimental to the freezing rate. The depth of ice that can be melted in a given year based on Dawson, Sego, and Pollock (1999) and Martel (1989) needs to be confirmed at the field level, on location. The melting depth will determine the size of the freezing area required. If greater depths can be melted, the area required will be smaller, correlating to lower construction costs.

One of the major variables affecting the efficiency of freeze separation is climate. Warm winters or cool summers will reduce the capacity of the system which may lead to increased costs or loss of production due to lack of storage or insufficient volume of recycle water. Precipitation may also significantly affect the efficiency of the freeze separation treatment system. Snowfall accumulation during the winter decreases the rate of heat transfer from the ice, resulting in less volume of ice produced leading to lower separation efficiency (Ashton, 1980; and Fertuck, 1969). Willoughby (2005) suggested saturating and melting the snow after each snowfall event with the waste water will reduce the detrimental effects snow may have on the system efficiency. Operational procedures for saturating and melting the snow need to be determined at the field scale. If significant deviations from the current pumping scheme are required, unit costs of the pulse-trickle system may increase, rendering the system less viable.

Several options may be available for the concentrated brine from the initial melt. Additional freezing cells may be constructed and utilized to further separate and concentrate the salts. The concentrated brine is similar to the experimental solution used in Freeze Test 9 from the laboratory experiments. Therefore, further freeze separation could reduce the 4.4 M m^3 of concentrated brine to approximately 2 M m^3 of brine at the concentration of seawater. It may be advantageous to divert the initial 5 % of concentrated melt water (1 M m^3) and treat separately from the remaining 17 % (3.4 M m^3). Approximately 50 % of the salts are removed in the initial 5 % of the melt water and is therefore highly concentrated in comparison. The highly concentrated brine may be stored while the remaining brine is recycled back to the freeze separation process or sent to a small RO plant for further treatment. The highly concentrated brine produced from the second freeze cycle or diverted from the initial freeze cycle can be further treated in evaporation ponds. A spray evaporation process or waste heat from the mine processing plants can be used to precipitate the salts from this highly concentrated brine further reducing the volume of waste. Storage of the highly concentrated liquid brine may be achieved subaqueously in MLSB. If suitable subaqueous, placement techniques are used, a layer of concentrated brine can be placed below the existing MLSB pond water due to the significantly greater density of the concentrated brine. The option chosen will depend on the mine operations and relative costs.

Calculated unit costs based on the current design are subject to change contingent upon the outcome of field scale testing. Refinement of the design will affect unit costs. For example, if greater ice depths can be melted in one season, a smaller freezing cell is required. This will translate into savings during earthwork construction, but will increase the pumping infrastructure and yearly operating costs. A balance of the freezing cell size and infrastructure costs is required to achieve the lowest cost.

3.7 Conclusions

Increasing contaminant concentrations in oil sands process waters are preventing reuse without some form of treatment. High treatment costs for the waste process water, due to the large volumes have mine operators looking to alternative methods to reduce costs. The current study was conducted to determine the cost of construction and operation of a pulse-trickle freeze system for treatment of oil sands process water. Research objectives included designing a pulse-trickle freeze separation treatment system for typical oil sands mine process water, estimating the capital and operating costs for construction and operation of the freeze separation system for a typical mine scenario including final treatment cost per cubic meter. A pulse-trickle freeze separation system was designed to treat 20 million m^3 of oil sands mine process water per year, yielding approximately 15.5 million m^3 of purified water. The capital investment for construction of the pulse-trickle freezing system was $127.2 million or $6.36/$m^3$ capacity. Yearly operating costs amounted to $0.13/$m^3$ of waste water. After distributing the capital investment over 10 to 30 years, capital and operational costs were within the unit price range of other desalination technologies such as RO. Pulse-trickle freeze separation may prove to be cheaper depending on field test results.

3.8 Figures

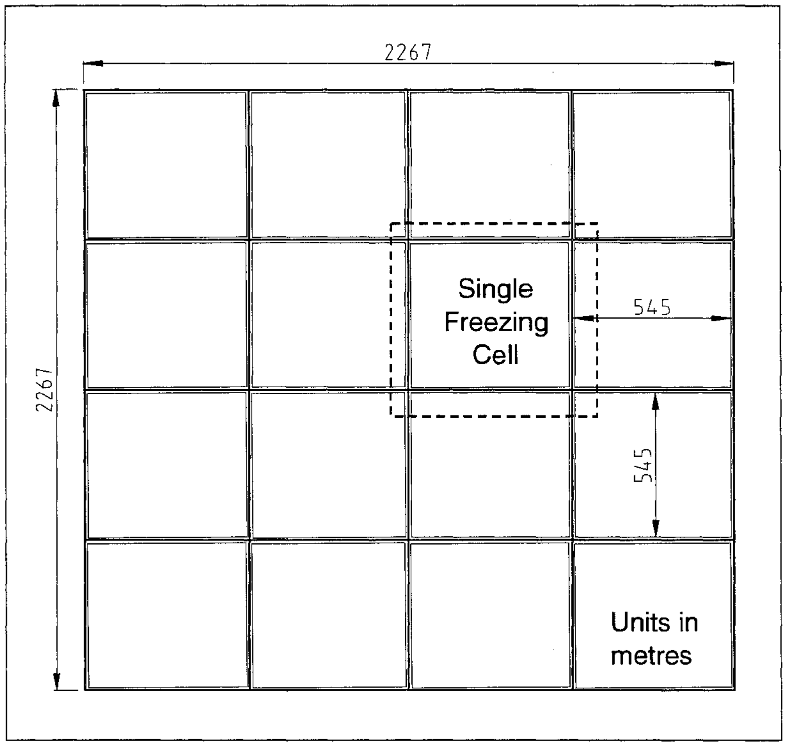


Figure 3.1 Plan view of the entire freezing field consisting of sixteen freezing cells. Piping and infrastructure not shown.

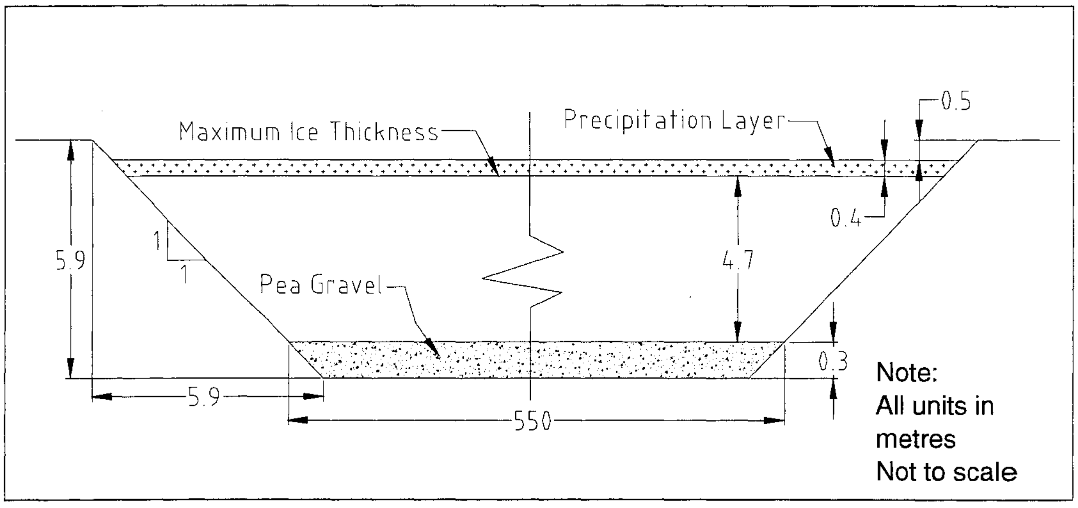


Figure 3.2 Cross-section of one freezing cell (typical).

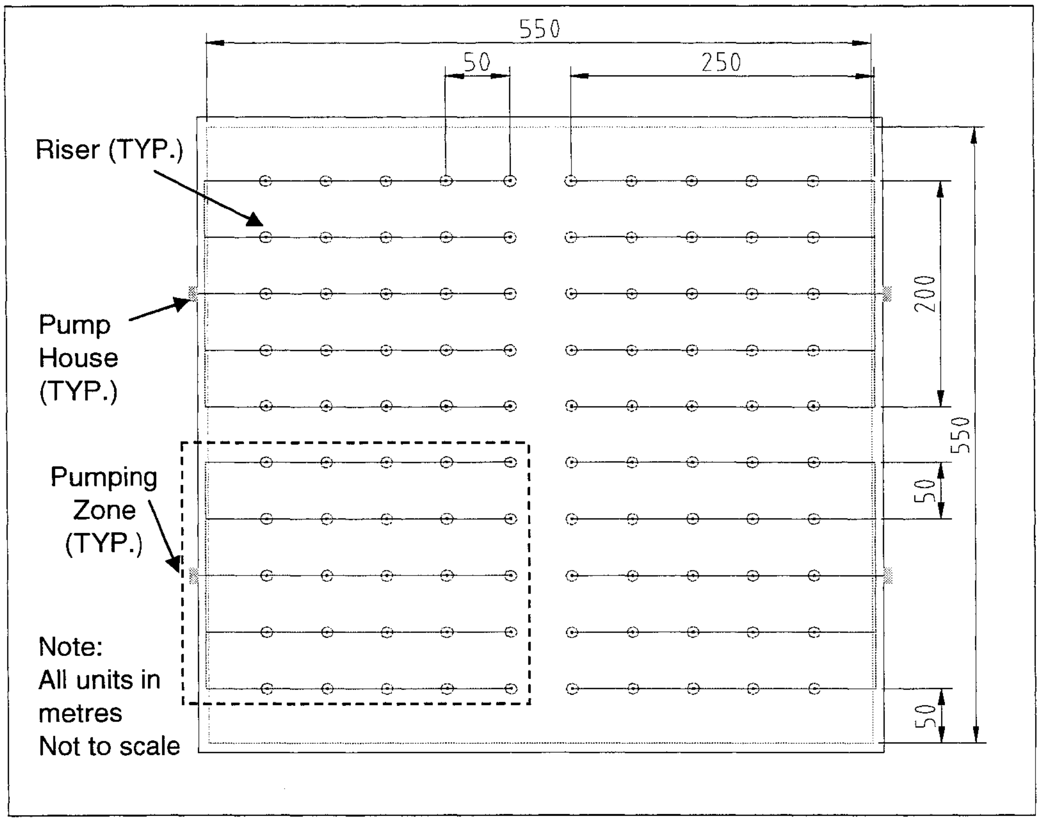


Figure 3.3 Plan view of a single freezing cell showing the waste water placement piping.

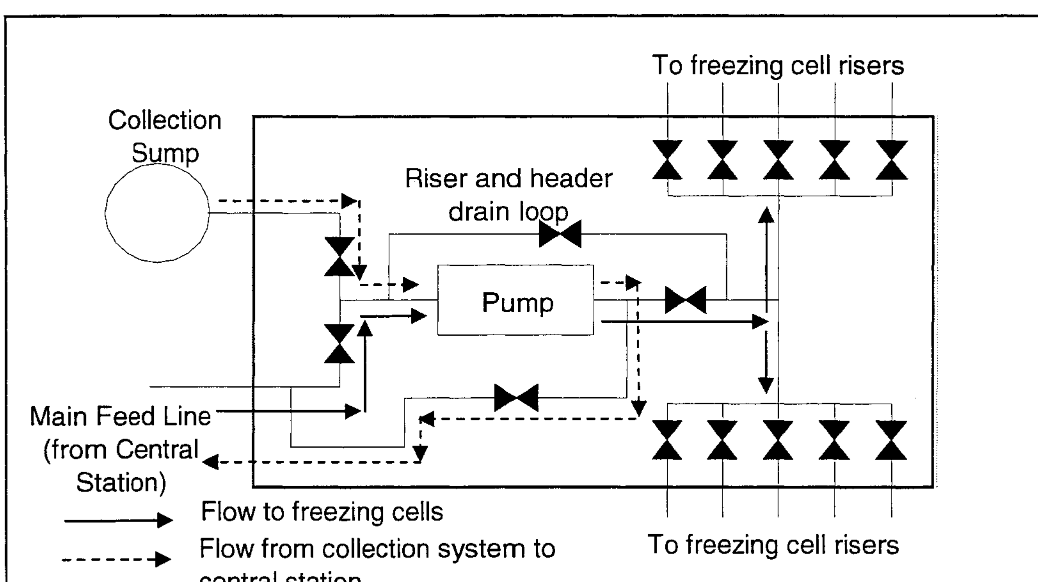


Figure 3.4 Schematic of the pump and valve layout for the waste water freezing system.

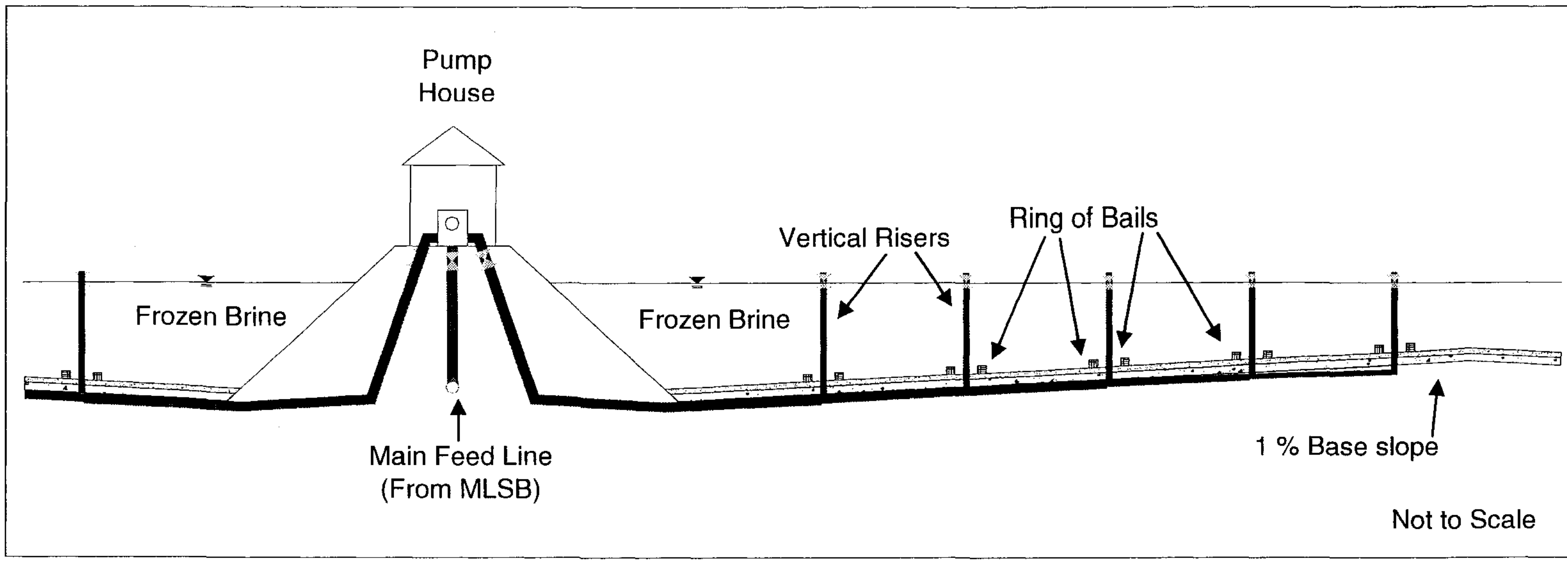


Figure 3.5 Cross-section of waste water placement infrastructure for two adjacent freezing cells.

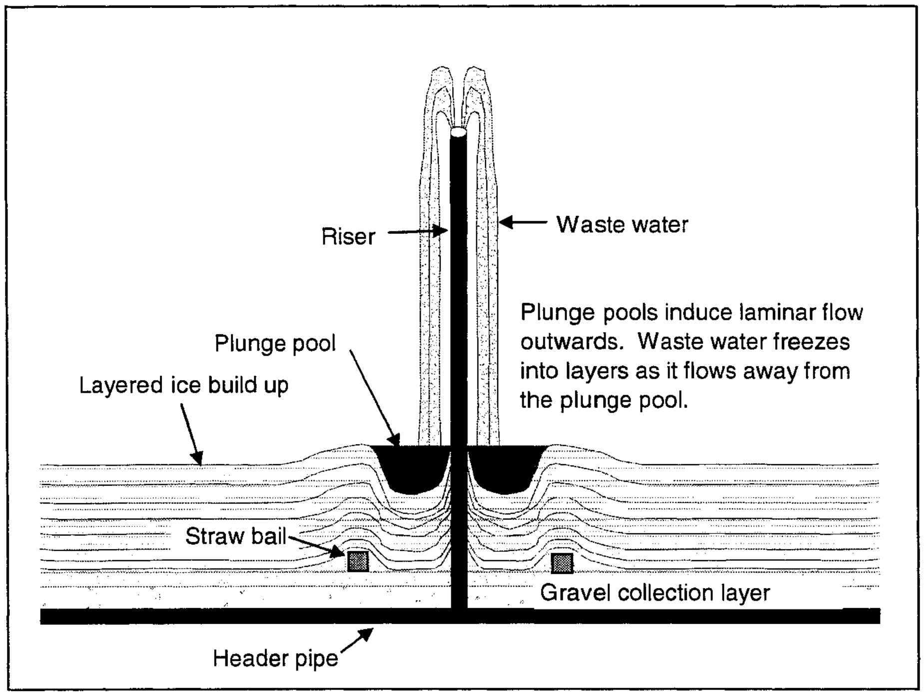


Figure 3.6 Schematic of the freezing process for water flowing out of a riser.

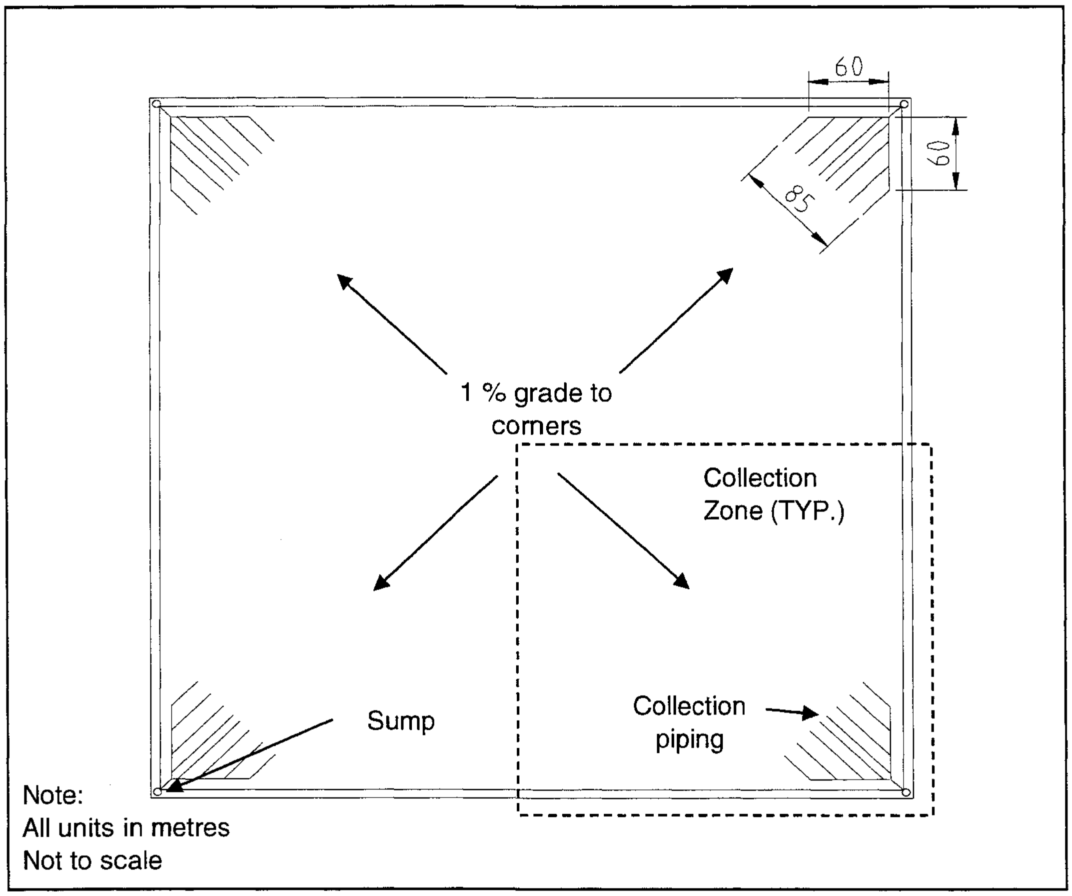


Figure 3.7 Plan view of a single freezing cell showing the collection system.

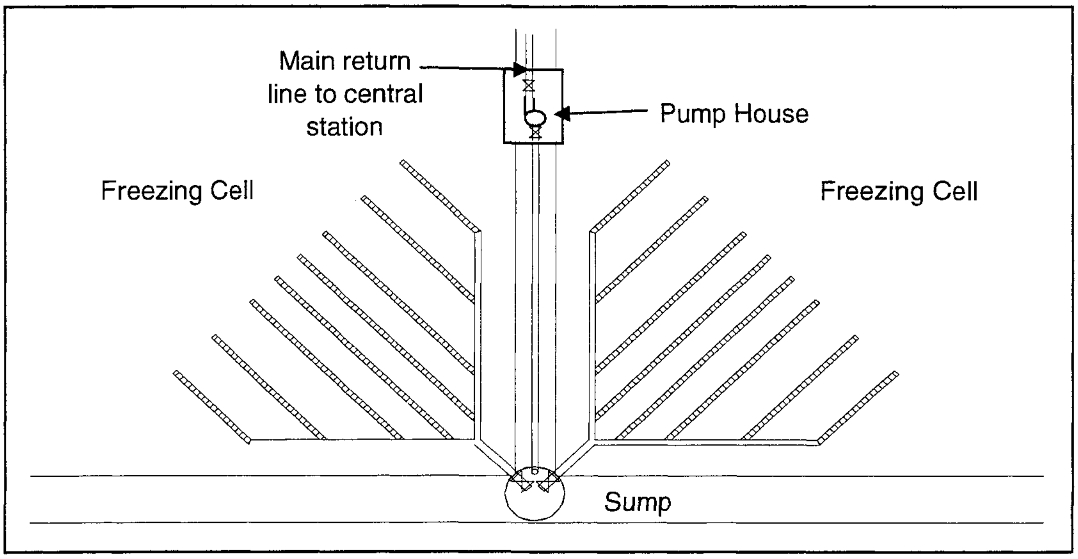


Figure 3.8 Schematic of the collection system for two adjacent freezing cells.

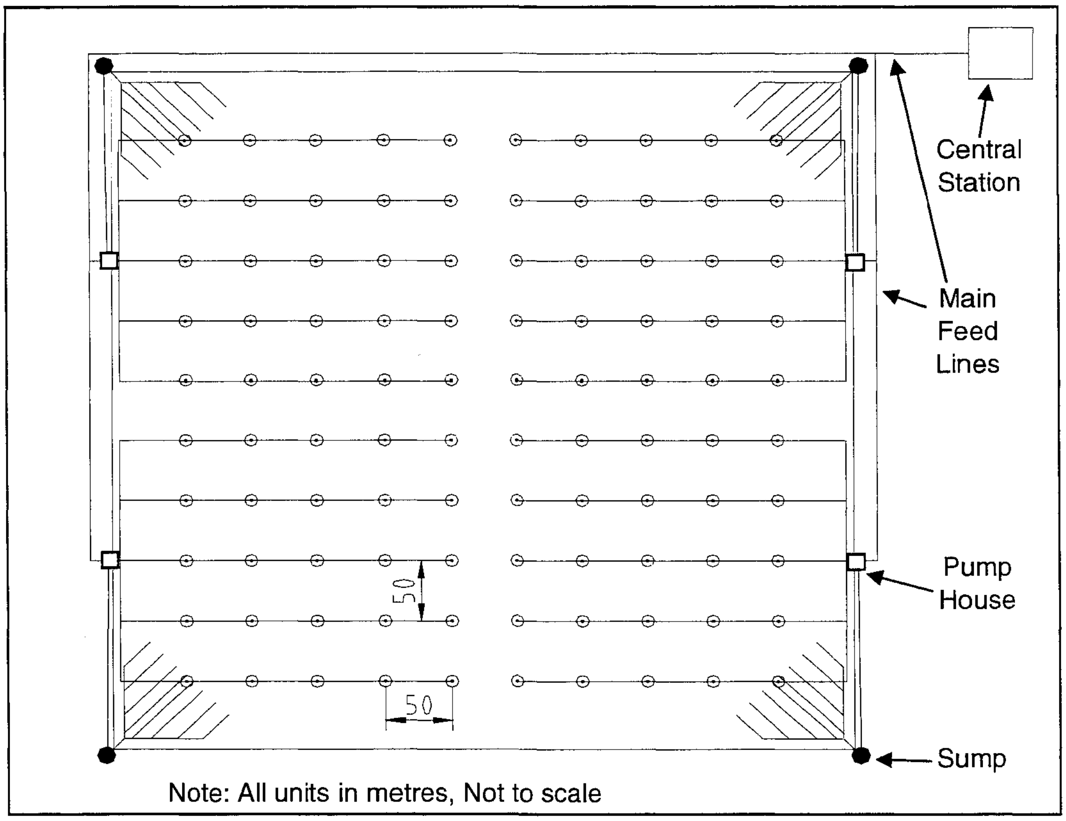


Figure 3.9 Schematic of one freezing cell from the freeze separation system to treat mine waste water.

3.9 Tables

Table 3.1 Summary of projected results from the freeze separation treatment for salt contaminated mine waste water.

	Volume (M m3)	Salt Concentration (g/L)	Salt (NaCl) Mass (tonne)
Raw Waste Water	20	3	60000
Concentrated Brine	4.4	13.6	60000
Purified Melt Water	15.6	0	0

Note: Based on 100 % salt removal into 22 % of the original volume

Table 3.2 Construction costs for a new pulsed trickle freeze separation system.

Earth Work					
Activity/Material	**Details**	**Quantity**	**Units**	**Cost**	**Total Cost**
Stripping	Strip topsoil (0.3 m depth)	1,541,784	m^3	5.25	8,094,366
Earth Work	Excavation and Berms	4,044,800	m^3	5.25	21,235,200
Clay Liner	Scarify and Compact	4,840,000	m^3	1.26	6,111,846
20 mm Gravel Drainage Layer	0.3 m Thick	1,452,000	m^3	40.76	59,176,260
Drainage Layer Install	Place and spread drainage layer	1,452,000	m^3	5.25	7,623,000
				Subtotal =	**102,240,700**

Waste Water System Placement					
Activity/Material	**Details**	**Quantity**	**Units**	**Cost**	**Total Cost**
Main Feed Lines	Average 24 " HDPE	2,268	m	253.78	575,579
	18 " HDPE	11,335	m	157.39	1,784,060
Main Feed Tees	24 " HDPE 4 way tees	5	-	2806.25	14,031
Main Feed Lines 24 " Install	Burried before berm construction (2 m)	2,268	m	99.11	224,785
Main Feed Lines 18 "Install	Burried before berm construction (2 m)	11,335	m	78.01	884,249
HDPE Header Pipe	14 " header from pump	35,200	m	97.61	3,435,824
	14 "	16,000	m	97.61	1,561,738
	12 "	16,000	m	82.36	1,317,716
	10 "	16,000	m	64.06	1,024,891
	8 "	16,000	m	51.24	819,912
HDPE 3 Way Tees	14 " tees	320	-	817.47	261,591
	12 " tees	320	-	689.36	220,595
	10 " tees	320	-	494.14	158,126
	8 " tees	320	-	372.13	119,083
HDPE Elbows	14 " elbow	320	-	780.87	249,878
	8 " elbow	320	-	273.30	87,457
Header Install (berm)	14 " header pipe burried as berm constructed with sump line	5,040	m	49.88	251,373
Header Install (berm)	14 " header pipe burried as berm is constructed	7,760	m	37.09	287,795
Header Install (cell)	Bedded on clay liner surface	86,400	m	10.81	933,671
HDPE Vertical Riser	8 "	9,600	m	51.24	491,947
Vertical Riser flow control valve	8 "	1,600	-	1006.59	1,610,542
Plunge Pool Ring	silt fence geotextile	9,600	m	1.44	13,849
Vertical Riser and Install	Materials and installation of support and geotextile installation	1,600	-	1000.00	1,600,000
14 " Automatic Shutoff Valves		520	-	3477.31	1,808,200
Automated Valve Control System	Host computer	1	-	12201.08	12,201
	Main controller unit	40	-	6100.54	244,022
	Start/stop valve controller	520	-	398.24	207,086
	Pump controller	40	-	1894.22	75,769
Pump	112 KW, 252 L/s with install	40	-	34651.06	1,386,042
Shed	6 x 3 m shed	40	-	5000.00	200,000
Shed Heater		40	-	100.00	4,000
500 kW Diesel Generator		2	-	125061.05	250,122
				Subtotal =	**22,116,100**

Table 3.2 Continued.

Collection System					
Activity/Material	**Details**	**Quantity**	**Units**	**Cost**	**Total Cost**
6 " perforated PVC		24,960	m	35.38	883,163
10" solid PVC header		7,680	m	52.46	402,928
PVC Wyes		640	-	158.61	101,513
6 " PVC pipe install	At surface of clay liner below gravel	24,960	m	3.22	80,439
10 " PVC pipe install	At surface of clay liner below gravel	7,680	m	7.30	56,082
12 " suction line from sump		5,040	m	82.36	415,081
Install suction line	burried in berm (included in previous section)	5,040	m	0.00	-
10 " Shutoff valve	To isolate collection piping from sump	50	-	1464.13	73,206
12 " check valve	For suction line to maintain prime	25	-	3904.34	97,609
Sump	3 m dia. Culvert tank	25	-	20000.00	500,000
Install Sump	Install prior to berms, only need 3 m depth	25	-	3000.00	75,000
Level Actuators	2 per sump	50	-	50.00	2,500
EC meter	EC meter, data logger and supplies	25	-	5000.00	125,000
				subtotal =	**2,812,500**

Total Cost		
Item	**Cost ($)**	**$/m^3**
Earth Work	102,240,700	5.11
Waste Water System Placement	22,116,100	1.11
Collection System	2,812,500	0.14
Total Construction Cost	**127,200,000**	**6.36**

Note:
Material costs include assembly and installation.

Table 3.3 Operating costs for a new pulsed trickle freeze separation system.

Freezing Operation					
Activity/Material	**Details**	**Quantity**	**Units**	**Cost**	**Total Cost**
Generator fuel	Diesel for daily operation	864,000	L/150 days	1.20	1,036,800
Operator	Daily operation supervision (3 shifts)	66	weeks	1360.00	89,760
Melting Operation					
Activity/Material	**Details**	**Quantity**	**Units**	**Cost**	**Total Cost**
Generator fuel	Diesel for daily operation	864,000	L/150 days	1.20	1,036,800
Analytical	Laboratory analyses	1		5000.00	5,000
Operator	Daily operation supervision (3 shifts)	66	weeks	1360.00	89,760
Maintenance	5 % of mechanical and electrical	5,769,473	$	5%	288,474
Total Operating Cost				**Total =**	**2,547,000**
				$\$/m^3$	0.13

3.10 References

Ashton, G.D. 1980. Freshwater ice growth, motion, and decay. In: Dynamics of Snow and Ice Masses, S.C. Colbeck, Editor. New York: Academic Press, Harcourt Brace Javanovich Publishers. pp 261-304.

Buros, O.K. 2000. The ABCs of Desalting. International Desalination Association. Massachusetts, USA.

CRC Press. 1999. Environmental Engineers' Handbook CRCnetBASE 1999 CD-Rom. CRC Press LLC, Boca Raton, Florida.

Dawson, R.F., Sego, D.C., and Pollock, G.W. 1999. Freeze-thaw dewatering of oil sands fine tails. Canadian Geotechnical Journal, **36**: pp 587-598.

Dore, M. 2005. Forecasting the economic costs of desalination technology. Desalination **172**: pp 207-214.

Fertuck, L. 1969. Water purification by freezing in resovoirs, work done during the season 1968-1969. Saskatchewan Research Council Report E 69-12, November 1969.

Gao, W. 1998. Partial freezing by spraying as a treatment alternative of selected industrial wastes. Ph.D. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, 1998.

Landcare Research and Consulting. 1996. Baseline Soil Survey, Soil Interpretations and Terrain Analysis of the Aurora Mine Local Study Area. Report prepared for Syncrude Canada Ltd. February, 1996, by Landcare Research and Consulting, C.L. Palylyk Consulting and Spatial Information Systems Laboratory. p. 198, 9 maps.

MacKinnon, M. 2004. Oil sands water quality issues: properties, treatment and discharge options. In CONRAD Oilsands Water Usage Workshop , Fort McMurray, Alberta.

Madwar, K. and Tarazi, H. 2002. Desalination techniques for industrial wastewater reuse. Desalination **152**: pp 325-332.

Martel, C. J. 1989. Development and design of sludge freezing beds. American Society for Civil Engineering Journal of Environmental Engineering, **115**:4 799-808.

Martin, S. 2002. Environmental Remediation Costs Data – Unit Price. 8th Edition. RS Means Company. Kingston, MA.

Mielke, J.E. 1999. Desalination R&D: The New Federal Program. Congressional Research Service (CRS) Report for Congress.

Mossman, M.J. 2002. Mechanical Cost Data. 25th Edition. RS Means Company. Kingston, MA.

Spencer, E. 2004. Heavy Construction Cost Data. 18th Edition. RS Means Company. Kingston, MA.

Van der Bruggen, B. and Vandecasteele, C. 2002. Distillation vs. membrane filtration: overview of process evolutions in seawater desalination. Desalination **143**: pp 207-218.

Voutchkov, N. 2005. Desalination - Water for the next generation. Filtration & Separation, **42**:2 PP 14-25.

Willoughby, A. 2005. Freeze Separation to Treat Swine Manure. M.Sc Thesis. Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, 2005.

4. CONCLUSIONS

Pulse-trickle freeze separation for the treatment of saline oil sands waste water was the focus of this research. Freeze separation may provide an environmentally sustainable, economical, treatment alternative for oil sands waste water. To explore this concept, laboratory testing was conducted to validate an existing mathematical model for trickle freeze separation of saline waste water. Results from the laboratory experiments were then used to design a field scale treatment system for saline oil sands mine waste water. The following sections detail the conclusions for this research.

4.1 Laboratory Experiment Results

The purpose of the laboratory experiments was to investigate the feasibility of pulse-trickle freeze separation for the concentration of salts from salt contaminated water. Research objectives included validating a freeze separation mathematical model and determining the degree of salt separation achieved during the freeze separation process. To achieve the objectives, freezing experiments were conducted in a flume. The experiments showed the assumptions concerning the freezing mechanisms used to develop the mathematical model for trickle freeze separation did not agree with experimental observations. The initial salt concentration did not significantly affect the ice production rate. A seven fold increase in salt concentration resulted in only a 7 % drop in ice production rate. Production of slush and subsequent channeling in the flume tests hindered the freeze separation process. An operational design must avoid the development of channeling to achieve efficient freezing. Melting actually proved to be more effective at concentrating salts than the freezing process. More than 80 % of the salts could be concentrated during melting into less than one third of the original volume. The pulse-trickle freeze separation method developed during this research may provide an environmentally sustainable treatment alternative for the oil sands waste water.

4.2 Field System Design and Limitations

Utilizing results from the laboratory scale experiments, a pulse-trickle freeze separation system was designed for 20 million m^3/year of saline oil sands process water. The freezing cells for the pulse-trickle system require an area approximately 2.5 km square. The capital investment for construction of the pulse-trickle freezing system was $127 million or $6.36/$m^3$ capacity. Yearly operating costs amounted to $0.13/$m^3$ of waste water. Unit costs amortized over 30 years at 8% were $0.69/$m^3$ of waste water.

It must be realized that the field system design is based on laboratory results. Field pilot scale testing must be conducted to confirm operating and design parameters and to develop a more accurate cost estimate. Limitations of the current design include the large containment cell required to house the produced ice, the reliance on variable climatic conditions as a key operational parameter, and the large capital investment required. The potential of this relatively simple desalination technique must be realized in order to overcome the limitations.

4.3 Recommendations for Future Work

Field testing is required to verify several operating parameters and techniques. Waste water placement rates need to be determined at various ambient temperatures other than -15 °C to optimize the freezing rates. Several placement techniques should be tested other than the proposed central fountain discharge to determine the most efficient method. The depth of ice that can be melted in a given year needs to be confirmed at the field scale, on location. The melting depth will determine the size of the freezing area required. Freezing experiments using actual mine waste water instead of simulated saline water is also required. The ability of pulse-trickle freeze separation for treatment of oil sands waste water is demonstrated by this research, but further work is required before it may be considered a robust treatment alternative.

Appendix 1: Relationship between Electrical Conductivity and Sodium Chloride Concentration

In an effort to reduce the number of chemical analyses required for the freeze separation experiments, a relationship was determined between NaCl salt concentrations and electrical conductivity (EC).

1.1 Prepared Sample Relationship

A series of standard solutions were prepared at various concentrations of table salt (NaCl) in Edmonton tap water. The EC was measured using a Fisher Scientific Accumet AR50 Dual meter calibrated to 10.43 mS/cm calibration solution. Due to the temperature dependence of EC, all measurements were taken at 2 °C. This temperature was estimated as the most common sample temperature to be encountered during the experiments. The relationship between NaCl concentration (C_{NaCl}) and EC can be seen in Figure A1.1. Error bars were based on equipment accuracy. Due to the non-linear behaviour of EC with high solute concentration, two relationships were calculated using Excel polynomial curve fitting tools:

$$C_{NaCl}\ (mg/L) = 2.55(EC)^2 + 735(EC) - 473 \qquad (EC < 80\ mS/cm) \qquad [A1.1]$$

$$C_{NaCl}\ (mg/L) = 7.72(EC)^2 - 250(EC) + 46732 \qquad (EC > 80\ mS/cm) \qquad [A1.2]$$

1.2 Analytical Sample Relationships

To assess the accuracy of the relationships, concentrations for sodium and chloride from experimental samples determined via ion chromotography were plotted versus corresponding EC based calculated concentrations (equations A1.1 and A1.2) in Figure A1.2. Measured concentrations were generally less than the calculated concentrations. Since the table salt used in preparing the standard solutions was likely not pure NaCl and the tap water also contained a small amount of dissolved species, this phenomena was not unexpected. Additional relationships were determined using the measured sodium and chloride concentrations and corresponding EC to complement the initial relationships. Relationships for EC less than (equations A1.3 and A1.5) or greater than 80 mS/cm (equations A1.4 and A1.6) can be found in Figures A1.3 and A1.4, respectively. The following relationships can be used to determine sodium (C_{Na}) and chloride (C_{Cl}) concentrations from EC, calculated using Excel polynomial curve fitting tools::

C_{Na} (mg/L) = $1.14(EC)^2 + 252(EC) + 3.99$ (EC < 80 mS/cm) [A1.3]

C_{Na} (mg/L) = $8.88(EC)^2 - 1567(EC) + 105593$ (EC > 80 mS/cm) [A1.4]

C_{Cl} (mg/L) = $1.67(EC)^2 + 354(EC) - 25.8$ (EC < 80 mS/cm) [A1.5]

C_{Cl} (mg/L) = $13.9(EC)^2 - 2583(EC) + 172886$ (EC > 80 mS/cm) [A1.6]

A1.3 Figures

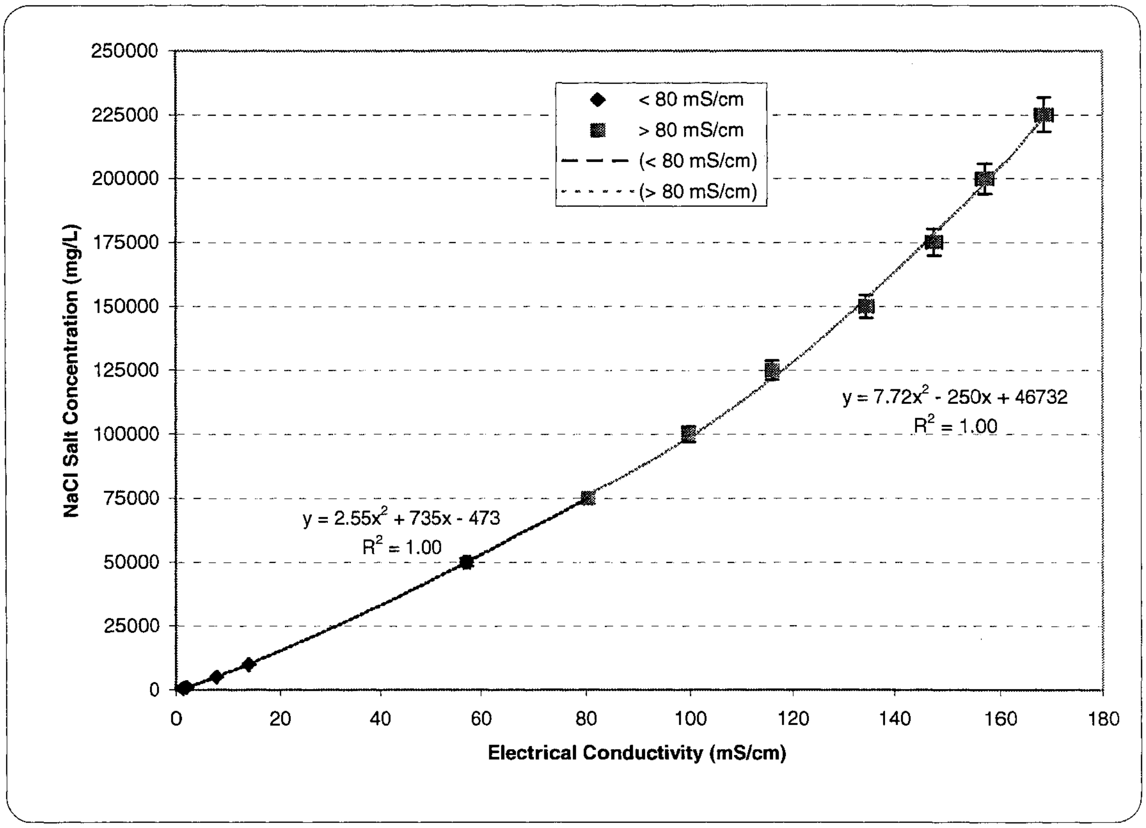


Figure A1.1 Calibration curves for electrical conductivity (EC) of prepared sodium chloride solutions for EC greater and less than 80 mS/cm.

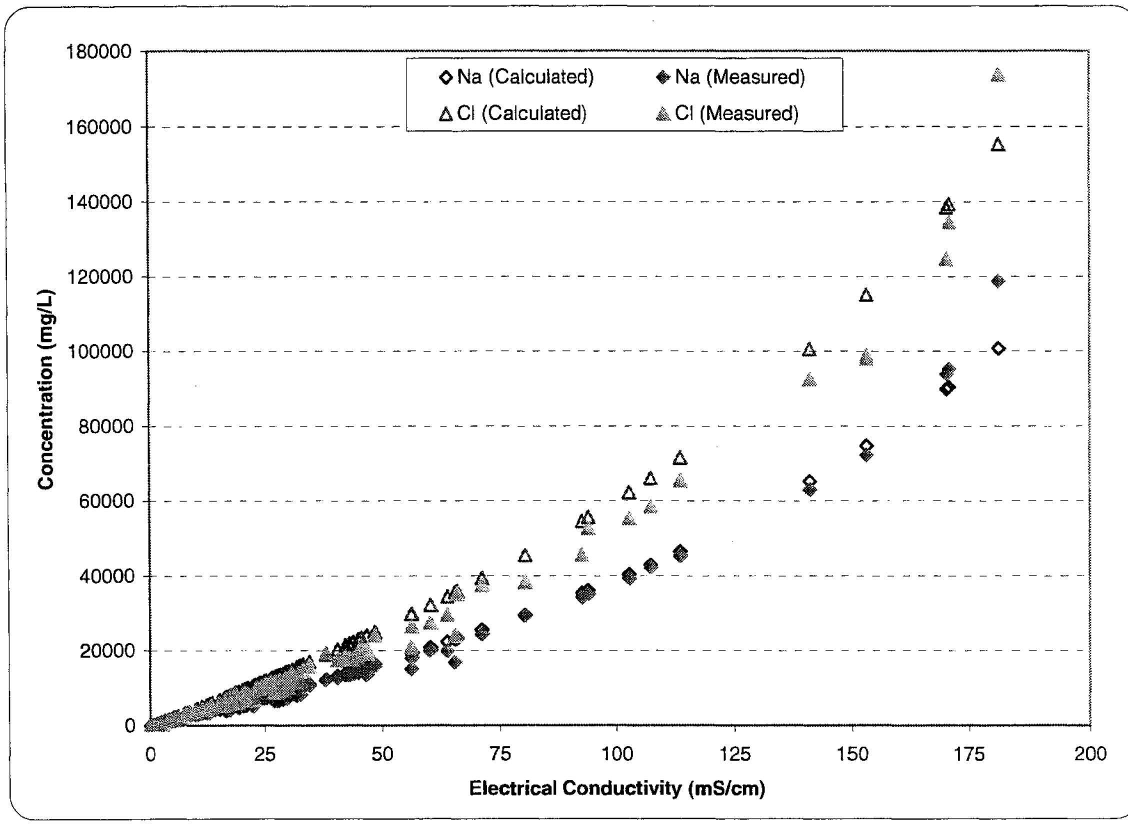


Figure A1.2 Comparison of calculated and measured concentrations for sodium and chloride at a given electrical conductivity.

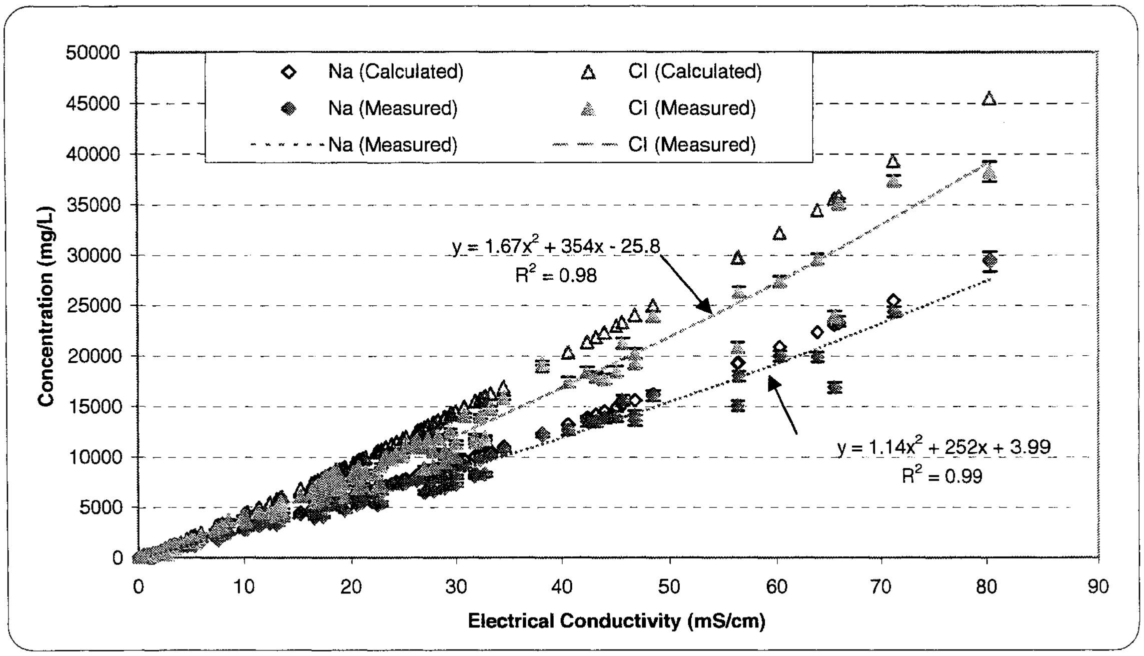


Figure A1.3 Calibration curves for electrical conductivity (EC) of laboratory analysed sodium and chloride for EC less than 80 mS/cm.

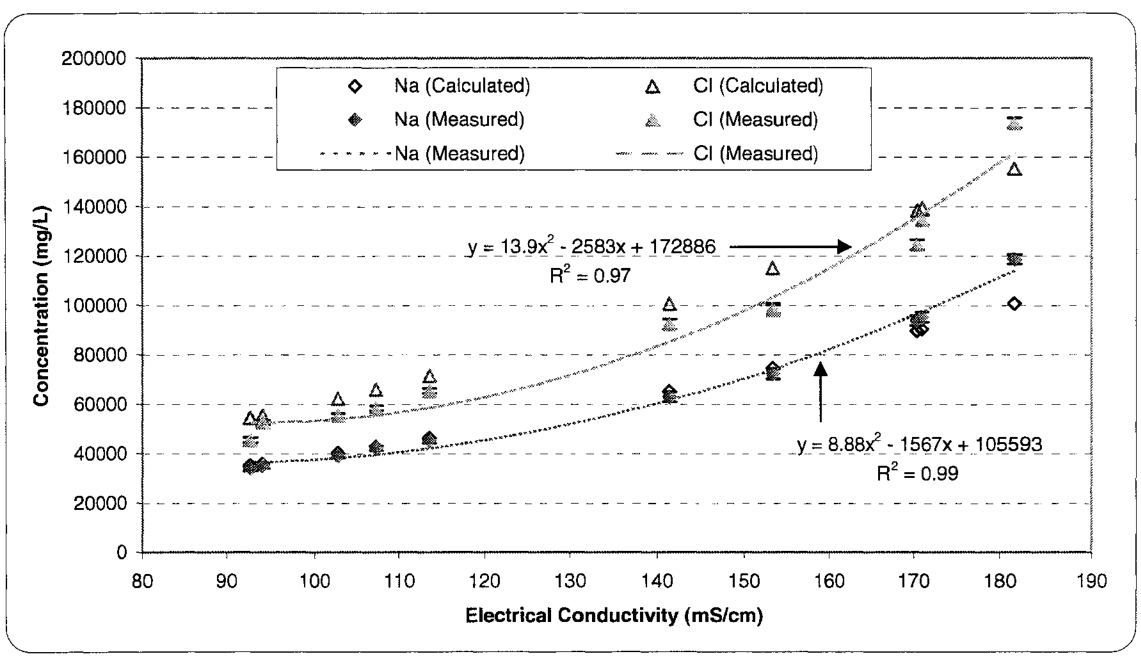


Figure A1.4 Calibration curves for electrical conductivity (EC) of laboratory analysed sodium and chloride for EC greater than 80 mS/cm.

Appendix 2: Load Cell Calibration

To measure the volume of collected runoff with time during the freezing and melting experiments, a load cell was utilized. A plastic barrel connected to the flume collection gutter was set upon the load cell. During the experiments, runoff was conveyed into the barrel. The load cell, connected to a data logger, provided load measurements with time. This information was required to aid in the mass balance calculations. To convert the load cell output to mass of water, a calibration was required. To determine the calibration, the barrel and load cell were set upon a standard scale. Water was added incrementally to the barrel and the corresponding load cell output was recorded. Two sets of calibrations were conducted. The relationship between load cell output and incremental mass of water can be found in Figure A2.1. To determine the mass of water from the load cell output (mV) the following conversion was obtained:

$$0.0216 \text{ mV/kg of water} \qquad [A2.1]$$

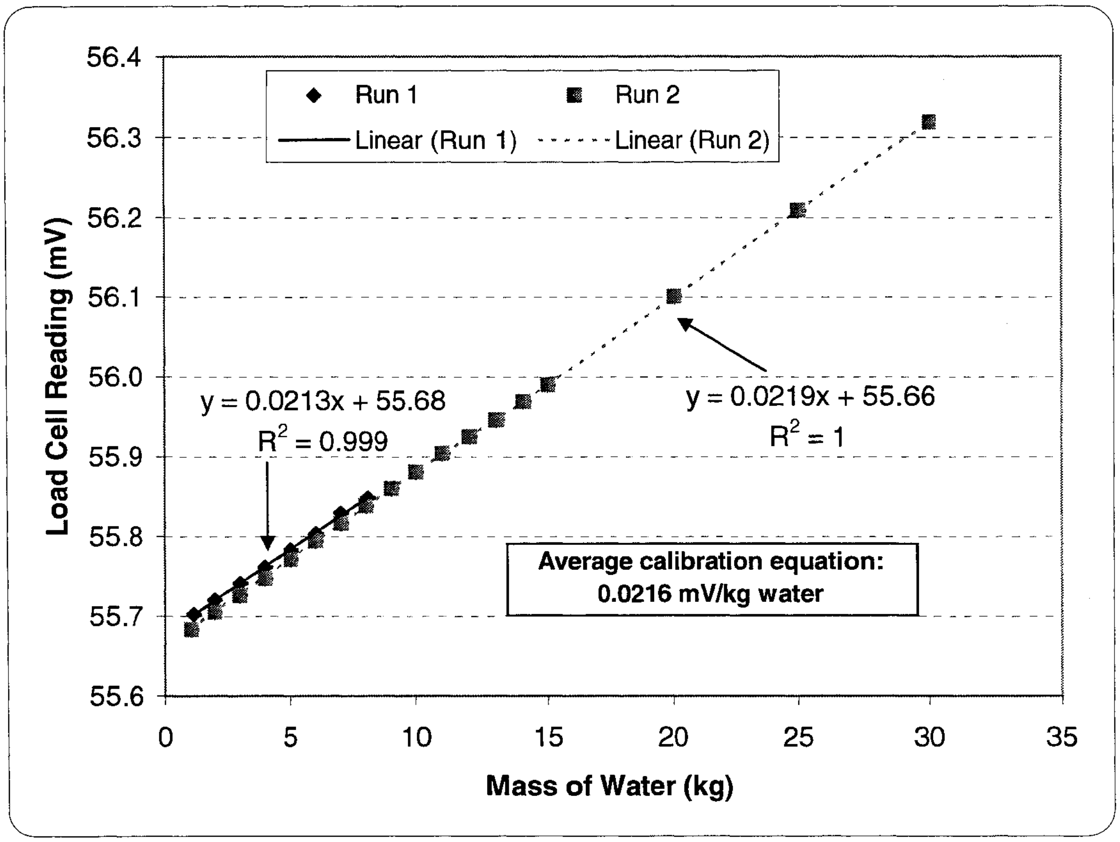


Figure A2.1 Relationship between load cell ouput and incremental mass of water.

Load cell ouput and mass of water data for determination of load cell calibration

	Scale		Load Cell	
	Mass kg	error kg	Output mV	error mV
Run 1				
	1.160	0.005	55.702	0.001
	2.015	0.005	55.720	0.001
	3.020	0.005	55.741	0.001
	4.015	0.005	55.761	0.001
	5.025	0.005	55.783	0.001
	6.030	0.005	55.803	0.001
	7.010	0.005	55.829	0.001
	8.080	0.005	55.848	0.001
Run 2				
	1.050	0.005	55.683	0.001
	2.000	0.005	55.705	0.001
	3.010	0.005	55.726	0.001
	4.005	0.005	55.747	0.001
	5.025	0.005	55.771	0.001
	6.015	0.005	55.794	0.001
	7.020	0.005	55.816	0.001
	8.010	0.005	55.838	0.001
	9.035	0.005	55.860	0.001
	10.030	0.005	55.881	0.001
	11.025	0.005	55.904	0.001
	12.045	0.005	55.925	0.001
	13.020	0.005	55.946	0.001
	14.055	0.005	55.969	0.001
	15.020	0.005	55.990	0.001
	20.065	0.005	56.101	0.001
	25.015	0.005	56.209	0.001
	30.035	0.005	56.319	0.001

Appendix 3: Freezing Trials for Optimization of Flow Rate and Ice Production

In an effort to increase the separation efficiency of the freezing experiments, freezing trials were conducted. Several freezing experiments were performed to find the optimal discharge method that would reduce the erosion of slush ice and increase the volume of produced ice.

3.1 Optimal Flow Rate

One way to increase the amount of produced ice was by pulsing the flow into the flume. Pulsed discharge would allow more sensible and latent heat to be removed from the salt solution compared to continuous discharge. Four pulsing scenarios were investigated:

1. Discharge flow 2 minutes off and 1 minute on;
2. Discharge flow 4 minutes off and 1 minute on;
3. Discharge flow 6 minutes off and 1 minute on; and
4. Discharge flow 6 minutes off and 2 minutes an.

The average target discharge rate per minute for each cycle was approximately 2.2 kg/min (0.037 kg/s). To achieve the average discharge rate, pumping rates during the on cycle were adjusted accordingly. Channels eroded into the produced slush ice in scenarios 1 and 2 due to insufficient heat removal (freezing) between pulses. Channels also formed in Scenario 3 because the pumping rate was too high. Scenario 4 offered an optimal balance between pumping and freezing with little channeling. Therefore, based on the trials, the optimum discharge method consisted of pulsed flow at 0.136 kg/s for 2 minutes on and 6 minutes off.

3.2 Prevention of Channeling

Channeling of the produced slush ice still occurred with pulsed discharge albeit to a lesser degree. To prevent the washout of the slush ice, additional modifications were required. Similar to silt fences in ditches, slush fences were designed to permit water movement but restrict solids movement, and their ability to reduce the detrimental effects of channeling was investigated. Several textile like materials were tested including cheese cloth, burlap, steel mesh with 6 mm openings, high density polyethylene (HDPE) mesh with 3 mm openings, and vinyl coated polyester window screen. The textiles were fixed to the front of a steel mesh frame with 6 mm openings for support. The steel frames were 10 cm high and 61 cm wide to fit within the flume (Figure A3.1). The textile slush fence was then situated down gradient of a simulated channel (Figure A3.2). The ability of each textile to disperse flow and prevent the washout of slush was observed.

Water froze to the upstream surface on the cheese cloth and burlap fences leading to ponding of the flowing water. Very little flow passed through these fences because the openings were too small. The steel mesh and HDPE mesh allowed the flow to pass with little or no ponding. Due to the large openings, they were not able to disperse the water in the channel. The window screen was the best suited for dispersing the flow and preventing washout of the slush (Figures A3.3 and A3.4). Therefore, to prevent the channeling and erosion of slush, fences consisting of vinyl coated window screen on a steel mesh frame were installed in the flume.

A3.3 Figures

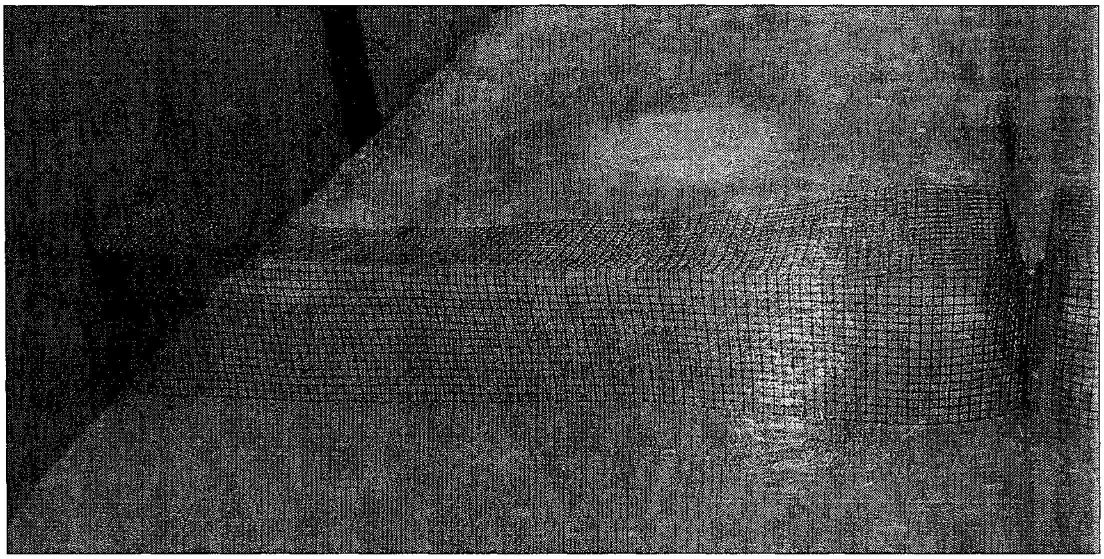


Figure A3.1 Slush fence steel support frame positioned in the flume.

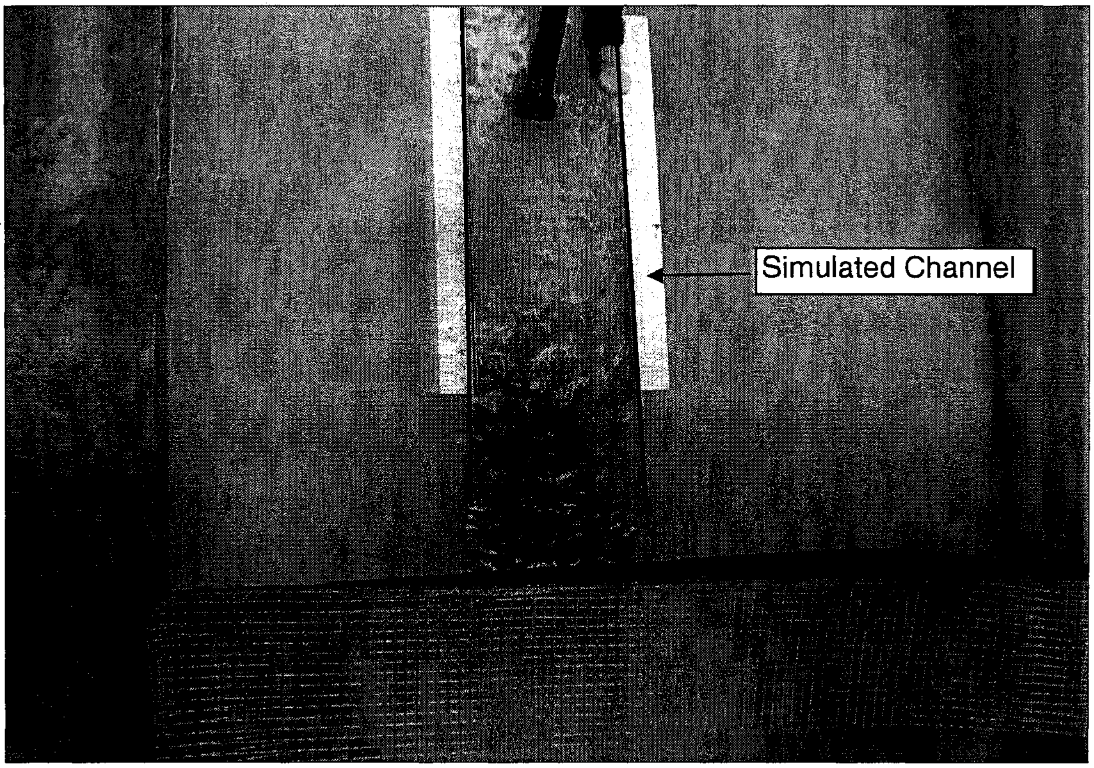


Figure A3.2 Simulated channel upstream of experimental slush fence.

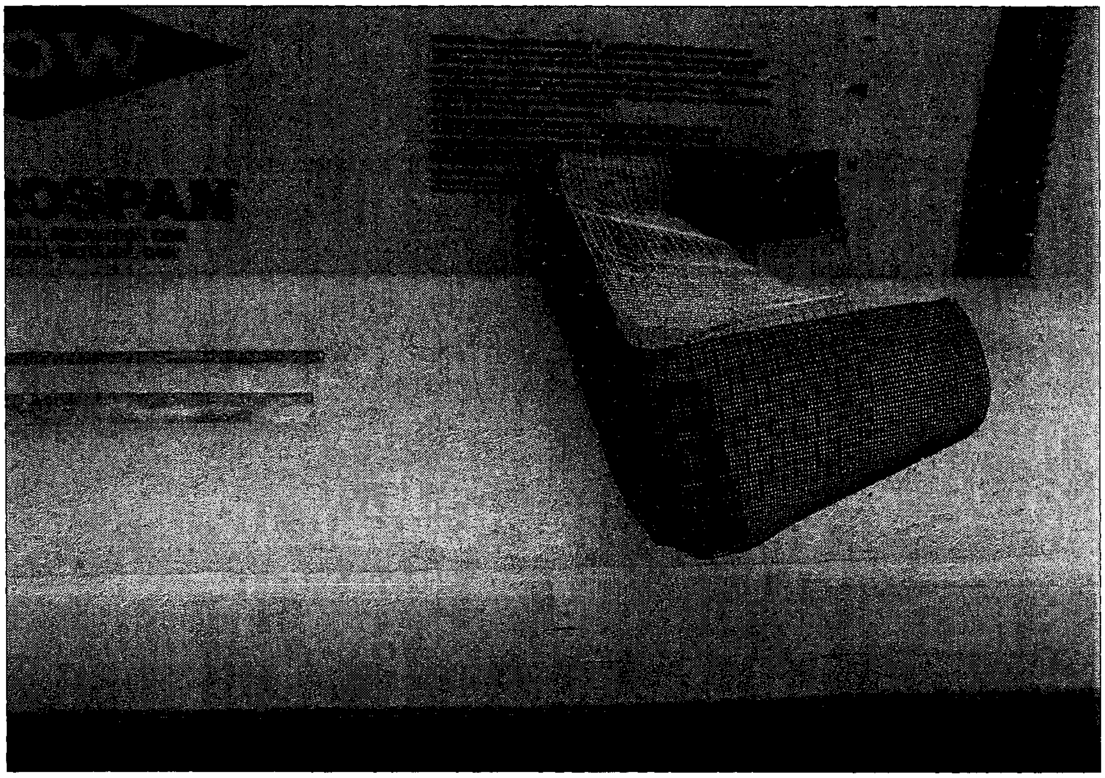


Figure A3.3 Window screen slush fence installed in the flume.

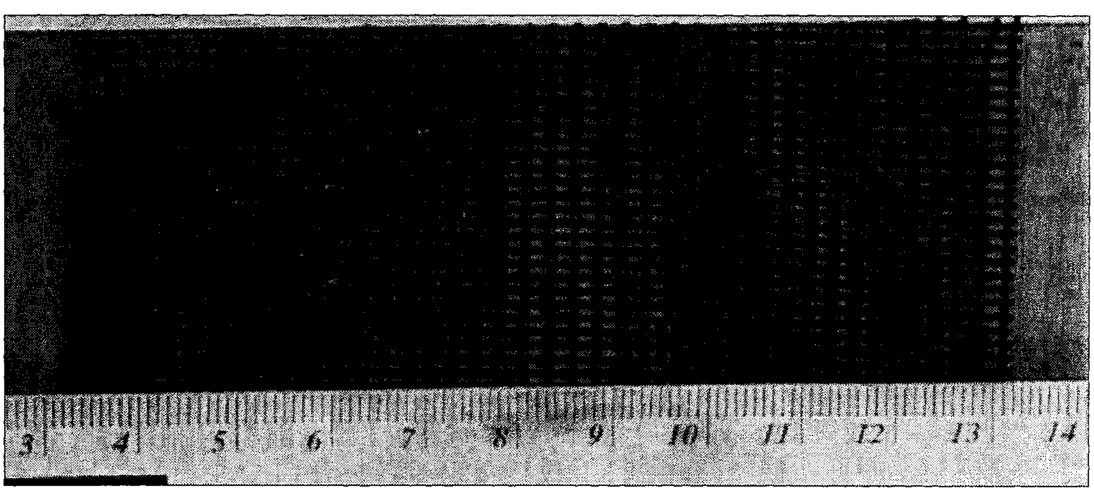


Figure A3.4 Closeup view of the window sceen

Appendix 4. Experimental Observations

Flume station number and corresponding horizontal distance

Station Number (Stn #)	Horizontal Distance (cm)
1	0.1
2	122
3	243
4	366
5	488
6	643
7	799
8	921
9	1043
10	1165
11	1287

Freeze Test 1 Sample Collection Data

Sample	EC (mS/cm)
inline Grab	1.005
tank Grab	1.004

Freeze Test 3: Experimental Observation Records

Test Name	Freeze Test 3	Room Temperature	-30 C
		Flow Rate	0.14 kg/s m
Date	Oct-05	Salt Concentration	22800 mg/L (NaCl)

Date/Time Oct. 5/04	
11:11	Start Flow. Filled width of flow path - no channels. Leading edge flowing evenly - no channels. Flow channel now evident on outside edge going into corner. No frazil ice forming at advance front in middle of bend.
11:20	Flow now midway through flume.
11:26	Fluid now past the bend. Some ice form at the leading edge, channel evident! Appears that frazil ice is freezing to the base and water fluid moves past it.
11:28	Frazil ice starting on straightaway.
11:30	Slowing down at 2 feet past the bend. Drop dye in some areas are stagnant. Ice dam formed at 800 cm. Dam failure leading to rapid drainage. Slush in the EC cell. Samples are now from gutter not EC cell. Once the reservoir behind the ice dam drained, channels were cut into the frazil ice up to the dam. The flow then started to develop ice again on the back straightaway - freezing process repeated itself. But EC did not increase anymore. One sample from in front of the water at the dam location had EC of 47 mS/cm. Sample was spilled and not kept. This sample was collected prior to breach of the dam. 5 cm of frazil ice built up behind and in front of the dam location. Flow meter dropped 4 % during the experiment. Unsure of exact time.
Oct. 6/04	Eutectic NaCl formed on the surface of the ice. Ice crystals in a flake pattern.

Freeze Test 3 Sample Collection Data

Date	Time	Sample	Horizontal Distance (cm)	Depth (cm below ice surface)	EC (mS/cm)	Sample Temperature (C)
5-Oct-04	9:24	IT inline	-	-	27.87	-
5-Oct-04	9:25	IT Tank	-	-	28.87	-
5-Oct-04	12:35	Dispenser	-	-	28.84	-
5-Oct-04	12:41	Dispenser 2	-	-	28.99	-
5-Oct-04	12:41	Tank 1	-	-	30	-
6-Oct-04	-	Core 1	1226	0-2.5	28.22	-
6-Oct-04	-	Core 1	1226	2.5-5	12.34	-
6-Oct-04	-	Core 2	1226	0-3	17.31	-
6-Oct-04	-	Core 2	1226	3-3.5	29.6	-
6-Oct-04	-	Core 3	1165	0-2.5	32.78	-
6-Oct-04	-	Core 3	1165	2.5-5	16.49	-
6-Oct-04	-	core 4	1043	0-0.5	56.33	-
6-Oct-04	-	core 4	1043	.5-2.5	32.73	-
6-Oct-04	-	core 4	1043	2.5-5	19.43	-
6-Oct-04	-	core 5	921	0-2	30	-
6-Oct-04	-	core 5	921	2.5-5.5	21.11	-
6-Oct-04	-	core 6	921	0-2.5	29.21	-
6-Oct-04	-	core 6	921	2.5-5.5	18.85	-
6-Oct-04	-	core 7	799	0-2.5	22.85	-
6-Oct-04	-	core 7	799	2.5-6	7.623	-
6-Oct-04	-	core 8	643	0-0.5	27.01	-
6-Oct-04	-	core 8	643	0.5-4	20.64	-
6-Oct-04	-	core 8	643	4-7.3	1.15	-
6-Oct-04	-	core 9	305	0-2	22.55	-
6-Oct-04	-	core 9	305	2-4	5.406	-
6-Oct-04	-	core 10	210	0-4	27.92	-
6-Oct-04	-	core 10	210	0-4	28.98	-

Freeze Test 4. Experimental Observation Records

Test Name	Freeze Test 4 (FT4)	Room Temperature	-15 C
		Flow Rata	0.10 kg/s m
Date	Nov. 16/04	Salt Concentration	20,000 mg/L (NaCl)

Date/Time	
Nov.16/04	
9:36	Start Flowing water
9:40	Leading edge of flow reached 1040 cm. Preferential flow path along wall and outside of curve
9:47	Leading edge of flow reached 1165 cm. Flow paths averaging from 12 to 6 cm wide evident up to 1040 cm.
9:51	Gutter reached. Flow in channel form until 920 cm then it spreads out. Frazil ice then produced.
10:00	Slush between 1040 and 1290 cm sliding down the slope floor. Flow to great or floor to steep?
	Lots of frazil ice over flow into gutter and into EC cell. EC of runoff may be diluted.
	End the test when EC is same as influent

Freeze Test 5. Experimental Observation Records

Test Name	Freeze Test 5 (FT5)	Room Temperature	-15 C
		Flow Rate	0.074 kg/s m
Date	Nov. 16/04	Salt Concentration	20,000 mg/L (NaCl)

Date/Time	
Nov.18/04	
	Adjust dispenser - block of foam at entrance to force flow into thin layer. Fill channels and pockets in ice from last test to make smooth flowing surface. used a spray bottle - led to a stippled surface affect.
10:35	Start test.
10:38	Flow is in a thin sheet - no channels evident yet.
10:40	Flow at Stn 4, no channels yet.
10:45	Channel developing into the corner. Outside edges freeze and then the flow eats through the ice and cuts a channel. The leading edge is not a channel yet
10:47	Front at stn 7 - no channels at front, flow evenly across flume width
10:55	Flow at stn 8
10:57	starting to dam up at stn 8. flow backing up to stn 6. Channels from beginning to stn 7 approx. 10-7 cm wide.
10:05	frazil ice very angular and platy card house structure. No ice layer on top. Still free water at surface.
11:06	Damming breach - slight drainage. Front advancing between stn 8 & 9 evenly. Channels form through frazil ice in curve section
11:09	flow spread from channel at stn 7-8 into frazil ice again. Front at stn 10
11:12	92 L flowed into flume so far. Front at stn 10.5. Channel from dispenser to stn 4 cut down to lexan base. From stn 7-10 no ice at surface of frazil ice flow. Frazil ice 2 cm thick at stn 8. Damming forming at stn 10.75. Very slow advancement of front now. Channel at stn 7 splits into two channels. 2 layers of ice evident between stn 7 - 8 in frazil ice.
11:38	EC 1 sample collected from dam location - free liquid.
11:40	back up water starting to go around corner stn 8-7-6.
11:47	Flow reached gutter. Just dribbling
12:05	surface not frozen between 7-11
12:50	ice surface frozen up to stn 10.5 frazil ice develops in EC chamber - ice forming in gutter flows into the EC cell.
12:53	Channel under the ice. Flow increased rapidly.
12:05	Channel now evident in frazil ice. Surface has sunken where channel is located. Flow increased a lot. In line EC meter dropped to 26 mS/cm same as input. 1:03
1:03	flow subsiding. Looks as though all ice is drained of pore fluid - short circuiting no more freeing.
1:15	Shut off pump.
Nov. 19/04	
	unfrozen water evident in channels. Collected 2 samples. Some fluid in gutter

Freeze Test 5 Sample Collection Data

Date	Sample	Horizontal Distance (cm)	Depth (cm)	EC (mS/cm)	Sample Temperature (C)
18-Nov-05	inlune EC 1		-	26.31	2
18-Nov-05	inftank 1		-	27.3	2
18-Nov-05	tank 2		-	28.64	2
25-Nov-05	Core 1	1290	0-3.3	18.17	3.1
25-Nov-05	Core 1	1290	3.3-5.9	13.36	3.1
25-Nov-05	Core 2 (outside)	1160	0-3.1	18.98	3.1
25-Nov-05	Core 2 (outside)	1160	3.1-5.4	20.58	3.1
25-Nov-05	Core 3 (inside)	1160	0-6.7	21.35	3.1
25-Nov-05	Core 3 (inside)	1160	0-6.7	21.39	3.1
25-Nov-05	Core 4	1040	0-2.8	15.14	3.1
25-Nov-05	Core 4	1040	2.8-5.7	19.22	3.1
25-Nov-05	Core 5	920	0-1.7	13.47	3.1
25-Nov-05	Core 5	920	1.7-5.5	16.22	3.1
25-Nov-05	Core 6 (outside)	800	0-4.4	18.58	3.1
25-Nov-05	Core 7	700	0-2.4	17.19	3.1
25-Nov-05	Core 7	700	2.4-4.2	18.89	3.1
25-Nov-05	Core 8 (outside)	360	0-2.5	18.59	3.1
25-Nov-05	Core 9 (outside)	240	0-1.2	12.32	3.1

Melt Test 4/5 Sample Collection Data

Date	Time	Sample	Cummulative Sample Mass (kg)*	EC (mS/cm)	Sample Temperature (C)
29-Nov-04	8:30:00	Melt 1	3.54	80.4	3
29-Nov-04	9:22:00	Melt 2	5.16	75.28	3
29-Nov-04	11:09:00	Melt 3	9.14	70.97	3
29-Nov-04	12:41:00	Melt 4	10.77	63.91	3
29-Nov-04	13:34:00	Melt 5	12.24	60.34	3
29-Nov-04	14:35:00	Melt 6	15.75	58.14	3
29-Nov-04	16:12:00	Melt 7	19.84	54.85	3
29-Nov-04	18:38:00	Melt 8	29.16	47.41	3
30-Nov-04	8:22:00	Melt 9	64.79	27	3
30-Nov-04	9:22:00	Melt 10	69.13	26.66	3
30-Nov-04	10:22:00	Melt 11	73.17	25.49	3
30-Nov-04	11:37:00	Melt 12	76.46	24.76	3
30-Nov-04	12:42:00	Melt 13	78.23	22.6	3
30-Nov-04	13:52:00	Melt 14	77.58	22.76	3
30-Nov-04	16:39:00	Melt 15	82.65	20.7	3
30-Nov-04	18:49:00	Melt 16	86.91	18.79	3
30-Nov-04	19:42:00	Melt 17	89.72	18.22	3
1-Dec-04	8:07:00	Melt 18	111.08	11.55	3
1-Dec-04	9:26:00	Melt 19	115.02	10.92	3
1-Dec-04	10:42:00	Melt 20	115.40	10.29	3
1-Dec-04	11:46:00	Melt 21	116.79	8.955	3
1-Dec-04	13:44:00	Melt 22	119.62	8.9112	3
1-Dec-04	14:50:00	Melt 23	123.29	8.353	3
1-Dec-04	15:44:00	Melt 24	124.04	7.939	3
1-Dec-04	22:11:00	Melt 25	126.62	5.037	3
2-Dec-04	8:37:00	Melt 26	140.15	2.755	3
2-Dec-04	12:00:00	Melt 27	142.97	2.331	3
2-Dec-04	13:58:00	Melt 28	145.43	1.957	3
3-Dec-04	8:17:00	Melt 29	148.63	0.836	3
3-Dec-04	15:01:00	Melt 29	160.45	1.475	3
3-Dec-04	20:50:00	Melt Final	161.43	0.813	3
1-Dec-04	22:15	Drip 1	-	6.355	3
1-Dec-04	22:15	Drip 2	-	5.815	3
2-Dec-04	13:15	Drip 3	-	4.295	3

* based on data from load cell collection system

Freeze Test 6. Experimental Observation Records

Test Name	Freeze Test 6 (FT6)	Room Temperature	-15 C
		Flow Rate	0.16 kg/s (pulse 6 to 2)
Date	7-Jan-05	Salt Concentration	22,800 mg/L (NaCl)

Date/Time	
7-Jan-05	
	947 L at 20000 mg/L (35 %)
	Flow test Vo = 7.425, Vf = 7.265
	EC test Vo = 7.365, Vf = 7.394, EC stable at 29.00 mS/cm
	Times EC logger (10:21), phone (10:23), temp logger (10:19), phone (10:21)
10:28	Start Vo = 7.398
	lead reached stn 8, final position was 9.5
10:36	Pulse 2 - reached stn 6.5 slight flow to inside,
	Pulse 3 - flow reached stn 10.5 after draining
10:54	pulse 4 channeling along inside (13 cm)
	flow reached gutter decrease flow to 30 % for remainder of test
11:07	free water at stn 9-11 continuous draining now possibly no more freezing just
11:13	elevation not increasing any more just flow under surface in channels and drain
11:20	terminate, Vf 7.525
	water flowed under frazil ice starting at bend and channeled to gutter. Any fluid that was added then drained with no freezing.
	flow was slightly to high,

Freeze Test 7. Experimental Observation Records

Test Name	Freeze Test 7 (FT7)	Room Temperature	-15 C
		Flow Rate	0.136 kg/s (pulse 6 to 2)
Date	11-Jan-05	Salt Concentration	2000 mg/L

Date/Time	
11-Jan-05	No ice base only glass Check EC standard 10.43 mS/cm OK EC test Vo 9.066, Vf 9.106, Flow test, Vo 9.128, Vf 9.150 Star test 888 L Vo 9.150
10:23	Start, flow reached stn 7 flowed evenly, surface ice very rough and wavy, a finger of fluid reached stn 8 along inside wall
	pulse 2 - flow over existing ice/frazil ice - almost evenly in sheet flow - reaches stn 8, rough frazil ice in first half of flow until stn 6 then smooth but free water still in stn 6 to 8 some free water in first half, frazil platy ice after stn 6-9
	rough ice appears to drain after flow stop, air bubbles evident under ice, flow over ice until stn 7 where frazil ice is then flow is through ice, flow did not advance past stn 8
10:51	Frazil ice (7-9) a lot more ice and stronger, less free water than at 20000mg/L flow rate slows down considerably after bend
10:58	first half of flume very rough ice surface, ice changes after stn 7 to frazil slush
11:00	flow is damming up at stn 8-9 no advancement
11:08	flow reached stn 9.25, layer evident in stn 7-9 ice side profile.
11:18	reached stn 10 surface freezing between flows on 2nd half of flume (stn 7-9)
11:25	flow reached stn 10.5, platy rough surface now from 7-9, 9-10.5 water on surface frazily ice
11:30	flow reached gutter has not entered barrel yet
11:31	first sample from gutter
11:36	EC is 5.3 mS/cm in runoff
11:40	160 L pumped so far
11:42	sample gutter EC from inline is 5.05 mS/cm
11:43	elevation only changed between stn 10 and 11, channeling up to stn 4, over surface flow until stn 8 then flows through frazil ice
11:53	EC 3.23, flow goes under ice surface in bend ice drains at off period then fills up during pulse
12:00	ice up to stn 8 drains in off time and fills up when pulsing - no more all over surface flow, slight surface flow but drains away after pulse, elevations have not changed since 11:30 except at stn 10-11
12:10	EC 2.6, collect sample , elevation unchanged
12:35	no elevation changes EC 2.3 mS/cm, same as input therefore stop test Vf 9.427

Freeze Test 8 (FT8) Experimental Observation Records

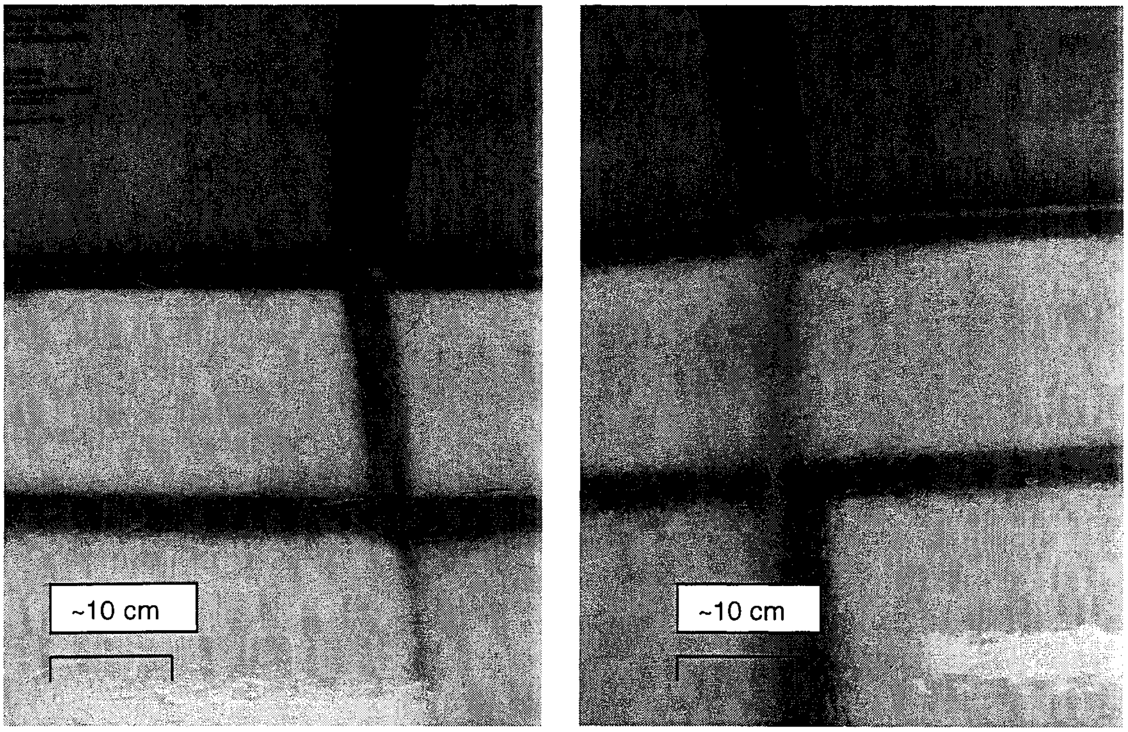
Room Temp	- 15 C	**NaCl Conc.**	3000 mg/L
Flow Rate	Pulse 6:2, 0.139 kg/s	**Date**	Feb 1 to Feb 4

Date/Time	Observations
Jan 31, 2005	976 L filled into tank, add 2.92816 kg to make 3000.2 mg/L
Feb 1, 2005	Need to set up a base layer of ice. Pump about 150 L into flume and stop
	Flow and EC test V0 = 18.859, Vf = 18.899. EC cell did not work right therefore retry. Tank EC sample = 5.110 mS/cm T = 10 C. Retry EC cell, Vo = 18.900, Vf = 18.914 EC is 4.35 mS/cm, T = 3.6 C therefore ok. Used 54 L from tank therefore only 922 L left. Install dam at station 3 where channeling usually occurs for preventative measures.
09:36	EC start time = 9:31, temp start 9:30
	Vo = 18.914
	Pulse 1 = flow reached stn 7 at end of pulse.
	Pulse 2 = flow reached stn 9, rough ice up to stn 8 then frazil ice
	Pulse 3 = front reached stn 7 as flow stopped, front advances as even flow
10:12	Stn 7.5 large plate like frazil ice approx 5cm not very dense. Frazil ice getting finer towards stn 9 final size is 1 cm and is very dense. See Figure A4.1.
10:19	V = 19.016. approx 100 L in flume fronts stopped at stn 10
10:22	Very little ice form at dispenser see picture
10:33	Flow head drained tips to stn 10.5. see video of flow from dispenser
10:39	First flow reached gutter collect sample.
10:43	Layers evident from stn 6 to 10
10:50	1 hour 14 min stop and let ice set up. V = 19.084. waited to long to stop as soon as drainage hits end I need to stop or I have too much drainage. ~ 5 L collected so far. EC probe peaked above 6 mS/cm and now is at 5.3 mS/cm. elevations from 10:43 same at end of last pulse, rapid drainage now occurring. Need to fill ice where dispenser was due to drainage.
11:06	Water is draining from ice at the bend – can see hollow porous ice structure.
11:27	Drainage evident from stn 5 to stn 7.5
11:33	Drain barrel 57.140 mV to 56.403 mV ~ 35 L, runoff subsided considerably.
11:40	Add water to flume to build up ice levels, add 10 L. See pictures of drained ice structure
11:57	Load cell 56.525 mV – flow almost stopped now approx 40 L total collected from this flow event, therefore 130 L in flume.
12:45	Unfrozen water from stn 7.5 to 11 under surface of ice – can deform surface with thumb, like a crust over the water.
13:11	Surface from stn 7.5 -11 just slightly deformable under high thumb pressure
15:45	Restart system, EC time start 6 h and 8 min. Vo = 19.100, time = 3:46, or 6h and 10 min.
	Pulse 1 = flow was even over top of old ice – some backing up a dam at stn 3 but eventually went through.
16:00	Pour hot water into (1L) gutter to remove ice blockage. EC increase due to temp
16:02	Stop flow Vf = 19.146, 6h 28 min. refilled hollow sections, flow reached stn 8. Add 2.5 L to dispenser end of flume. Flow tip reached stn 9.
Feb 2, 2005	
	No water runoff over night. Restart flowing water.

08:30	Drain 2.5 L from plumbing and EC cell to allow fresh water to be metered. Time check, 08:32 = 22 h 56 m, EC start 22h:58m
08:44	Start time 23h:08m, Vo = 19.149
	Pulse 1= flow reached stn 3 at shutoff, drain to stn 6.5. Flow freezes to ice base and surface with frazil/platelets in between. Flow was even together – no channels, flowed through dam evenly.
	Pulse 2 = plunge pool at dispenser – eating through previous ice. Advancing front flow over previous layers, flow reached stn 6.5
	Pulse 3 = flow reached stn 6.5. rough surface ice up to stn 5, frazil ice from 5 to 6.5, surface does not freeze
	Pulse 4 = flow reached stn 6.75
	Pulse 5 = flow fairly even – see photos before/after dam at stn 3. dam may be freezing up between pulses.
09:26	Flow is no longer over surface of old layers. More through the layers. As water enters flume response at stn 5, water pushes up through the surface ice skim. Front at stn 7
09:37	Install ice dam at stn 6.25. front is not moving , backing up water. Vol 19.260, ~ 110 L in flume
09:46	Ice level building up – no real advancement of ice front. Up to stn 3 layered rough ice surface freezes between pulses then water added. Stn 3-5 frazil ice and surface freezes Stn 5 to 7 no surface ice only frazil ice. Dispenser pool eaten to base lexan.
09:50	Leading tip passed stn 7
09:57	Pictures of ice surface and side profiles Surface not freezing at dispenser, plunge pool approx. 0.5 m in front of dispenser.
10:06	Stop 24 h:30 m, Vf = 19.324. Stop because from dispenser to stn 5 free water under surface of slush/ice. Short circuiting of flow and less freezing. Need to let ice set up before adding more fluid. Repulse in about 5 hours. Front at stn 7.25, final elevations at 10:06
11:30	Front at stn 8, from stn 1-6 unfrozen water under surface of ice need to wait until frozen solid.
12:15	Stn 8.5 is front
20:28	Leading front at stn 9 Unfrozen film of fluid on surface at front location, ice approx solid throughout flume.
20:31	Restart, EC logger time 24 h + 10h:55min (8:31), temp logger 24h 10 h:57m (8:33)
20:37	Vo=19.324, start flow 24 h + 11h:01 m
	Pulse 1 = centre line sunken ~ 0.5 – 1 cm from stn 2 to 4.5, ice drained to advance front. Flow reached stn 5. flow is retarded at stn 3 dam – must rise above old ice crust to pass through dam.
20:50	Rough surface ice up to stn 3. stn 3 to stn 6 frazil like ice.
20:58	Front at stn 6, surface of layer freezes up to stn 5 then unfrozen to stn 6 (frazil)
21:03	Flow after stn 3 – up through surface – not across / over. flow reached dam at stn 6.25
21:10	Waster is not advancing as far as before due to level surface of base ice. Nat as much frazil ice/layer ice forming.
21:18	Front at stn 6.5
21:27	115 L into flume large plunge pool at 0.75 m in front of dispenser.
21:40	Flow has not surpassed stn 6.5
21:55	Flow reached stn 6.75

21:59	Vf= 19.507, stop flow. 180 L in flume. Stn 1 to stn 4 fluid build up under ice, flow reached stn 7.
Feb 3, 2005	
10:40	Front reached stn 8.5 no runoff. EC logger time 48 h + 1h:13 m, 10:49 phone Start 1h:29, 11:05 AM, Vo = 19.507 Flow rate at 33 % (5 % > than previous)
	Centreline of flume (stn 1- to 4) approx 0.5 - 1 cm lower than edges. Flow reached stn 5 had to fill low levels in ice first.
	Pulse 2 – front reached stn 5.5 rough surface ice forming stn 2-3, 3-5.5 frazil like ice w/surface ice layers.
	Pulse 3 = front reached stn 6 advancing evenly, front edge freezes to ice base and is dense frazil ice.
11:35	Rough surface ice to stn 5 Frail ice with no surface ice from stn 5 to 6.25 Ice/flow at dam at stn 6.25. ~ 5mL of unfrozen water in gutter, see picture
11:39	93 L so far in flume. Freezing as before. Clear dam face at stn 6.25, flow advance to stn 7
11:51	Clean 6.25 dam – flow advance to stn 7.25
12:05	Front at stn 7.25, V = 19.655 ~ 150 l in flume now. Ice surface rough and freezes up to stn 6 Frazil ice unfrozen surface stn 6- 7.75
12:07	Plunge pool at dispenser. Water under ice surface stn 1 to stn 4.5 then layered frazil ice to stn 7.75. stop after next pulse.
12:11	Stop 48 h + 2 h:35 min, Vf = 19.675, Vol 168 L
12:15	Front at stn 8 Barrel 56.055. no runoff.
13:35	Front at stn 9.75, no runoff
18.14	Restart EC logger, 48 h 8 h 38 m, ~ 168 L left in tank
18:43	Start flowing, (48 = 9h 07 min) Vo = 19.677 at 33%. Centre line sunken again stn 1 to 5 Stn 5 to 7 ice drained slightly, can see clear ice instead of blue filled ice. Leading edge of ice at stn 10.25
	Pulse 1 - filled centre depression up to stn 4.5 continuing as before
19:12	Reached stn 6.25 dam, 75 L in flume. Freezes as before
19:17	Rough surface ice up to stn 5, then frazil ice 5 to 6.5
19:25	Front at 6.75 ~110 L in flume so far in flume,
19:40	Plunge pool a dispenser, surface is froze, water flows under ice surface to front at stn 7
19:42	Vol 19.820, 142 L
19:49	Stop vf = 19.837, 160 L in flume. Insert dispenser rtd into ice/water mixture at stn 2 approx .7 from surface of ice
19:55	Front at stn 7.25
Feb 4, 2005	
08:30	Front reached stn 9.75 overnight put rtd from tank into room air for logging purposes.
Feb 6, 2005 Ice cores	
Stn 3a (inside)	14.5 cm layers evident, solid.
Stn 3b (outside)	14.5 cm same as above. Sample preserved in cold room

Stn 4	15 cm, Layers evident, solid, see picture and ice elevation sheet. Bands correspond to flow regimes very well. RTD stn 2 cm, wall rtd 4cm, stn rtd 8 cm placed in core hole measured from base of flume.
Stn 6	17 cm layers evident, solid structure, some hollow spots
Stn 7a (inside)	15 cm layers evident, porous layer at 3-4.5 cm from top (angular platy ice). Porous layer at 11.8-13 cm from top – hollow cavities like it was drained. Preserved.
Stn 7b (outside)	15 cm, Layers evident porous structure not as defined.
Stn 8	12.3 cm, layers evident. Solid structure, bubbles at base.
Stn 9	7.7 cm, layered ice, solid see pictures. RTD stn 10 at 1 cm and wall RTD at 4.5 cm from base.
Stn 10a (inside)	5 cm, 3 layers evident bubbles and softer ice at base as compared to top
Stn 10b (outside)	Preserved.
Stn 10.5	3.4 cm, solid ice, some bubbles evident in bottom 0.5 cm of sample



a. b.

Figure A4.1 a. Large (5 cm), vertical platelet ice crystals at station 7.5 to 8.
b. Finer (1 to 2 cm), dense, vertical platelet ice crystals at station 9.

Freeze Test 8 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
Influent Samples						
Feb-01	8:50	EC tank 1	-	-	4.623	1.2
Feb-01	9:00	EC inline	-	-	4.628	1.2
Feb-03	10:50	Ec tank 2	-	-	4.632	1.2
Ice cores Before Melting						
Feb-11	-	Core 3a	0-2.5	-	3.091	1.2
Feb-11	-	Core 3a	2.5-5.5	-	3.191	1.2
Feb-11	-	Core 3a	5.5-8.5	-	2.686	1.2
Feb-11	-	Core 3a	8.5-13	-	2.869	1.2
Feb-11	-	Core 4	0-2.5	-	2.905	1.2
Feb-11	-	Core 4	2.5-5.5	-	2.847	1.2
Feb-11	-	Core 4	5.5-8.5	-	2.538	1.2
Feb-11	-	Core 4	8.5-12.5	-	2.454	1.2
Feb-11	-	Core 4	8.5-12.5 dup	-	2.52	1.2
Feb-11	-	Core 6	0-2	-	3.263	1.2
Feb-11	-	Core 6	2-5.5	-	2.173	1.2
Feb-11	-	Core 6	2-5.5 dup	-	2.15	1.2
Feb-11	-	Core 6	5.5-8.5	-	2.417	1.2
Feb-11	-	Core 6	8.5-12	-	2.681	1.2
Feb-11	-	Core 6	12-16	-	2.723	1.2
Feb-11	-	Core 7	0-3	-	2.41	1.2
Feb-11	-	Core 7	3-6	-	2.944	1.2
Feb-11	-	Core 7	6-8.5	-	2.607	1.2
Feb-11	-	Core 7	6-8.5 dup	-	2.593	1.2
Feb-11	-	Core 7	8.5-11	-	2.646	1.2
Feb-11	-	Core 7	11-14.5	-	3.312	1.2
Feb-11	-	Core 8	0-2	-	2.277	1.2
Feb-11	-	Core 8	2-5	-	2.402	1.2
Feb-11	-	Core 8	5-7	-	3.803	1.2
Feb-11	-	Core 8	7-9.5	-	2.951	1.2
Feb-11	-	Core 8	9.5-12.3	-	3.009	1.2
Feb-11	-	Core 9	0-1.5	-	3.987	1.2
Feb-11	-	Core 9	1.5-4.0	-	3.505	1.2
Feb-11	-	Core 9	4-7	-	3.175	1.2
Feb-11	-	Core 10	0-2	-	6.165	1.2
Feb-11	-	Core 10	0-2 dup	-	6.418	1.2
Feb-11	-	Core 10	2-4.5	-	5.343	1.2
Feb-11	-	Core 10.5	-	-	5.144	1.2
Ice Cores after Melting						
Mar-08	-	M3	0-2.5 dup	-	0.139	1.2
Mar-08	-	M3	0-2.5	-	0.11	1.2
Mar-08	-	M3	2.5-5	-	0.194	1.2
Mar-08	-	M3	5-7.5	-	0.318	1.2
Mar-08	-	M3	7.5-10	-	0.279	1.2
Mar-08	-	M4	0-2.5	-	0.279	1.2
Mar-08	-	M4	2.5-5	-	0.464	1.2

Freeze Test 8 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
Mar-08	-	M4	5-9	-	0.682	1.2
Mar-08	-	M4	9-11	-	0.851	1.2
Mar-08	-	M6	0-2.5	-	0.223	1.2
Mar-08	-	M6	2.5-5	-	0.346	1.2
Mar-08	-	M6	5-7.5	-	0.586	1.2
Mar-08	-	M6	7.5-11	-	0.837	1.2
Mar-08	-	M6	11-14	-	0.874	1.2
Mar-08	-	M6	11-14 dup	-	0.875	1.2
Mar-08	-	M7	0-2.5	-	0.417	1.2
Mar-08	-	M7	2.5-5.	-	0.541	1.2
Mar-08	-	M7	5-7.5	-	0.728	1.2
Mar-08	-	M7	5-7.5 dup	-	0.744	1.2
Mar-08	-	M7	7.5-10.5	-	0.811	1.2
Mar-08	-	M7	10.5-1	-	0.907	1.2
Mar-08	-	M8	0-2.5	-	0.24	1.2
Mar-08	-	M8	2.5-5	-	0.619	1.2
Mar-08	-	M8	5.0-7.0	-	0.4897	1.2
Mar-08	-	M8	7.0-9.5	-	0.912	1.2
Mar-08	-	M9	0-2.0	-	0.589	1.2
Mar-08	-	M9	2.0-4	-	0.3	1.2
Melt Runoff Samples						
Feb-08	9:40	melt 1	-	0.3	170.4	1.2
Feb-09	11:33	melt 2	-	2.5	166.3	1.2
Feb-10	9:30	melt 5	-	0.3	113.6	1.2
Feb-11	8:15	melt 6	-	1.5	110.3	1.2
Feb-12	10:00	melt 9	-	2	61.47	1.2
Feb-13	9:40	melt 10	-	5	45.78	1.2
Feb-13	20:15	melt 11	-	3	35.04	1.2
Feb-14	7:40	melt 12	-	6.5	26.41	1.2
Feb-14	10:11	melt 14	-	1.5	23.36	1.2
Feb-14	16:45	melt 16	-	2.75	22.4	1.2
Feb-14	20:30	melt 16a	-	2.2	21.26	1.2
Feb-15	4:35	melt 17	-	4.3	19.05	1.2
Feb-15	9:20	melt 18	-	2.4	18.6	1.2
Feb-15	13:00	melt 19	-	1.95	18.54	1.2
Feb-15	15:21	melt 20	-	0.75	18.71	1.2
Feb-15	19:22	melt 21	-	2.4	18.35	1.2
Feb-15	23:58	melt 22	-	2.75	18.17	1.2
Feb-16	7:58	melt 23	-	4.225	17.48	1.2
Feb-16	11:28	melt 24	-	1.5	17.87	1.2
Feb-16	13:35	melt 27	-	1.7	16.55	1.2
Feb-16	19:28	melt 28	-	5.05	16.25	1.2
Feb-17	7:50	melt 30	-	14.04	12.29	1.2
Feb-17	10:00	melt 32	-	2.15	12.12	1.2
Feb-17	11:55	melt 33	-	2.425	11.98	1.2
Feb-17	14:35	melt 35	-	2.83	11.59	1.2

Freeze Test 8 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
Feb-17	20:20	melt 37	-	6.98	11.39	1.2
Feb-17	23:44	melt 38	-	3.5	11.26	1.2
Feb-18	7:45	melt 40	-	9.9	10.44	1.2
Feb-18	10:00	melt 41a	-	2.35	10.16	1.2
Feb-18	12:00	melt 42	-	2.1	10.11	1.2
Feb-18	14:51	melt 43	-	3.74	10.02	1.2
Feb-18	17:05	melt 44	-	3.4	9.594	1.2
Feb-19	0:00	melt 45	-	7.1	8.958	1.2
Feb-19	9:20	melt 47	-	10.47	8.599	1.2
Feb-19	12:07	melt 49	-	2.15	8.261	1.2
Feb-19	15:25	melt 50	-	4.2	7.975	1.2
Feb-20	12:05	melt 51	-	23.625	6.531	1.2
Feb-20	19:00	melt 53	-	7.05	5.752	1.2
Feb-21	12:30	melt 54	-	11.1	4.684	1.2
Feb-21	18:00	melt 55	-	3.275	4.422	1.2
Feb-22	7:50	melt 57	-	6.75	3.996	1.2
Feb-22	12:07	melt 59	-	2	3.715	1.2

* Based on volume measurement of grab samples

Freeze Test 9 (FT9) Experimental Observation Records

Room Temp	- 15 C	NaCl Conc.	20,000 mg/L
Flow Rate	Pulse 6:2, 0.118 kg/s	Date	Feb 25 to March 2, 2005

Date/Time	Observations
Feb 25/05 14:00	Collect influent samples and measure flow rates. Set rate to 30 %.
	Vol in tank 960 L. Mass of salt = 19.2004 kg
	EC flow test Vo = 21.169, vf= 21.190. EC = 26.93 mS/cm
	939 L left in tank.
Feb 26/05 10:39	Start pulse layer 1. phone = 10:39, temp computer =10:30. Ice fence at station 3, vo = 21.192. Start flow at 10:42 on phone.
10:42	Pulse 1 flow reached stn 7, slush ice form in flow field. Flow rate to large, flow front advance to stn 8 and drainage pathways form. Cut flow to 20 %
	All fluid freeze into slush and to base on first pulse, advance front to stn 8.75
10:50	Pulse 2. 20 % flow, front advance over previous layer evenly, reached stn6 @ shutoff, some ice slush forming, very little initially.
	Stn 6- stn 4 fine frazil platelets form
	Stn 6 to stn 8.5 dense slush (only fluid from 1 pulse), rough ice up to stn 4. Surface relatively unfrozen up to stn 6, slight freezing up to stn 3. 12 L added during pulse
	Pulse 3. Surface almost freeze before start of pulse. Flow in channels to stn 3 ice fence and then disperses. Advance to stn 6 at end of pulse. Continue past stn 6 and flow evenly from stn 4 through and over previous ice layer. Flow reach stn 6.75 total. Rough ice up to stn 5.5 then fine frazil ice. Vol = 21.233. Flow along glass surface up to stn 3 ice fence.
	Pulse 4. Reach stn 6 at pump shutoff. Flow over and through old slush layers. Evenly from stn 4 onward. Channeling at dispenser. Bump flow to 25 % to advance front on next pulse.
	Pulse 5. vol = 21.244, flow = 25 %. Front reached stn 6.5 at shutoff. Flow a little faster up to end, still over and through slush layers. Rough ice surface (drained structure?) frazil ice up to stn 5.5 then fine frazil platelets. Front drain to stn 9. @ stn 9 front wasted out slush. Try 22% for next pulse.
	Pulse 6. vol = 21.259, 22% flow. Pulse reach stn 6 at shut off. Drain to stn 10. Flow to fast, stop flow for 20 min to let ice set up.
11:30	Stop. Next pulse vol = 21.271. Flow tips drain to 10.5. Flow was under the surface from stn 6 onward – crusty ice surface that's why flow advanced so far with no freezing.
11:42	Leading tip drain to stn 11, just before gutter. Let set up longer.
11:52	Add 2.5 L to dispenser stn 2 – stn 3 to even out ice. Drips starting at gutter.
12:08	Drips at gutter up to 200 mL so far. Add another 2.5 L to dispenser ice.
1:00	No sample collected from gutter – only slush that was put back into flume. Ice still soft stn 5 to stn7.5 all other areas ice is hard. Stn 10 – 11 ice is soft.
2:10	Skim of ufw on surface of ice stn 5 to stn 7. film not enough to sample.
2:40	Restart. Vol = 21.277. Flow at 20 %. Pulse 1 slight damming at stn 3 ice fence. Clear screen front on ice fence – now draining. Flow drain to stn 3.75. ~ 11 L
	Pulse 2. Rough surface slush ice up to stn 5.5 then dense small frazil plate ice to unfrozen tip at stn7 (as far as it advanced).
	Pulse 3. Flow evenly across old layers – advance to stn 6.5. Rough slush up to stn 5.5 then fine dense frazil ice. Vol = 21.312
	Pulse 4. Roughness of surfaces comes from draining of slush structure to advance the front.

	Pulse 5. Flow drain to stn 7, no dense ice developed.
	Pulse 6. front at stn 7 all across
3:24	Flow is over old layers and then drains from stn 1 to stn 5.5
3:31	Front at stn 7.25. Rough drained ice surface up to stn 6 then dense frazil stn 6 to 7.25.
3:47	Vol = 21.381 ~100 L in flume, front at stn 7.5. Plunge pool erode ice to glass 12 cm from dispenser. Channels forming up to ice fence at stn 3. No layered ice evident from side view.
4:00	Stop. Defrost start. Flow at stn 6.75. vol = 21.407
4:05	At stn 8
4:33	At stn 8.5
Feb 27, 2005	
11:10	Runoff collected into 3 sample vials. Ufw in channel from stn 3 to stn 6.5. Surface skim on ice but no enough to sample. Leak at stn 9 collected into drip tray. Front advance to stn 8.5 only elevation change at stn 8 overnight. Start next pulse.
11:50	Vol = 21.407, 20 % flow.
	Pulse 1 slight channeling up to stn 3 ice fence due to ice structure from previous test. Flow filled in old channel from stn 3 to 5.5 then stopped. Slight damming/backing up of flow at stn 3. 12 L in to flume.
	Pulse 2. 1 st layer pulse froze to base ice layer. Base ice up to stn 6 is rough due to drained structure. Flow reach stn 5. Surface of pulse barely freezes before next pulse starts, frazil ice developing.
	Pulse 3. Front has not surpassed stn 5. Advances through and over previous slush ice. Up to stn 3 – slush ice slightly drained between pulses, stn 3 -5 slush ice – less dense and more free liquid. Pulses do not freeze as much as FT8.
12:20	In front of ice fence (stn 3) 2 cm of free water and little slush in plunge pool. Front has not passed stn 5. Increase flow to 25 %.
12:21	Vol = 21.454
	Flow erode away slush at dispenser in plunge pool. 2.5 cm deep plunge pool to 15 cm away from dispenser. Then 1.5 cm of slush throughout up to stn 3. up to 2 cm of frazil stn 3 to stn 4. Front reached stn 5.5. platelet frazil ice forming stn 3 to stn 5, water and some slush ice up to stn 3
12:30	Flow – comes up through slush not over the surface any more. Surface barely freezes stn 3-5 then unfrozen surface to stn 5.5. Front almost at stn 6.
12:40	Plunge pool eating into old ice layer. Flow advance to stn 6.25. a channel is developing stn 3 to stn 4.5
12:48	Vol = 21.513. Channel stn 3 to stn 5 unfrozen. 2 cm deep approx 15 cm wide. After stn 5 flow disperses into frazil – put screen at stn 5 to prevent channeling from advancing
12:52	Front at stn 6.5
1:00	Vol = 21.525
	Very faint layering evident at stn 5 side. Plunge pool almost to glass base.
1:11	Very dense frazil at front (stn 6-6.5) then layer plates stn 5-6. stn 3-5 very large plates.
1:12	Stop vol = 21.550. 3.5 cm deep plunge pool at dispenser and 3 cm of free water in channel from stn 3 to stn 5.
6:25	No runoff in EC cell. Ice at dispenser not solid – can break with thumb. Still unfrozen liquid on surface of ice. Add 5 L to channel at stn 3-5 and dispenser. Collect 150 mL from drip tray at stn 9 into sample. Do not add to ice, not solid enough.
Feb 28, 2005.	
8:05	Collect leak water into sample.

8:15	Collect runoff from EC cell. Ice even and solid up to stn 5. Unfrozen skim stn 5 to stn 6.5 then porous deformable ice to stn 6.75. Sample of skim 2 mL very hard to collect.
9:04	Vol = 21.555 flow 25 %, ice fence at stn 3 and 5. Pulse 1. Flow advance through ice fence 3 evenly- no back up of flow. Front reached stn 3.5 at shut off, 14 L in flume. Drain to stn 4
	Pulse 2. Flow over previous layer evenly. First pulse freeze to base ice. Front reach stn 4. Appear to be damming behind ice fence stn 3.
	Pulse 3. Clean ice fence 3 with ruler, flow advance to stn 4.5 flow evenly over old ice. Frazil platelets forming up to stn 3. Surface partially freeze after stn 3. vol = 21.598. Surface skim of ice stn 2 to stn 4. Plunge pool up to stn 2. stn 4 to stn 4.75 unfrozen.
	Plunge pool starting to erode into base ice. (2-3 mm)
	Pulse 4. Front reach ice fence at stn 5.
	Pulse 5. Clean ice fence at stn 5, flow advance to stn 5.5. no channels appear to have formed yet.
9:42	Vol = 21.625. Frazil slush through out ice layers. Stn 1-2 open water plunge pool, ~ 5 mm into old ice. Stn 2-3 slush with platelets (vertical) ~2.5 cm lots of free water Stn 3-4 slush with platelets 2-2.5 cm fairly dense ice Stn 4-5 fine platelets 1-2 cm and dense Stn 5-5.5 0.5-1 cm platelets and dense Stn 3-5 structure drains between pulses and fluid advances the front. Surface slightly freezes between pulses.
9:57	Clean screen flow advances to stn 6.25. vol = 21.653, slight channel forming at stn2 – 3.5 along in side half of flume approx. 10 cm wide.
10:00	Flow is under and through slush stn 1-3
10:15	Flow front reach stn 6.75 location of yesterday's front. Response of flow in slush almost instant at stn 5 after pulse starts. Lots of free water connecting under the surface layers. Surface of soft ice/slush stn 2-4 ~ 1 cm thick with unfrozen water underneath. Open channel stn 3-4.5 and slush full depth else where. Stn 4.5 slush with lots of frazil ice. Stn 5-6 dense-fine frazil ice.
10:20	Front at stn 7
10:30	Front at stn 7.25
10:35	Stop vol = 21.730
	Lots of free water at dispenser
10:44	Front at stn 7.5
3:50	Runoff in EC cell. Front advance to stn 8. Ice up to stn 5 – drained, fill in low spots. Stn 7.5 to 8 very dense slush and free liquid. Deformable under thumb pressure.
6:50	Restart. Ice midline sunken at stn 2- stn3 approx 1 cm
	Vol = 21.735. Pulse 1. just enough vol to fill sunken ice to existing level
	Pulse 2. Clean ice fence stn 3. front advances to stn 5 before next pulse
7:20	Front at stn 5.25. Ice structure same as before, frazil ice and water.
7:35	Flow reaches stn 6
7:40	Flow reaches stn 6.25
7:43	Front reached stn 6.5. Channel from stn 3 to 5 again, same as before due to slightly lower base ice in this area. Plunge pool as before
7:45	Front reaches stn 7. More free water than last test. Lower density of frazil platelets but same size distribution. Base ice not as cold as previous layers base.
7:58	Front at stn 7.25
8:06	Stop. Vol = 21.876. Do not want to loose liquid at stn 9 leak. Reseal stn 9.
8:24	Front at stn 7.9

March 1, 2005	
8:10	Reseal of stn 9 worked, no new leaks. Collect EC cell samples. Front reached stn 7.75. Unfrozen skim in bend ice surface. Channel drop 0.5 to 1 cm from stn 3 to stn 5. Dispenser plunge pool down 1 cm stn 1 to stn 2.5. Unfrozen liquid in channel base. Stn 9 had 3-4 mm of free liquid
9:08	Restart, 21.8785
	Pulse 1. Reach stn 3.5. Filled in low areas. Ice fence at stn 3 under ice.
	Pulse 2. Flow evenly over pulse 1 layer, slush froze to base layer. Advance to stn 4
	Pulse 3. Flow evenly over old layer and advance to stn 4.5. Slush ice forming through out. Surface partially freezes before next pulse.
	Pulse 4. Flow advance to stn 5, plunge pool open water at stn 2.
	Pulse 5. Front reached stn 5.25.
	Pulse 6. Flow dives under ice surface at stn 2.5 and resurfaces at stn 3.5 to flow over through frazil ice. Front advances to stn 5.5
	Pulse 7. stn 2 – stn 3.75. surface layer of ice slush crust (0.5 cm) water underneath. Stn 3.75 to 5.5 2.5 cm frazil not very dense to dense 0.5 cm frazil plates at stn 5.5.
10:02	Layering evident between pulses.
10:04	Front reach stn 6
10:10	Front at stn 6.5
10:25	Front reach stn 6.75, ice and frazil forming as before.
10:30	Stn 4 to stn 7. Less dense large ice plates to dense fine ice plates, surface unfrozen between pulses from stn 3.5 to stn 6.75.
10:50	Front reach stn 7.25. density of frazil increasing from stn 3.5 to stn 5.5
	Plunge pool erode 1 cm into base ice layer.
10:55	Stop vol = 22.082
11:00	Front at stn 7.5
11:15	Front at stn 8
12:01	Front at stn 9
9:35 PM	Free liquid skim on ice surface. Collect sample of runoff.
March 2, 2005	Ice cores
Stn 3a (inside)	15 cm ice core, free liquid at base. Layers evident from each pulse. Soft, porous ice easy coring.
Stn 3b (outside)	15.5 cm ice core. 2.5 cm of unfrozen liquid at base of core hole.
Stn 4	17.5 cm recovered. Soft ice, porous, layers evident. Free liquid at base
Stn 6a (inside)	18.5 cm core ice. Soft porous ice, layers evident. Free liquid at base
Stn 6b (outside)	Same as before
Stn 8	7 cm Soft porous and wet ice. 3 layer evident
Stn 9	2 cm, very soft wet ice
Stn 10	1.5 cm, soft porous ice with liquid at base
Stn 10.5	1.0 cm, Same as above

Freeze Test 9 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
Influent Samples						
26-Feb-05	-	Ecinline	-	-	23.88	1.5
26-Feb-05	-	inlfuent ec tank 1	-	-	24.31	1.5
26-Feb-05	-	ec tank 2	-	-	24.99	1.5
Ice cores before melting						
2-Mar-05	-	Core 10.5	0-1	-	66	1.5
2-Mar-05	-	Core 10	0-1.5	-	40.66	1.5
2-Mar-05	-	Core 9	-	-	65.6	1.5
2-Mar-05	-	Core 9 dup	-	-	65.5	1.5
2-Mar-05	-	Core 8a	0-2	-	26.3	1.5
2-Mar-05	-	Core 8a	2-4.5	-	22.61	1.5
2-Mar-05	-	Core 8a	4.5-7.0	-	42.44	1.5
2-Mar-05	-	Core 8a dup	4.5-7.0	-	42.64	1.5
2-Mar-05	-	Core 7	0-3	-	23.47	1.5
2-Mar-05	-	Core 7	3-5.5	-	22.88	1.5
2-Mar-05	-	Core 7	5.5-7.5	-	20.38	1.5
2-Mar-05	-	Core 7	7.5-10	-	16.49	1.5
2-Mar-05	-	Core 7	10-12	-	20.97	1.5
2-Mar-05	-	Core 6b	0-4	-	20.89	1.5
2-Mar-05	-	Core 6b	4-7	-	17.8	1.5
2-Mar-05	-	Core 6b	7-10.5	-	16.81	1.5
2-Mar-05	-	Core 6b dup	10.5-13	-	17.08	1.5
2-Mar-05	-	Core 6b	10.5-13	-	17.3	1.5
2-Mar-05	-	Core 6b	13-15.5	-	18.27	1.5
2-Mar-05	-	Core 6b	15.5-18.5	-	23.3	1.5
2-Mar-05	-	Core 4	0-3	-	20.77	1.5
2-Mar-05	-	Core 4	3-6	-	19.37	1.5
2-Mar-05	-	Core 4 dup	3-6.	-	19.19	1.5
2-Mar-05	-	Core 4	6-7.5	-	17.6	1.5
2-Mar-05	-	Core 4	7.5-9.5	-	20.57	1.5
2-Mar-05	-	Core 4	9.5-12.5	-	20.68	1.5
2-Mar-05	-	Core 4	12.5-14.5	-	18.06	1.5
2-Mar-05	-	Core 4	14.5-16.5	-	26.87	1.5
2-Mar-05	-	Core 3	0-3	-	20.23	1.5
2-Mar-05	-	Core 3	3-6.	-	18.37	1.5
2-Mar-05	-	Core 3	6-9.	-	18.54	1.5
2-Mar-05	-	Core 3 dup	6-9.	-	18.4	1.5
2-Mar-05	-	Core 3	9-12.5	-	18.29	1.5
2-Mar-05	-	Core 3	12.5-15	-	20.77	1.5
2-Mar-05	-	ufw stn 3 core water	-	-	141.4	1.5
2-Mar-05	-	ufw stn 4 core water	-	-	127.8	1.5
2-Mar-05	-	ufw stn 6 core water	-	-	128.8	1.5
Ice cores after melting						
24-Mar-05	-	M 2b	0-6	-	0.341	1.5
24-Mar-05	-	M 2b dup	0-6	-	0.16	1.5
24-Mar-05	-	M 3b	0-3.5	-	0.068	1.5
24-Mar-05	-	M 3b	3.5-7.0	-	0.094	1.5

Freeze Test 9 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
24-Mar-05	-	M 3b	7-11.0	-	0.039	1.5
24-Mar-05	-	M 3b dup	7-11.0	-	0.038	1.5
24-Mar-05	-	M 4	0-3.0	-	0.065	1.5
24-Mar-05	-	M 4	3-6.0	-	0.057	1.5
24-Mar-05	-	M 4	6-9.0	-	0.048	1.5
24-Mar-05	-	M 4	9-12.0	-	0.09	1.5
24-Mar-05	-	M 5	0-4.0	-	0.24	1.5
24-Mar-05	-	M 5	4-15.0	-	0.136	1.5
24-Mar-05	-	M 6	0-3.0	-	0.044	1.5
24-Mar-05	-	M 6 dup	0-3.0	-	0.041	1.5
24-Mar-05	-	M 6	3-6.0	-	0.04	1.5
24-Mar-05	-	M 6	6-9.	-	0.075	1.5
24-Mar-05	-	M 6	9-12.	-	0.109	1.5
24-Mar-05	-	M 6	12-14.	-	0.171	1.5
24-Mar-05	-	M 7	0-5	-	0.072	1.5
24-Mar-05	-	M 7 dup	0-5	-	0.137	1.5
24-Mar-05	-	M 7.5	0-2.5	-	0.26	1.5
24-Mar-05	-	M 7.5 dup	0-2.5	-	0.241	1.5
Melt Runoff Samples						
27-Feb-05	11:00	runoff 1	-	0.055	171.8	1.5
27-Feb-05	11:00	runoff 2	-	0.075	171	1.5
27-Feb-05	11:00	runoff 3	-	0.085	172.6	1.5
27-Feb-05	11:30	leak 9	-	0.25	170.3	1.5
27-Feb-05	18:40	drip stn 9	-	0.2	165.6	1.5
28-Feb-05	8:10	leak stn 9	-	0.5	168.3	1.5
28-Feb-05	8:15	leak stn 9	-	0.207	169.1	1.5
28-Feb-05	8:15	runoff 2	-	0.082	181.6	1.5
28-Feb-05	8:15	runoff 2	-	0.369	172.9	1.5
28-Feb-05	15:50	runoff 2	-	0.468	175	1.5
1-Mar-05	8:10	runoff 1	-	0.49	173.4	1.5
1-Mar-05	8:10	runoff 2	-	0.3	175	1.5
1-Mar-05	11:05	runoff 2	-	0.455	171.2	1.5
1-Mar-05	21:35	runoff 1	-	2.4	169.2	1.5
2-Mar-05	8:00	runoff 1	-	0.47	170.9	1.5
2-Mar-05	8:00	runoff 2	-	0.385	171.3	1.5
2-Mar-05	18:45	runoff 2	-	0.495	175.7	1.5
3-Mar-05	8:00	runoff 2	-	-	176.2	1.5
3-Mar-05	15:00	melt 1a	-	0.496	153.3	1.5
3-Mar-05	15:00	melt 1b	-	0.495	151.4	1.5
3-Mar-05	15:00	melt 1c	-	0.305	153.3	1.5
3-Mar-05	22:45	melt 2	-	2.4	151.9	1.5
4-Mar-05	8:15	melt 3a	-	0.48	145.2	1.5
4-Mar-05	8:15	melt 3b	-	0.495	145.3	1.5
4-Mar-05	14:00	melt 4	-	1.875	126	1.5
5-Mar-05	6:20	melt 5	-	3.27	107.3	1.5
5-Mar-05	16:30	melt 6	-	2	104.1	1.5

Freeze Test 9 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
6-Mar-05	0:05	melt 7	-	7.09	96.1	1.5
6-Mar-05	10:23	melt 8	-	5.36	93.02	1.5
6-Mar-05	15:35	melt 9	-	2.625	92.91	1.5
6-Mar-05	21:50	melt 10	-	2.7	92.68	1.5
7-Mar-05	9:40	melt 11	-	6.45	83.17	1.5
7-Mar-05	12:30	melt 12	-	1.7	81.53	1.5
7-Mar-05	16:05	melt 13	-	2	79.19	1.5
7-Mar-05	19:25	melt 14	-	3.93	75.7	1.5
8-Mar-05	8:00	melt 15	-	8.267	71.29	1.5
8-Mar-05	10:30	melt 16	-	2	71	1.5
8-Mar-05	14:30	melt 17	-	4.57	70.05	1.5
8-Mar-05	21:55	melt 18	-	7.09	66.89	1.5
9-Mar-05	8:30	melt 19a	-	11.9	64.08	1.5
9-Mar-05	8:30	melt 19b	-	0.45	64.77	1.5
9-Mar-05	11:30	melt 20	-	2.56	63.89	1.5
9-Mar-05	14:25	melt 21	-	2.56	64.07	1.5
9-Mar-05	21:15	melt 22	-	10.3	61.24	1.5
10-Mar-05	7:50	melt 23	-	16.55	57.02	1.5
10-Mar-05	10:20	melt 24	-	3.635	56.84	1.5
10-Mar-05	12:20	melt 25	-	2.5	56.46	1.5
10-Mar-05	14:25	melt 26	-	2.8	54.18	1.5
10-Mar-05	20:25	melt 27	-	5.84	53.14	1.5
11-Mar-05	7:45	melt 28a	-	16.45	48.29	1.5
11-Mar-05	-	melt 28b	-	2	49.23	1.5
11-Mar-05	10:00	melt 29	-	5.025	47.43	1.5
11-Mar-05	12:00	melt 30	-	2.4	46.96	1.5
11-Mar-05	15:20	melt 31	-	6.1	45.62	1.5
11-Mar-05	18:17	melt 32	-	4.7	44.11	1.5
11-Mar-05	23:00	melt 33	-	7.75	42.58	1.5
12-Mar-05	8:45	melt 34	-	16	40	1.5
12-Mar-05	15:15	melt 35	-	7.7	38.22	1.5
13-Mar-05	9:10	melt 36	-	23.5	34.97	1.5
13-Mar-05	15:25	melt 37	-	7	34.04	1.5
13-Mar-05	21:35	melt 38	-	8.1	34.06	1.5
14-Mar-05	8:00	melt 39	-	9.35	30.2	1.5
14-Mar-05	12:00	melt 40	-	4.6	30.78	1.5
14-Mar-05	15:50	melt 41	-	2.55	29.64	1.5
14-Mar-05	20:20	melt 42	-	4.75	28.65	1.5
15-Mar-05	8:10	melt 43	-	8.55	27.34	1.5
15-Mar-05	14:20	melt 44	-	5.8	26.71	1.5
15-Mar-05	21:10	melt 45	-	6	25.28	1.5
16-Mar-05	8:25	melt 46	-	10.1	23.27	1.5
16-Mar-05	13:00	melt 47	-	5.46	20.89	1.5
16-Mar-05	20:10	melt 48	-	7.5	21.02	1.5
17-Mar-05	8:15	melt 49	-	13.5	18.18	1.5
17-Mar-05	13:25	melt 50	-	5.8	16.87	1.5

Freeze Test 9 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
17-Mar-05	20:42	melt 51	-	9.2	15.19	1.5
18-Mar-05	8:15	melt 52	-	12.5	13.33	1.5
18-Mar-05	11:45	melt 53	-	3.625	12.63	1.5
18-Mar-05	19:15	melt 54	-	7.3	11.45	1.5
19-Mar-05	12:10	melt 55	-	16	8.611	1.5
19-Mar-05	18:16	melt 56	-	6.45	7.356	1.5
20-Mar-05	12:25	melt 57	-	15.775	5.348	1.5
20-Mar-05	21:00	melt 58	-	6.8	5.025	1.5
21-Mar-05	8:10	melt 59	-	8.8	3.557	1.5
21-Mar-05	15:20	melt 60	-	6.31	3.104	1.5
21-Mar-05	21:56	melt 61	-	4.6	3.096	1.5
22-Mar-05	16:06	melt 62	-	14.5	2.118	1.5
22-Mar-05	23:52	melt 63	-	7.2	1.702	1.5
23-Mar-05	11:30	melt 64	-	8.5	1.231	1.5
23-Mar-05	19:11	melt 65	-	5.41	1.057	1.5
24-Mar-05	10:21	melt 66	-	13.75	0.682	1.5
24-Mar-05	12:00	melt 67	-	1.3	0.579	1.5

* Based on volume measurement of grab samples

Freeze Test 10 (FT10) Experimental Observation Records

Room Temp	- 15 C	**NaCl Conc.**	500 mg/L
Flow Rate	Pulse 6:2, 0.139 kg/s	**Date**	Mar 26 to Mar 29, 2005

Date/Time	Observations
Mar 26/05	500 mg/L ~1.009 mS/cm
9:42	Start base layer. Pulse 1. vol = 24.064. Flow tips reached stn 9. Freezing to base. A portion of the flow is moving along the inside wall to the gutter. Install ice fence at stn 3.
	Pulse 2. Flow over old ice and advance evenly to stn 6 at end of pulse. Drain to stn 9. Reduce flow to 17 % for base layer.
	Pulse 3. Ice fence at stn 3 slows down the flow. Rough porous ice stn 1 to stn 3. Frazil platelets from stn 7 to gutter. 300 mL in gutter.
10:16	Draining to gutter stopped.
10:24	Put a ice fence at stn 6 to slow down flow at bend. Rough porous ice up to stn 6, then frazil platelets to stn 11. Appears that ice is draining from structure up to stn 5 and then fluid is advancing to stn 11.
10:30	Bump flow to 23 %, 70 L in flume.
10:36	Vertical platelets frazil ice for all ice structure. Up to stn 5 the frazil is slightly drained of free water.
10:51	28.5 % flow again. Fairly dense ice structure. Surface layer freezes in between pulses. More ice is produced than FT9. Individual ice layers evident between pulse layers.
11:03	Vol = 24.190
11:09	Stop. Vol = 24.208. Approx. 0.5 L in gutter.
6:30 pm	Drained porous ice up to stn 6. Stn 6 to stn 10, solid ice that developed from drained liquid after pumping had stopped.
6:50	Restart. Vol = 24.208 at 28.5 %
	Pulse 1. flow advances to at 3.5 and end of pulse. Just filling in depression and porous drained old ice. Not flowing in thin layers yet.
	Pulse 2. Flow evenly across surface and reaches stn 5.5. Plunge pool erodes ice to glass base at dispenser.
7:12	Flow reaches stn 6.25. platelet and surface freezing ice up to stn 5 in between pulses. 47 L in flume. Frazil ice stn 5 to stn 6.5
	Pulse 4. Flow over old layers and advance to stn 6.5. Up to stn 3 porous ice – layered from surface freezing and drained in between pulses. Stn 3 to stn 5 – frazil platelets and surface freeze between pulses. Stn 5 to stn 6.5 – frazil ice unfrozen surface.
7:33	Flow tip advance to stn 7, 100 L in flume now
7:40	Very little ice formation up to stn 3.
7:46	Flow has not passed stn 7. still freezing as before. Density of ice platelets and size reduces from stn 4 to stn 7 (3 -5 cm at stn 4 to 0.5 to 1 cm at stn 7).
8:17	Flow tip at stn 7.25
8:21	Stop. Vol =24.400. 192 L in flume.
Mar 27/05	
8:45 am	Front advances to stn 9 – slightly porous drained ice up to stn 5 the solid ice to stn 9. old ice very solid and completely frozen.
9:08	Restart. Vol = 24.400. Pulse 1. slightly sunken midline to stn 3 first pulse fills in low areas.
	Pulse 2. Flow past stn 3 and drains to stn 6 over old ice. Surface starts to freeze up to stn 3.

9:35	Front reach stn 6.25. Surface freezes in between pulses like a surface skim. Small frazil platelets from stn 4.5 to stn 6. Large platelets and surface ice up to stn 4.5.
9:43	Leading tip at stn 7. surface freezes between pulses. Ice structure as before. Plunge pool erodes 1.5cm into base ice up to 30 cm away from dispenser.
9:50	Flow is now through ice structure not over. Dye injection flows through the entire depth of the flow through the slush.
9:55	Surface freezes all the way to stn 6 in between pulses. Layers evident in side profile. 97 L in flume.
9:57	Bump flow to 32 %.
10:15	Entire front at stn 7. freezing as previously described.
10:20	Front at stn 7.5. stop flow at 10:23. vol 24.570, 170 L in flume.
18:45	Flow advance to stn 9.5 fairly solid ice structure. Some unfrozen liquid below ice surface at dispenser at stn 3. stn 1-5 drained structure, 1.5 cm drop at dispenser.
18:50	Restart. Vol = 24.570, 32 %
	Pulse 1. Fill low spots and hollow spots up to stn 3, drain to stn 3.75.
	Pulse 2. Flow to stn 5 and fill low spots/ hollow spots. Stn 3-5 surface freeze between pulses.
	Pulse 3. Flow reached stn 6 at end of pulse.
	Pulse 4. Flow at stn 7. Only small tip has reached this far. Surface freezes between pulses.
19:18	75 L in flume so far
19:23	Flow is through layers and then pushes up through the surface skim layer. Flow tends to follow the low spots between stn 1 and 4. Freezes as previous layers.
19:47	Ice fence at stn 6 surpassed. Plunge pool 4 cm deep 40 cm long
19:57	Stop pumping. V= 24.723. front at stn 7.5.
Mar 28	
08:30	Front advance to stn 9.25. slightly drained structure to stn 5 then solid ice. Stn 1-3 the centre line sunk about 1 cm.
8:46	Restart. Vol =24.724, 32 %
	Pulse 1. Fill in low spots/hollow spots cavities up to stn 4.5
	Pulse 2. stn 6.5 reached by front. Surface freeze up to stn 5.
9:15	Vol= 24.792. flow reach stn 7. surface freeze between pulse to stn 6.
9:26	Both ice fences surpassed. Freezing as before. Surface freezes as well as vertical platelets. Decreasing size as you progress along the flume. Flow tip at stn 7.5
9:30	100 L in flume.
9:52	Stop vol = 24.875, 151 L
18:40	Front reached stn 7.9, at stn 3 and stn 4.5, the ice expanded upwards approx 2cm and is soft and wet. Like a pingo??? Ice structure not drained as much as previous layers.
18:46	Restart vol = 24.875
	Pulse 1. stn 4.5 at end of pulse.
	Pulse 2. Stn 5.5 at end of pulse.
	Pulse 3.. Stn 6 is leading tip, 50 L in flume. Surface freeze between pulses.
	Pulse 4. Front at stn 6.25 and freezing as before.
	Pulse 5. Front at stn 6.5.
19:27	Stop vol = 24.976
Mar 29	
08:30	Flow did not advance beyond stn 7.25

FT10 ice cores	
Core 3a	17 cm. 6 layers evident, solid ice with trapped air bubbles
Core 4	17.5 cm. 6 layers evident, solid ice with trapped air bubbles and 3 very porous layers.
Core 6a/b	18 cm. 6 layers evident, solid ice with trapped air bubbles
Core 7	16.5 cm. 6 layers evident, solid ice with trapped air bubbles
Core 8a/b	11 cm. 5 layers evident, solid ice with trapped air bubbles.
Core 9a	7 cm full recovery, 4 layers evident, soft ice. Trapped bubbles in ice.

Freeze Test 10 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
Influent Samples						
25-Mar-05	-	ec cell 1	-	-	1.006	1.7
25-Mar-05	-	ec tank 1	-	-	1.009	1.7
25-Mar-05	-	tap water	-	-	0.306	1.7
Ice core samples before melting						
1-Apr-05	-	Core 3a	0-2	-	1.54	1.5
1-Apr-05	-	Core 3a	0-2 dup	-	1.59	1.5
1-Apr-05	-	Core 3a	2-5.	-	2.16	1.5
1-Apr-05	-	Core 3a	5-8.5	-	1.312	1.5
1-Apr-05	-	Core 3a	8.5-12	-	1.13	1.5
1-Apr-05	-	Core 3a	12-15.	-	1.587	1.5
1-Apr-05	-	Core 3a	15-17.	-	2.736	1.5
1-Apr-05	-	Core 4	0-2.5	-	0.761	1.5
1-Apr-05	-	Core 4	2.5-5	-	0.6208	1.5
1-Apr-05	-	Core 4	5-7.	-	0.5	1.5
1-Apr-05	-	Core 4	7-11.	-	0.809	1.5
1-Apr-05	-	Core 4	11-15.	-	0.637	1.5
1-Apr-05	-	Core 4	15-17.5	-	1.17	1.5
1-Apr-05	-	Core 4	15-17.5 dup	-	1.184	1.5
1-Apr-05	-	Core 6b	0-2.	-	0.93	1.5
1-Apr-05	-	Core 6b	2-5.	-	0.68	1.5
1-Apr-05	-	Core 6b	5-7.5	-	0.428	1.5
1-Apr-05	-	Core 6b	7.5-10.5	-	0.328	1.5
1-Apr-05	-	Core 6b	10.5-15.5	-	0.588	1.5
1-Apr-05	-	Core 6b	10.5-15.5 dup	-	0.607	1.5
1-Apr-05	-	Core 6b	15.5-18	-	0.751	1.5
1-Apr-05	-	Core 7	0-2.	-	1.431	1.5
1-Apr-05	-	Core 7	2-5.	-	0.885	1.5
1-Apr-05	-	Core 7	5-7.5	-	0.672	1.5
1-Apr-05	-	Core 7	7.5-11	-	0.655	1.5
1-Apr-05	-	Core 7	11-14.	-	0.606	1.5
1-Apr-05	-	Core 7	11-14. dup	-	0.623	1.5
1-Apr-05	-	Core 7	14-16.5	-	1.488	1.5
1-Apr-05	-	Core 8a	0-2.5	-	0.753	1.5
1-Apr-05	-	Core 8a	2.5-5	-	0.718	1.5
1-Apr-05	-	Core 8a	5-7.5	-	0.838	1.5
1-Apr-05	-	Core 8a	5-7.5 dup.	-	0.836	1.5
1-Apr-05	-	Core 8a	7.5-9.5	-	0.813	1.5
1-Apr-05	-	Core 8a	9.5-10.5	-	1.085	1.5
1-Apr-05	-	Core 9	0-1.5	-	1.152	1.5
1-Apr-05	-	Core 9	1.5-4	-	2.035	1.5
1-Apr-05	-	Core 9	1.5-4 dup	-	1.621	1.5
1-Apr-05	-	Core 9	4-6.	-	0.691	1.5
1-Apr-05	-	Core 9	6-7.	-	1.143	1.5
Ice core samples after melting						

Freeze Test 10 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
15-Apr-05	-	M 3b	0-3	-	0.213	1.7
15-Apr-05	-	M 3b dup	0-3	-	0.167	1.7
15-Apr-05	-	M 3b	3-6.	-	0.263	1.7
15-Apr-05	-	M 3b	6-10.	-	0.22	1.7
15-Apr-05	-	M 3b	10-14.	-	0.388	1.7
15-Apr-05	-	M 4	0-3	-	0.217	1.7
15-Apr-05	-	M 4	3-5.5	-	0.249	1.7
15-Apr-05	-	M 4	5.5-8.5	-	0.292	1.7
15-Apr-05	-	M 4	8.5-11	-	0.262	1.7
15-Apr-05	-	M 4 dup	8.5-11	-	0.258	1.7
15-Apr-05	-	M 4	11-14.	-	0.306	1.7
15-Apr-05	-	M 6b	0-3.5	-	0.218	1.7
15-Apr-05	-	M 6b	3.5-6	-	0.22	1.7
15-Apr-05	-	M 6b	6-8.5	-	0.304	1.7
15-Apr-05	-	M 6b	8.5-12.5	-	0.416	1.7
15-Apr-05	-	M 6b	12.5-16	-	0.375	1.7
15-Apr-05	-	M 6b dup	12.5-16	-	0.37	1.7
15-Apr-05	-	M 7	0-2	-	0.315	1.7
15-Apr-05	-	M 7	2-4.5	-	0.313	1.7
15-Apr-05	-	M 7	4.5-7.5	-	0.396	1.7
15-Apr-05	-	M 7	7.5-10.5	-	0.268	1.7
15-Apr-05	-	M 7	10.5-14.5	-	0.308	1.7
15-Apr-05	-	M 7 dup	10.5-14.5	-	0.329	1.7
15-Apr-05	-	M 8	0-3	-	0.244	1.7
15-Apr-05	-	M 8	0-3 dup	-	0.244	1.7
15-Apr-05	-	M 8	3-5.5	-	0.318	1.7
15-Apr-05	-	M 8	5.5-9	-	0.395	1.7
15-Apr-05	-	M 8 dup	5.5-9	-	0.376	1.7
15-Apr-05	-	M 9	0-2	-	0.313	1.7
Melt runoff samples						
4-Apr-05	9:15	melt 1	-	0.22675	102.8	1.7
4-Apr-05	23:00	melt 2	-	0.2115	72.03	1.7
5-Apr-05	10:10	melt 3	-	0.08525	79.37	1.7
5-Apr-05	14:50	melt 4	-	0.1665	60.32	1.7
5-Apr-05	18:15	melt 5	-	0.203	44.05	1.7
6-Apr-05	9:38	melt 6a	-	0.503	39.79	1.7
6-Apr-05	9:38	melt 6b	-	0.067	39.79	1.7
6-Apr-05	13:30	melt 7	-	0.185	37.38	1.7
6-Apr-05	19:00	melt 8	-	1.495	26.75	1.7
7-Apr-05	9:05	melt 9	-	2.51	21.4	1.7
7-Apr-05	12:36	melt 10	-	0.485	17.54	1.7
7-Apr-05	19:20	melt 11	-	1.04	18.82	1.7
8-Apr-05	9:30	melt 12	-	1.239	17.84	1.7
8-Apr-05	20:35	melt 13	-	0.88	18.17	1.7
9-Apr-05	9:15	melt 14	-	0.475	16.28	1.7
9-Apr-05	15:55	melt 15	-	0.49	13.02	1.7

Freeze Test 10 Sample Collection Data

Date	Time	Sample	Depth (cm)	Sample Volume (L)*	EC (mS/cm)	Sample Temperature (C)
10-Apr-05	12:15	melt 16	-	6.1	7.78	1.7
10-Apr-05	19:15	melt 17	-	3.18	7.856	1.7
11-Apr-05	8:15	melt 18	-	8.42	4.895	1.7
11-Apr-05	12:00	melt 19	-	2	3.891	1.7
11-Apr-05	15:15	melt 20	-	2	3.522	1.7
11-Apr-05	21:10	melt 21	-	4	3.44	1.7
12-Apr-05	8:15	melt 22	-	7.085	3.075	1.7
12-Apr-05	12:10	melt 23	-	2.5	2.975	1.7
12-Apr-05	15:00	melt 24	-	1.7	2.927	1.7
12-Apr-05	20:00	melt 25	-	3.815	2.894	1.7
13-Apr-05	8:20	melt 26	-	8.00	2.493	1.7
13-Apr-05	15:00	melt 27	-	5	2.422	1.7
13-Apr-05	20:30	melt 28	-	3.9	2.453	1.7
14-Apr-05	8:45	melt 29	-	9.94	2.108	1.7
14-Apr-05	12:15	melt 30	-	2	2.08	1.7
14-Apr-05	21:00	melt 31	-	6.65	2.08	1.7
15-Apr-05	8:15	melt 32	-	9.05	1.834	1.7
15-Apr-05	13:30	melt 33	-	4.89	1.803	1.7

* Based on volume measurement of grab samples

Appendix 5. Ambient Temperature Profiles

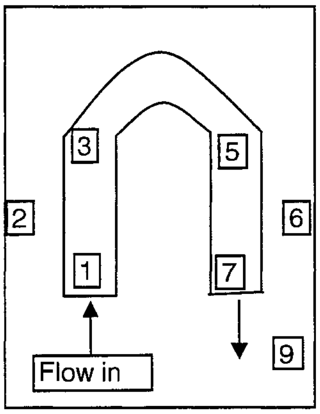
RTD Location and Zero Reading

Horizontal Distance (cm)	Location*	Zero Reading** (mV)
120	1 Flume ice surface	100.00
240	2 Cold room wall above the flume	100.00
400	3 Flume ice surface	100.00
800	5 Flume ice surface	100.00
920	6 Cold room wall above the flume	100.72
1040	7 Flume ice surface	100.18
Beaker	9 Antifreeze beaker at collection end of flume***	100.00

* See sketch below

** Based on reading from 0 °C ice bath

*** RTD within beaker of antifreeze to dampen minor flucuations in ambeint temperature



A5. Ambient Temperature Profiles

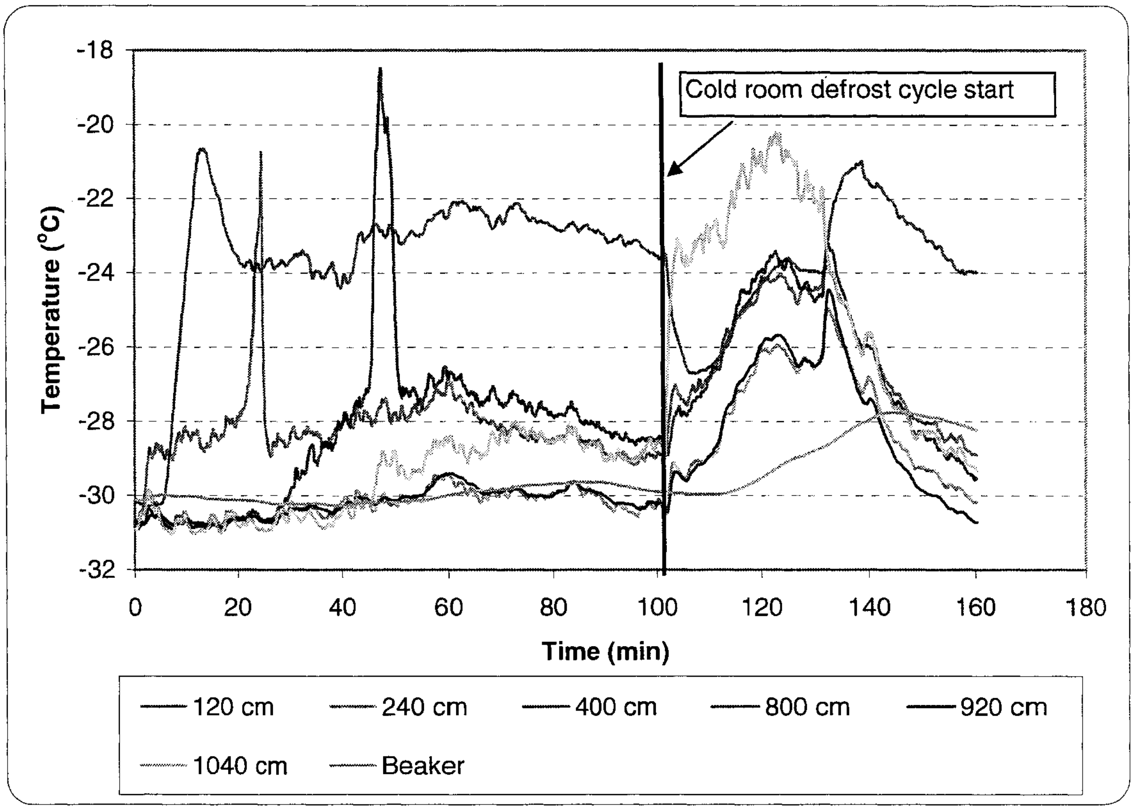


Figure A5.1 Ambient temperature profiles during Test 1.

Summary:
- temperature spikes at 20 min for RTD 120 cm and at 45 min for RTD 800 cm are due to contact with salt water during pumping.
- RTD 400 cm positioned too close to the water surface during the pumping or from poor heat removal due to flume walls resulting in temperatures as warm as -22 °C.
- RTD 1040 increased at 45 min due to multiple entries into the cold room as runoff collection began.
- cold room ambient temperatures (240, 9020, Beaker) were generally -30 °C.
- ambient temperatures in the flume above the ice surface ranged from -31 to -27 °C.

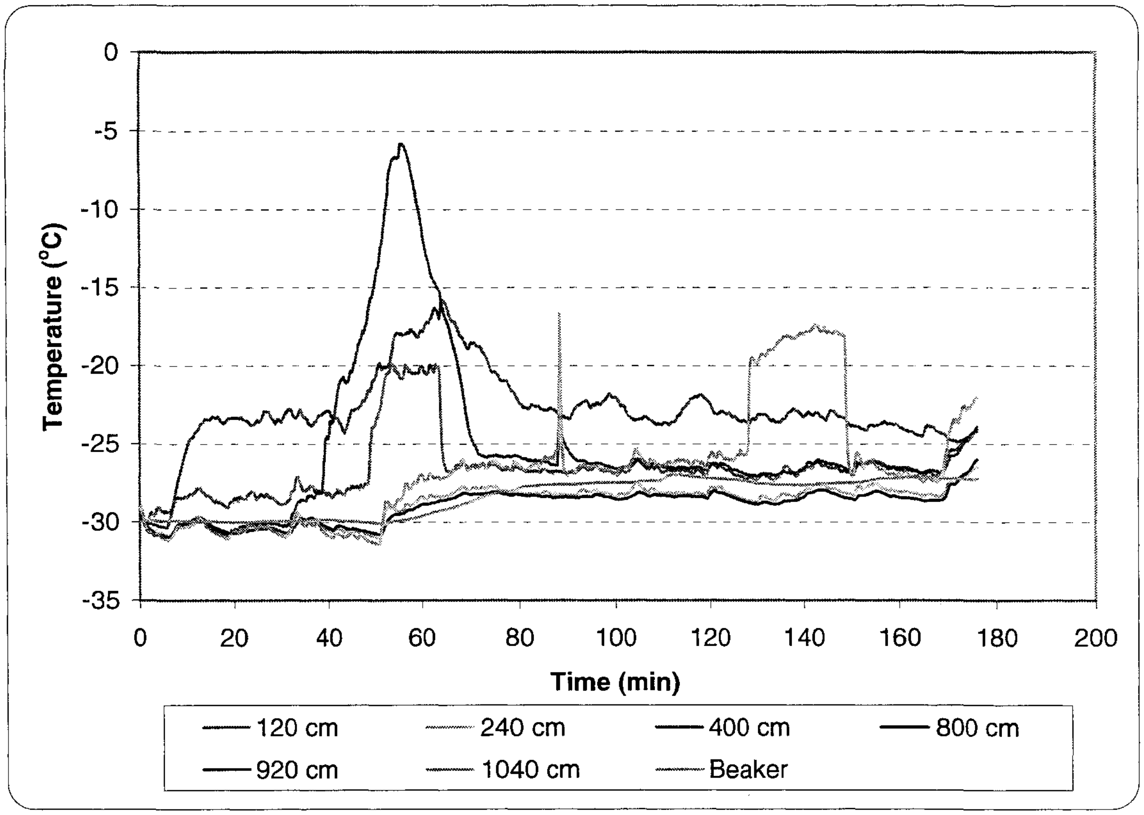


Figure A5.2 Ambient temperature profiles during Test 3.

Summary:
- temperature spikes at 40 to 50 min for RTDs 120, 400, and at 800 cm are due to contact with salt water during pumping.
- RTD 400 cm positioned to close to the water surface during the pumping or from poor heat removal due to flume walls resulting in temperatures as warm as -22 °C.
- the general increase in temperature at 50 minutes is due to multiple entries into the cold room as runoff collection started.
- cold room ambient temperatures (240, 9020, Beaker) were generally -30 to -27 °C.
- ambient temperatures in the flume above the ice surface ranged from -30 to -26 °C.

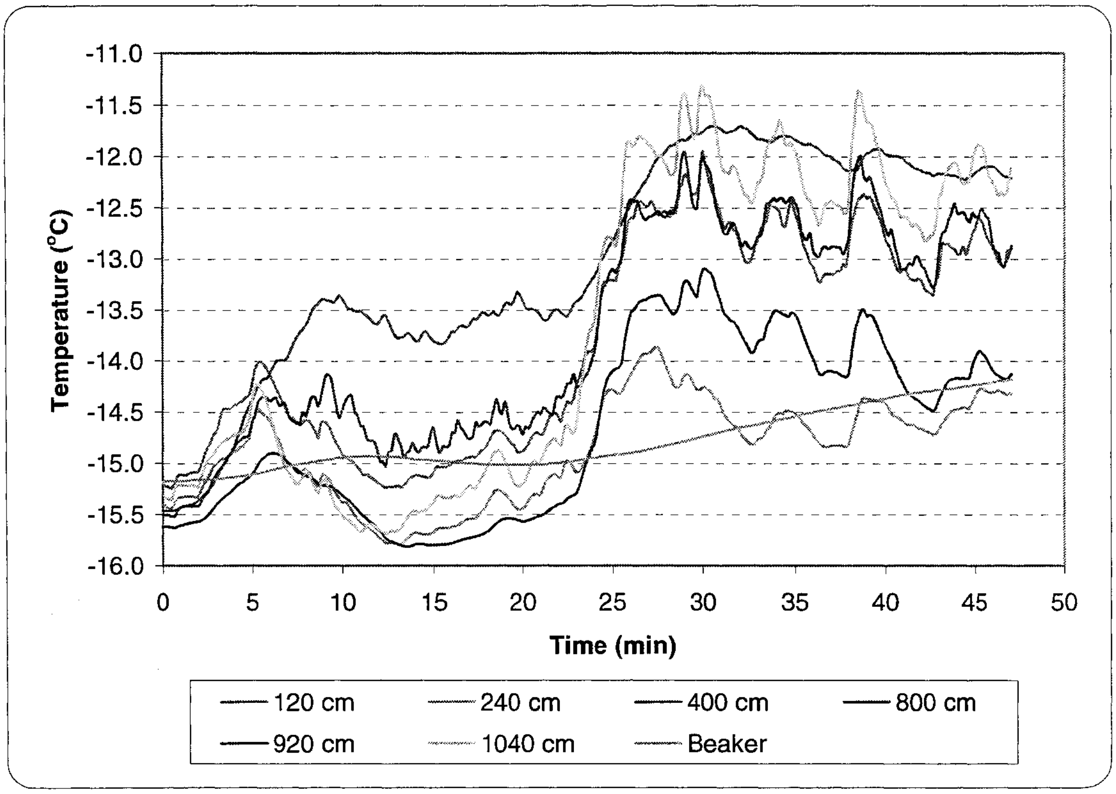


Figure A5.3 Ambient temperature profiles during Test 4.

Summary:
- the temperature spike at 5 min is due to multiple cold room entries.
- RTD 400 cm positioned to close to the water surface during the pumping or from poor heat removal due to flume walls.
- the general increase in temperature at 23 minutes is due to multiple entries into the cold room as runoff collection started.
- cold room ambient temperatures (240, 9020, Beaker) were generally -15 to -14 °C.
- ambient temperatures in the flume above the ice surface ranged from -15 to -12 °C.

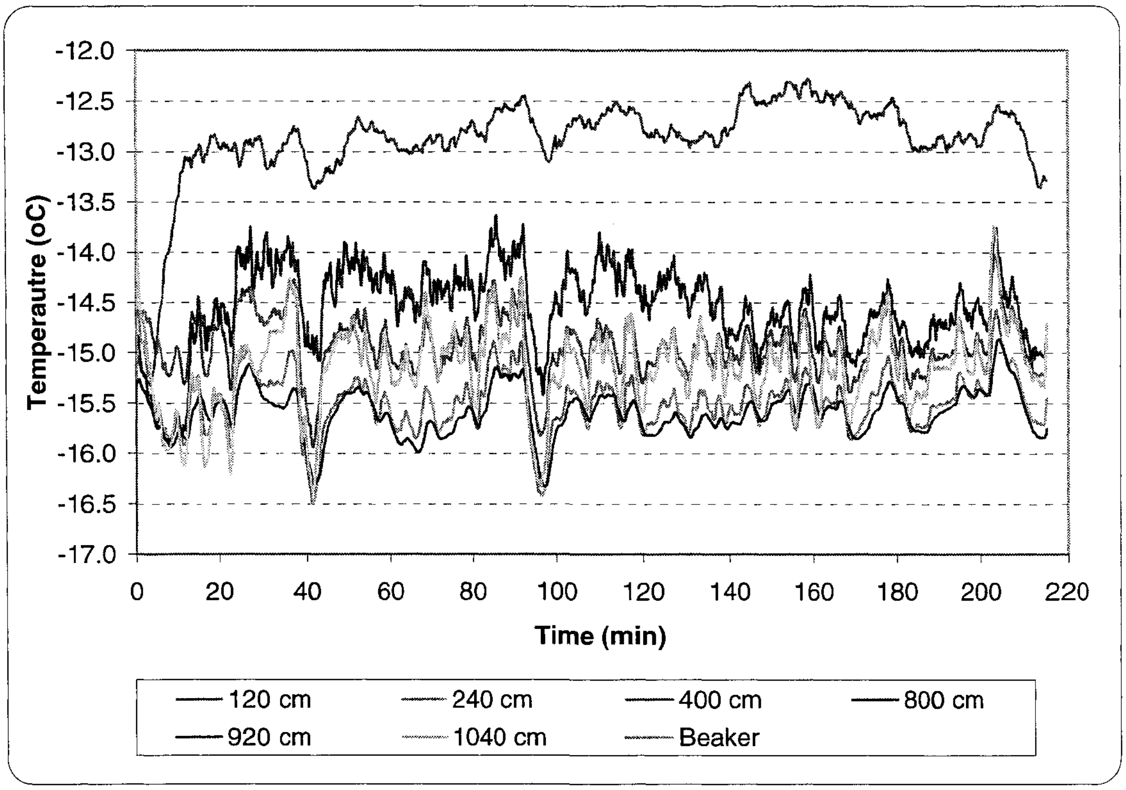


Figure A5.4 Ambient temperature profiles during Test 5.

Summary:
- the temperature spike at 5 min is due to multiple cold room entries.
- RTD 400 cm positioned to close to the water surface during the pumping or from poor heat removal due to flume walls resulting in temperatures as warm as -12.5 °C.
- the general increase in temperature at 23 minutes is due to multiple entries into the cold room as runoff collection started.
- cold room ambient temperatures (240, 9020, Beaker) were generally -16.5 to -14.5 °C.
- ambient temperatures in the flume above the ice surface ranged from -15 to -13.5 °C.

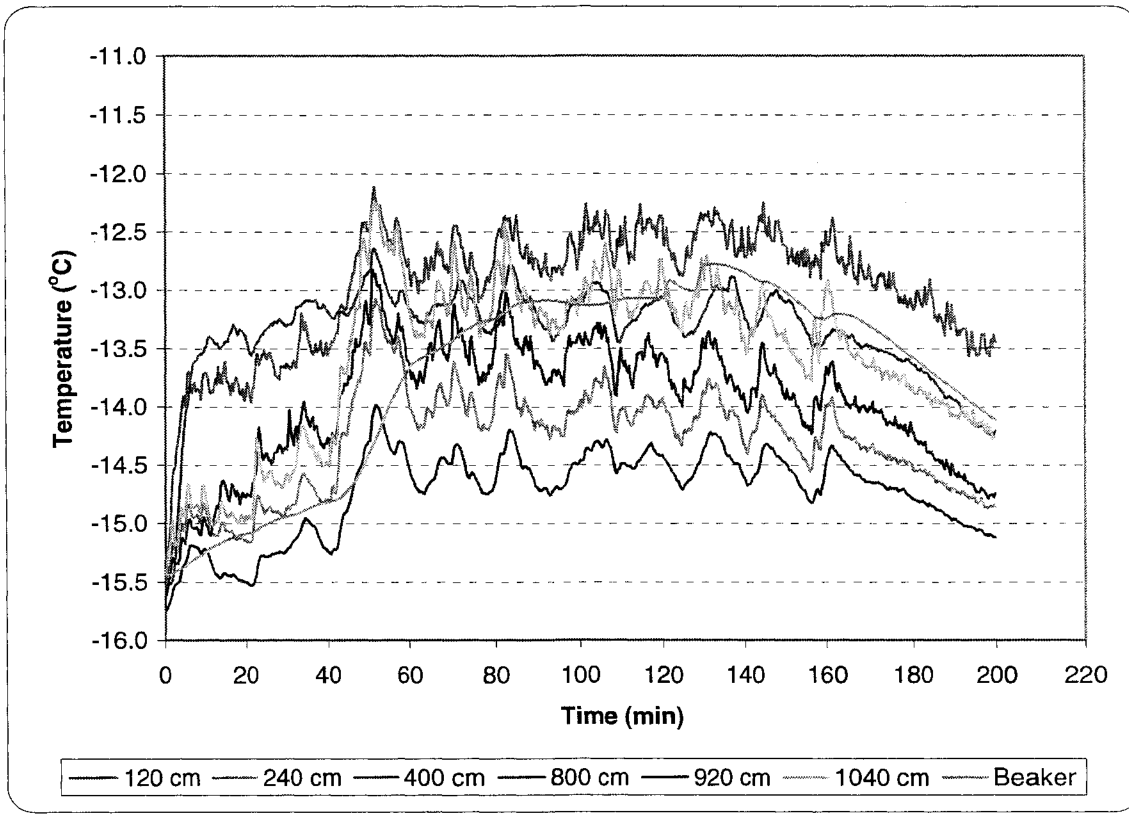


Figure A5.5 Ambient temperature profiles during Test 7.

Summary:
- the temperature spike at 45 min is due defrost cycle in cold room.
- RTD 120 and 400 cm positioned to close to the water surface during the pumping or from poor heat removal due to flume walls.
- cold room ambient temperatures (240, 9020, Beaker) were generally -15.5 to -14.5 °C until defrost. After the defrost cycle began temperatures rose to -13 °C.
- ambient temperatures in the flume above the ice surface ranged from -15 to -13 °C and up to -12.5 °C during the defrost.

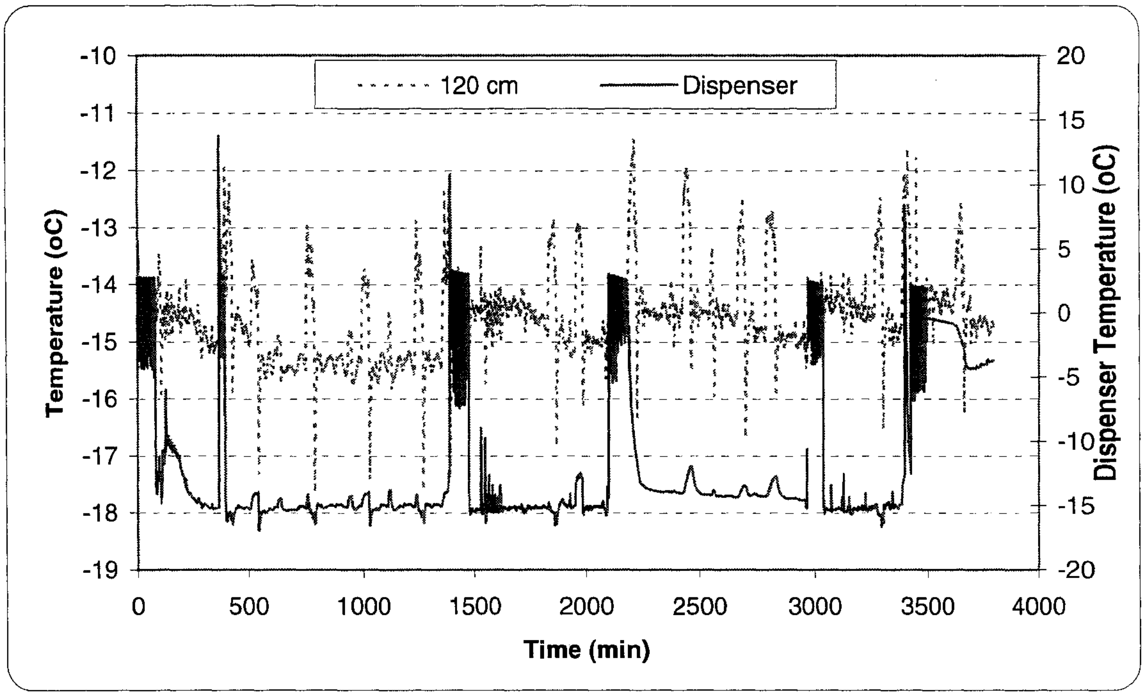


Figure A5.6 Temperature profiles from RTDs at 120 cm and in the dispenser for Freeze Test 8.

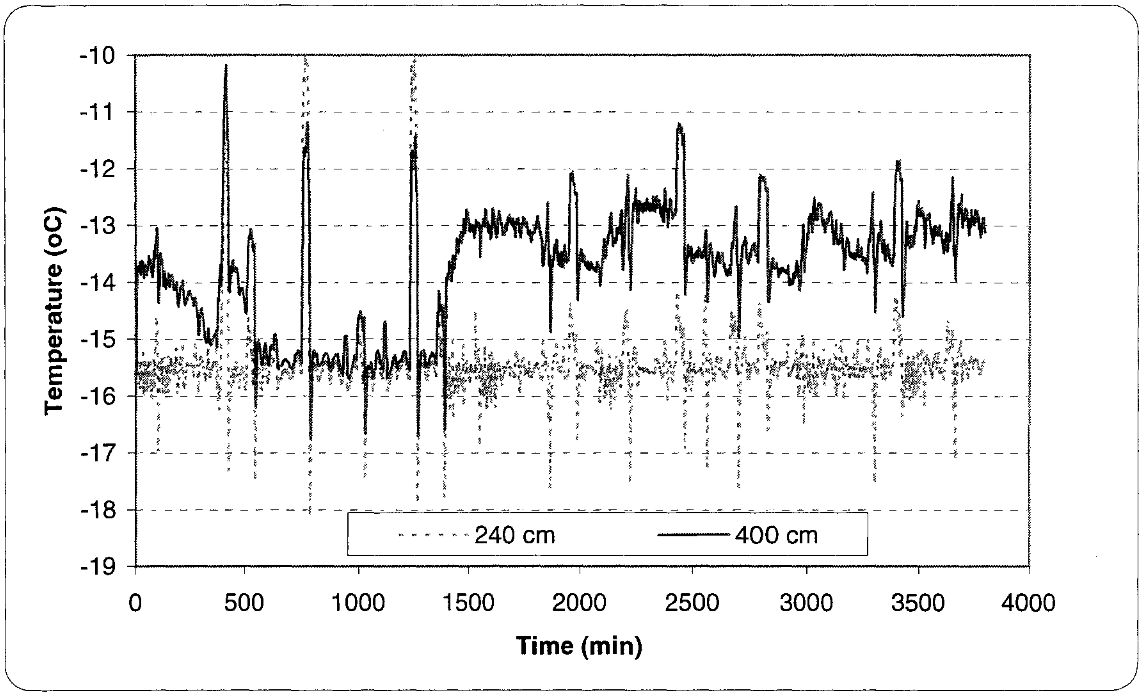


Figure A5.7 Temperature profiles from RTDs 240 and 400 cm for Freeze Test 8.

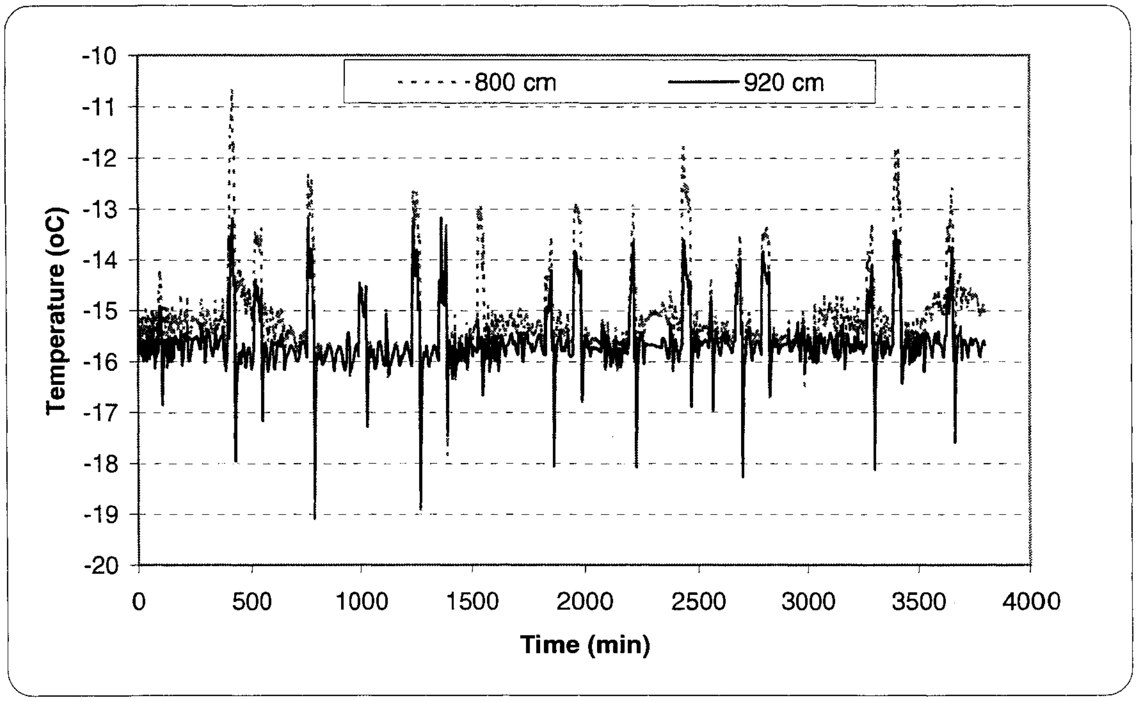


Figure A5.8 Temperature profiles from RTDs 800 and 920 cm for Freeze Test 8.

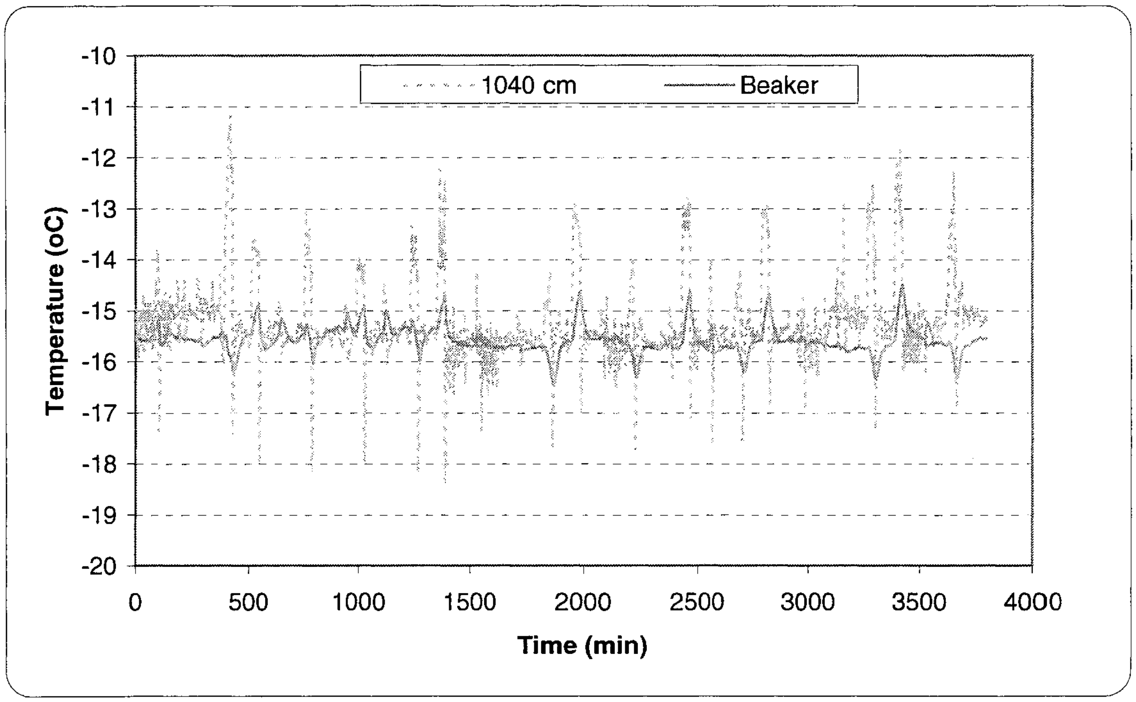


Figure A5.9 Temperature profiles from RTDs 1040 cm and in the antifreeze beaker for Freeze Test 8.

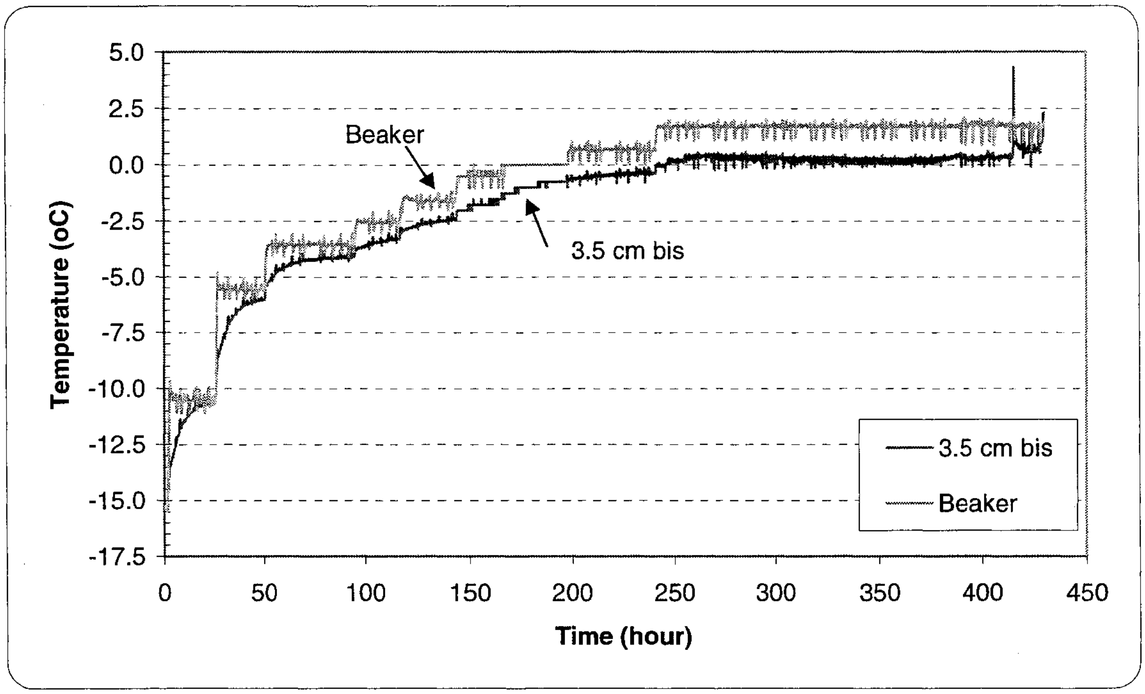


Figure A5.10 Ice temperature profile at station 120 cm during melting for Test 8. RTD frozen into the ice prior to melting. (cm bis = cm below ice surface).

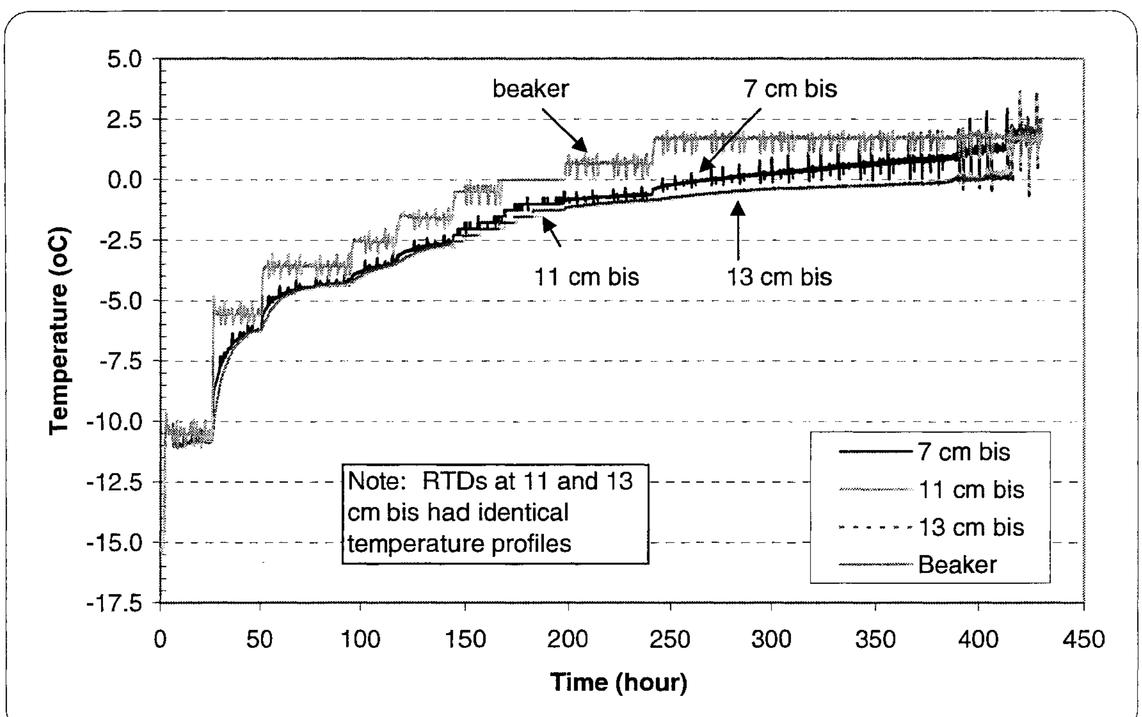


Figure A5.11 Ice temperature profile at station 400 cm during melting for Test 8. RTD frozen into the ice prior to melting. (cm bis = cm below ice surface).

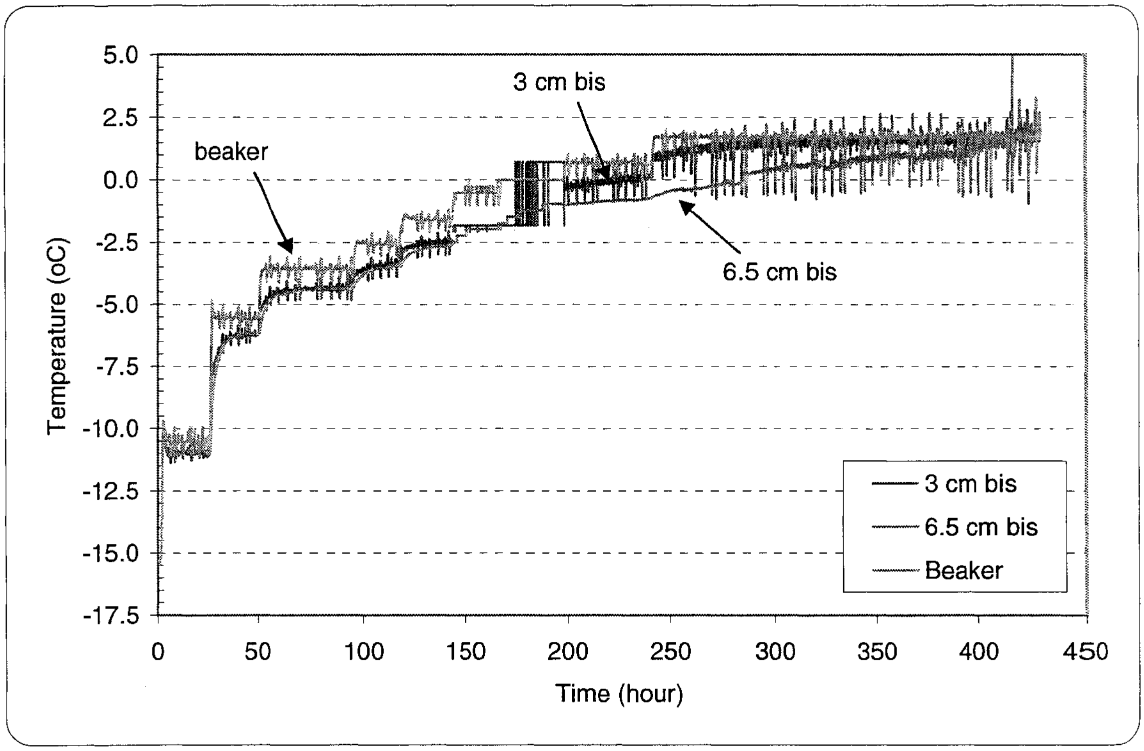


Figure A5.12 Ice temperature profile at station 1040 cm during melting for Test 8. RTD frozen into the ice prior to melting. (cm bis = cm below ice surface).

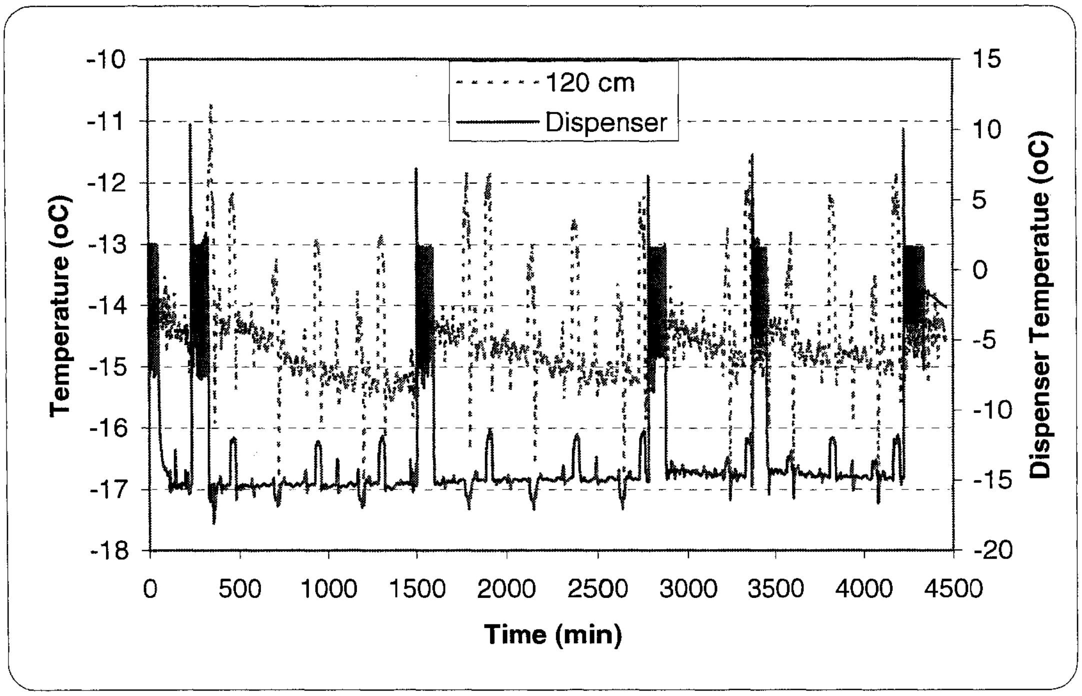


Figure A5.13 Temperature profiles from RTDs at 120 cm and in the dispenser for Freeze Test 9.

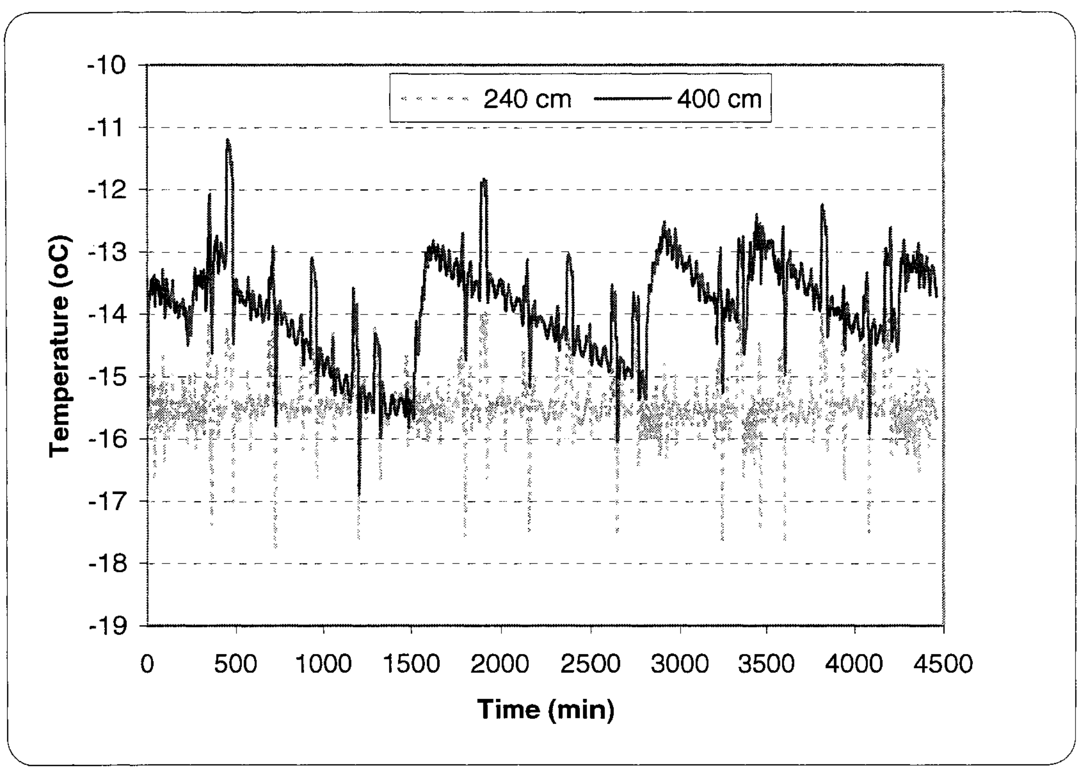


Figure A5.14 Temperature profiles from RTDs at 240 and 400 cm for Freeze Test 9.

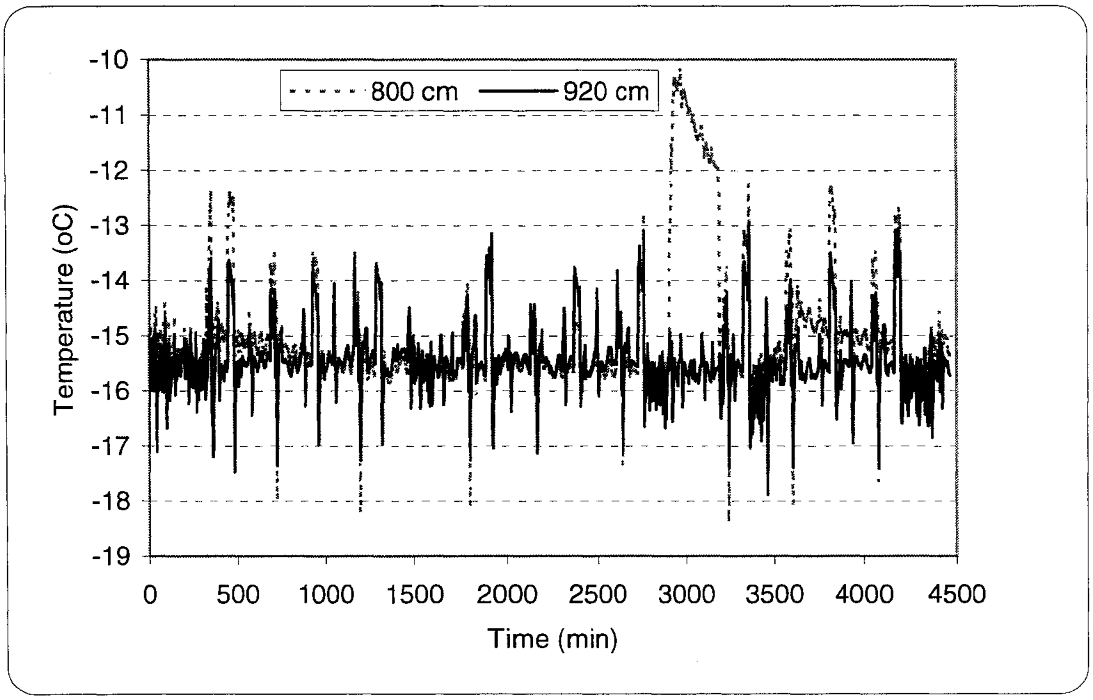


Figure A5.15 Temperature profiles from RTDs at 800 and 920 cm for Freeze Test 9.

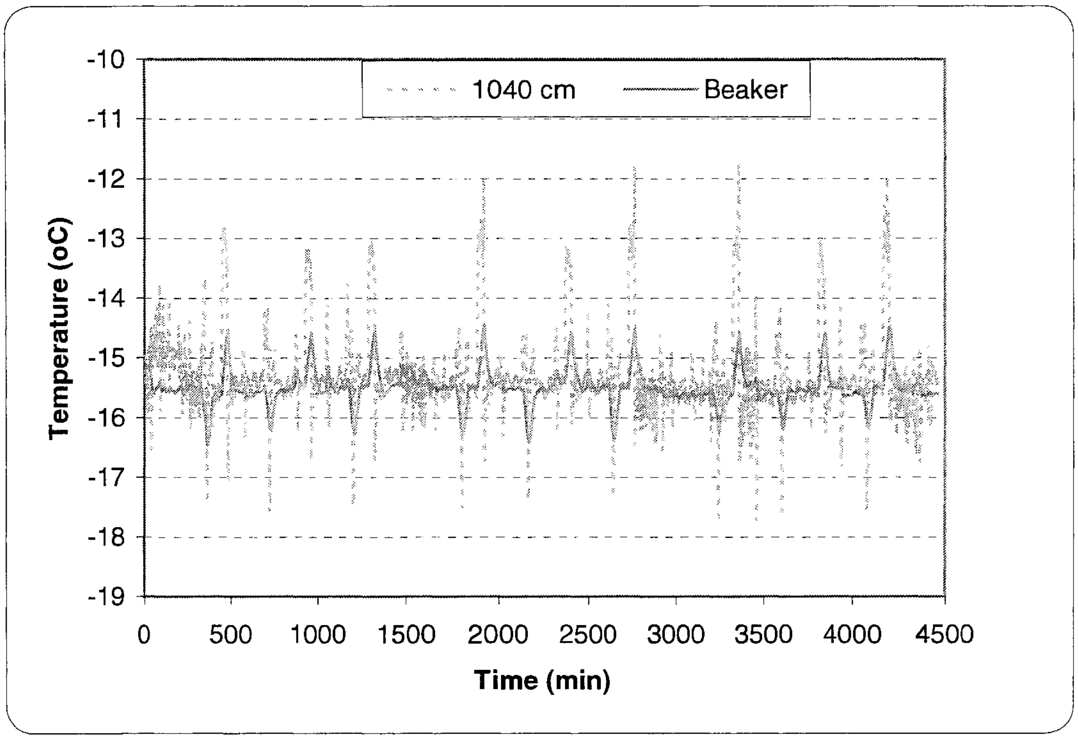


Figure A5.16 Temperature profiles from RTDs at 1040 and in the antifreeze beaker for Freeze Test 9.

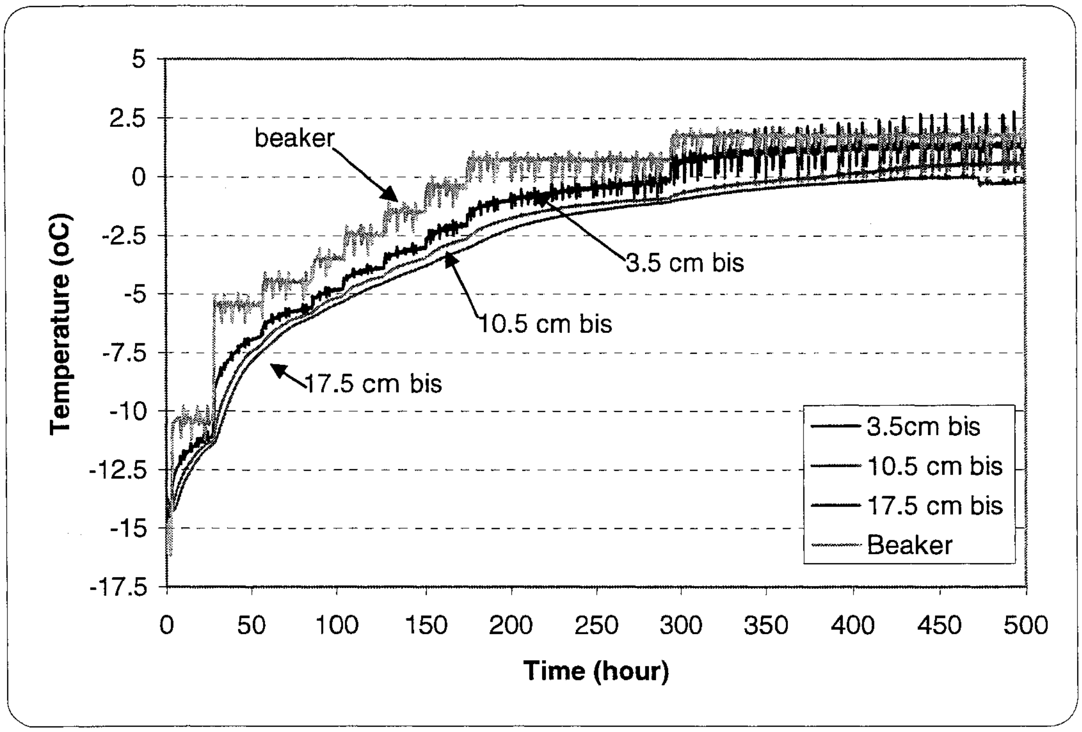


Figure A5.17 Ice temperature profile at station 365 cm during melting for Test 9. RTD frozen into the ice prior to melting. (cm bis = cm below ice surface).

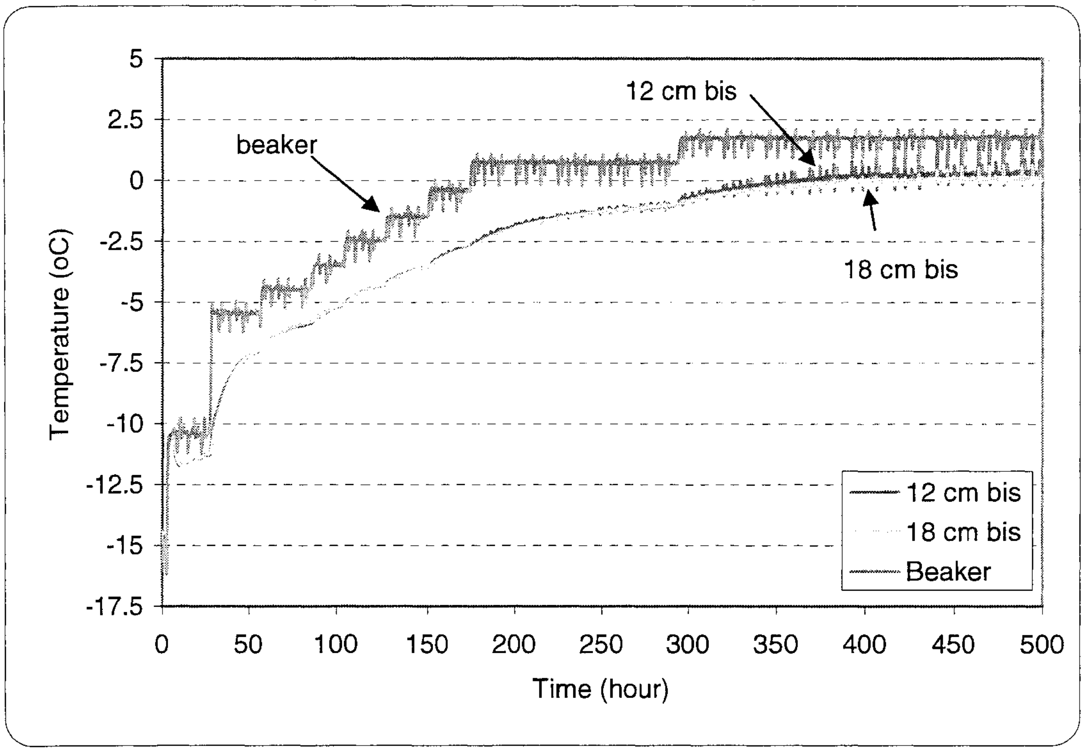


Figure A5.18 Ice temperature profile at station 643 cm during melting for Test 9. RTD frozen into the ice prior to melting. (cm bis = cm below ice surface).

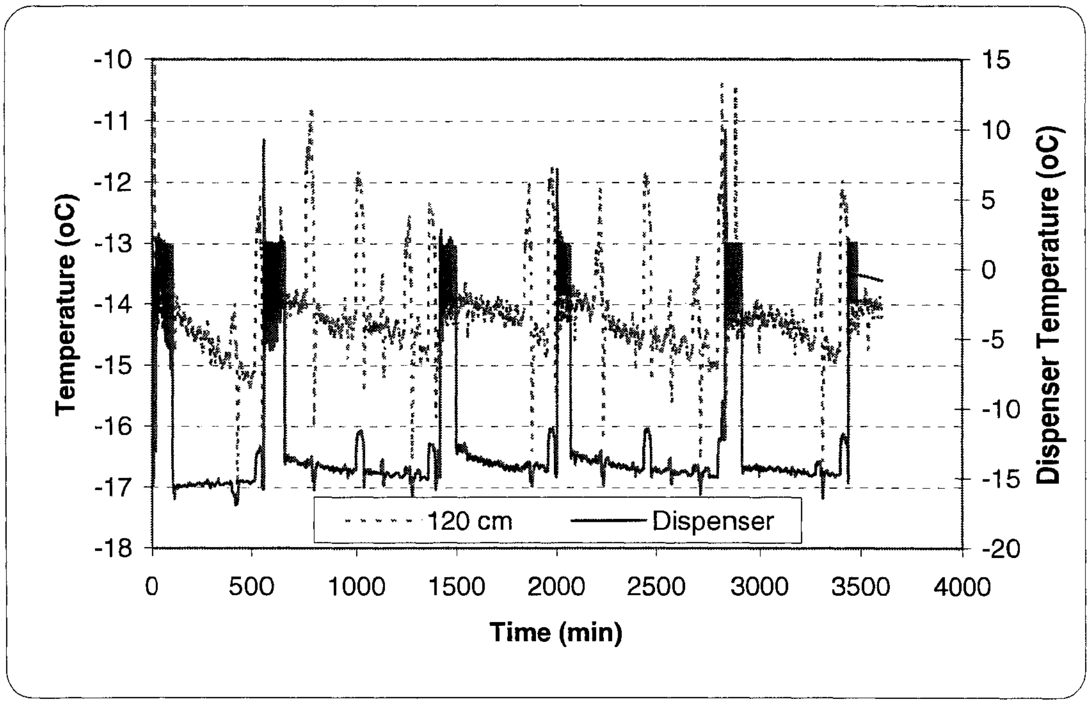


Figure A5.19 Temperature profiles from RTDs at 120 cm and in the dispenser for Freeze Test 10.

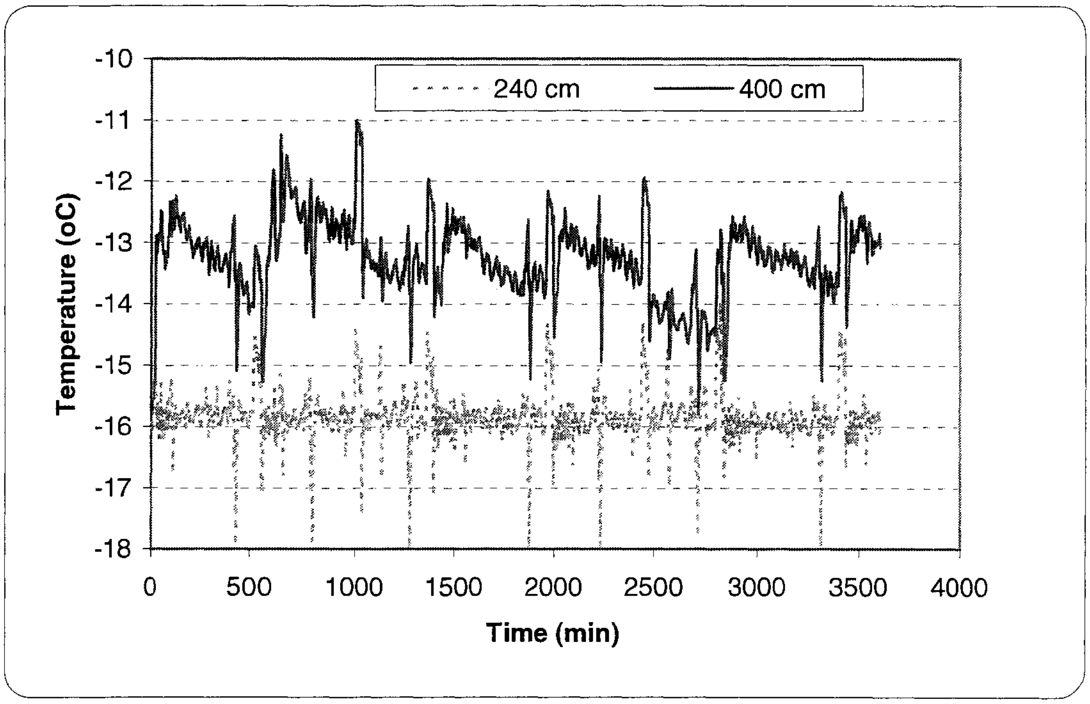


Figure A5.20 Temperature profiles from RTDs at 240 and 400 cm for Freeze Test 10.

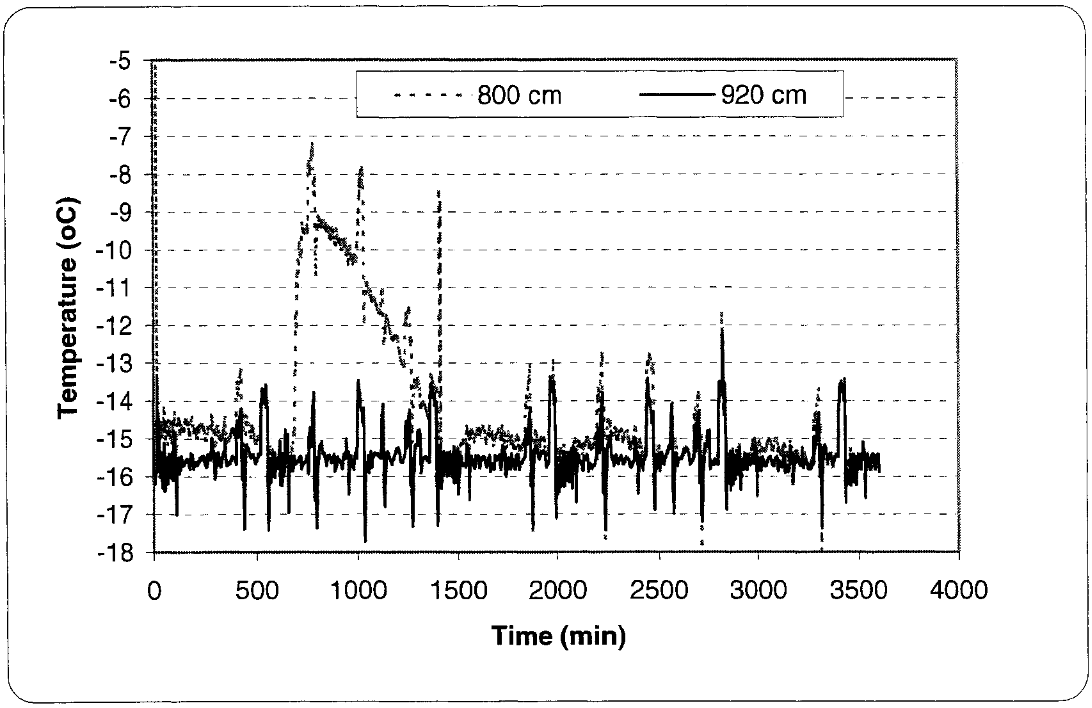


Figure A5.21 Temperature profiles from RTDs at 800 and 920 cm for Freeze Test 10.

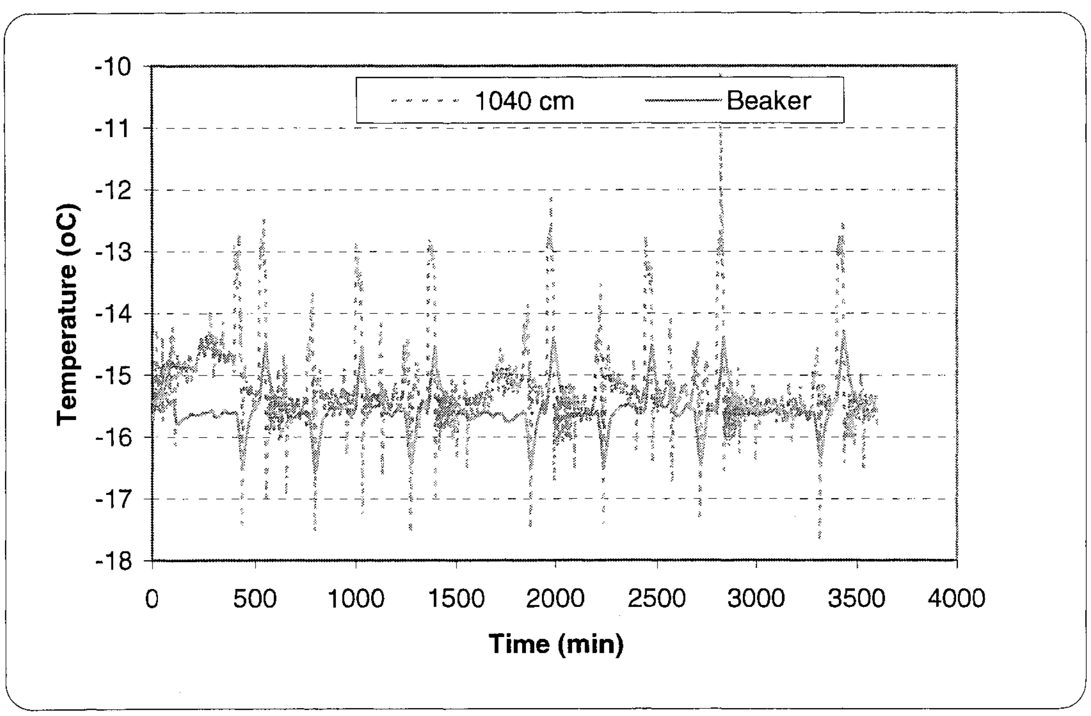


Figure A5.22 Temperature profiles from RTDs at 1040 and in the antifreeze beaker for Freeze Test 10.

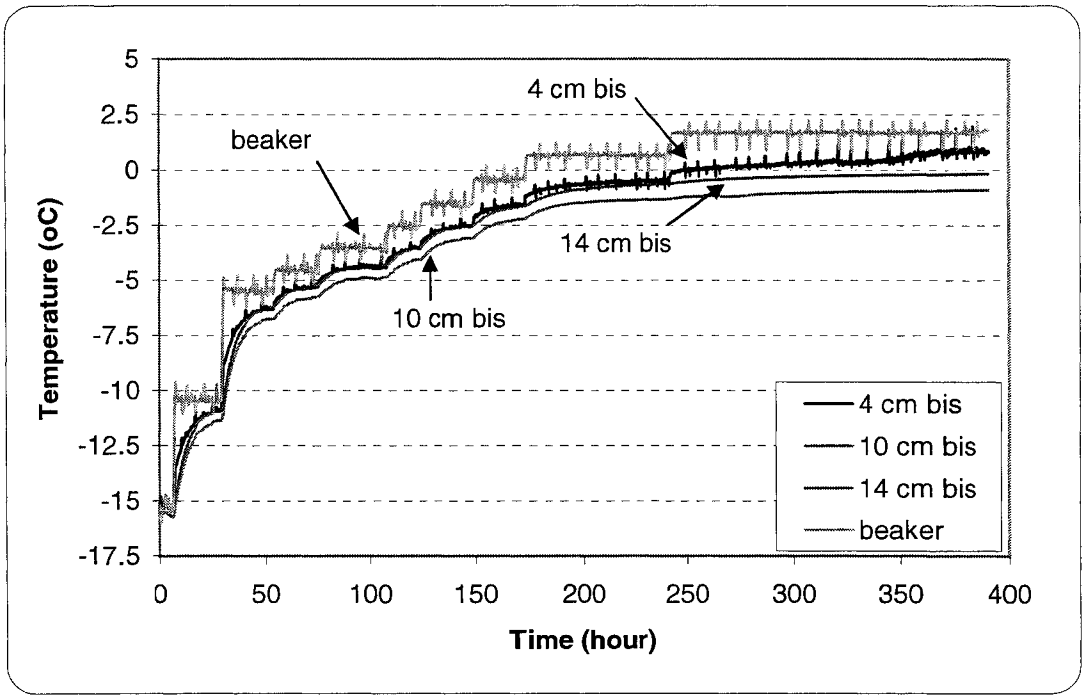


Figure A5.23 Ice temperature profile at station 365 cm during melting for Test 10. RTD frozen into the ice prior to melting. (cm bis = cm below ice surface).

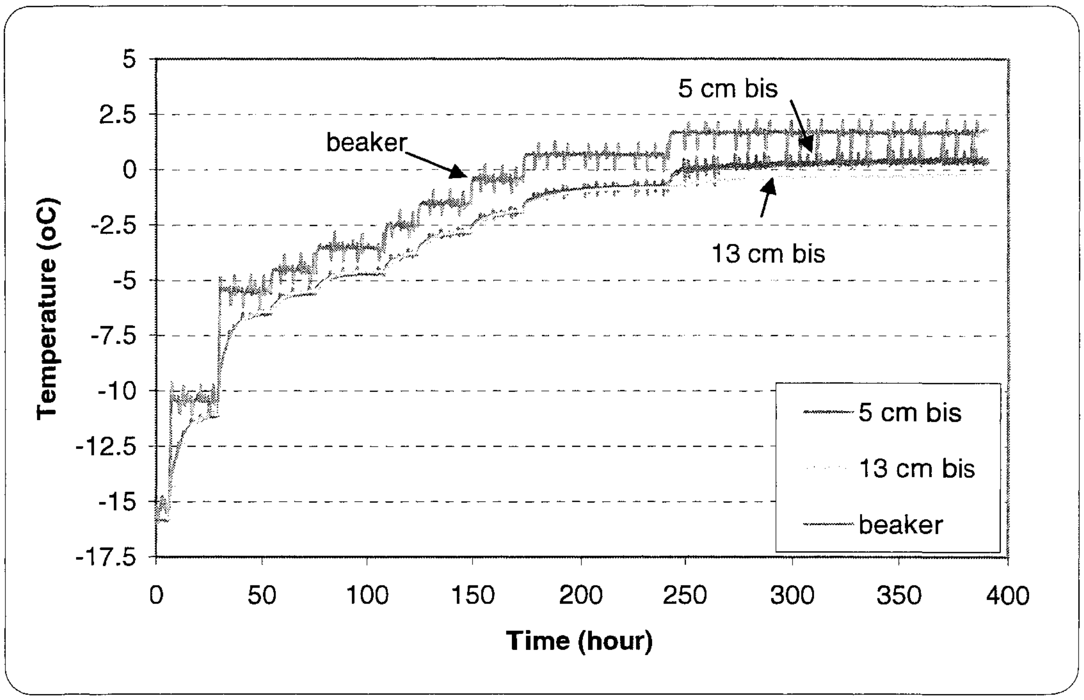


Figure A5.24 Ice temperature profile at station 800 cm during melting for Test 10. RTD frozen into the ice prior to melting. (cm bis = cm below ice surface).

Appendix 6 Design Calculations and Assumptions

Freezing Cell Design

Assumptions:

20 M m^3 of waste water to be treated per year
Maximum ice thickness is 4.5 m
9 % expansion at freezing
Precipitation of 0.45 m/m^2 (Note 1., Environment Canada)
0.5 m of Freeboard required
Side slope of 1:1 of compacted clay
150 days of freezing (Note 2.)
150 days of melting (Note 2.)

Freezing area required

20 M m^3 / (4.5 m/1.09)

4.84E+06 m^2

gives a square area of 2200 x 2200 m

or 16 cells @ 550 X 550 m base width

Water Volume per cell required (Vol req)

= 20 M m^3 / 16

1250000 m^3

Single Freezing Cell Dimensions

Base length (L)	550 m	
Base width (W)	550 m	Vmax = L x W x Hice + $Hice^2$ x L + $Hice^2$ x W
Height of ice (Hice)	4.5 m	
Max Volume of Cell (Vmax)	1383525 m^3	
Treated volume available (Vol treat)	1269289 m^3	Note 3.
Volume of precip (Vol ppt)	136125 m^3	
Height of Precip (Hppt)	0.39 m	Hppt = (Vol ppt - (Vol treat - Vol req))/ (L x W)

Notes:
1. Precipitation data is from canadian climate normals for Fort McMurray (1971 to 2001). Environment Canada, 2005. Canadian Climate Normals. Government of Canada website http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html, accessed August 9, 2005.
2. Dawson, R.F., Sego, D.C., and Pollock, G.W. 1999. Freeze-thaw dewatering of oil sands fine tails. Canadian Geotechnical Journal, 36: pp 587-598.
3. Treated volume available allows for 9 % expansion upon freezing to Vmax.
4. Treated volume required is less than treated volume available therefore the freezing cell is adequate.
5. Additional height is required for the precipitation layer therefore add 0.4 m hieght.

Freezing Cell Construction Volume Summary

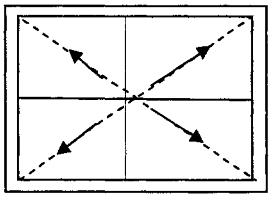
Summary for one cell

Material	Area (m^2)	Depth (m)	Volume (m^3)
Stripping	321205	0.3	96362
Compact Clay	302500	1	302500
20 mm Gravel	302500	0.3	90750

Berm Construction (balance cut and fill)

Divide berm into 8 quadrants. (1 % slope from middle to outer corners)

Volume of berm	11280 m^3
Volume from floor	52000 m^3
Materials handling during construction of berms and floor	31600 m^3
Total material handling per cell	252800 m^3



Split the cell into 8 quadrants representing 4 sloped zones from the centre to the berm. There is 11280 m^3 of material needed to build up each 1/8 berm section. 52000 m3 of material needs to be cut from the floor to get a 1 % slope (assuming all cut from flat surface) for each 1/8 section. To balance of the cut and fill, 11280 m^3 from the floor cut will be used as fill for the berms, leaving 40720 m^3 of cut from the floor. Balancing cut and fill equally from the floor requires 20360 m^3 to be cut placed as fill to slope the remaining portion of the floor. Therefore each 1/8 section will require 11280 m^3 of berm material and 20360 m^3 of floor material to be handled.

Pumping Rate Required

Assumptions

4 pumping zones per freezing cell
5 headers per pumping zone
Each header has 5 risers
100 risers per cell
Only one header pumping at a time
Pulsed flow for 1 hour per cycle, 3 cycles a day
Pulse for 2 min on and 8 min off, for 1 hour cycle
Area available to each riser ~ 50 m x 50 m
150 freezing days

Volume at each cell per year (4.15*550*550)	Vy =	1255375 m^3
Volume at each riser per year (Vy/100)	Vr =	12554 m^3
Daily volume (Vr/150)	Vd =	83.692 m^3
1 hour cycle volume (Vd/3)	Vc =	27.897 m^3
2 minute pulse volume (Vc/6)	Vp =	4.650 m^3
Flow rate per riser (Q1 = Vp/120 s)	Q1 =	0.039 m^3/s
Flow rate per header (Q2 = Q1*5)	Q2 =	0.194 m^3/s

Compare with Lab flow rate	
freezing length	12 m
freezing width	208 m
riser area	2500 m^2
lab flow rate	0.26 L/s m width
riser flow rate	54.2 L/s
header flow rate	0.271 m^3/s

Lab flow rate is greater than the calculated flow rate, Q2, required to meet the yearly volume of 20 M m^3 per year. Therefore use the calculated flow rate, Q2.

Waste Water Placement

Use Hazen-Williams Equation, for circular, plastic pressure pipe flowing full.

Use calculated header flow rate, Q2 0.194 m^3/s

Riser flow rate, Q1 = 0.039 m^3/s

Hazen-William Equation

$$Q = 0.278CD^{2.63}S^{0.54}\text{ , or}$$

$$D = [Q/(0.278CS^{0.54})]^{1/2.63}$$

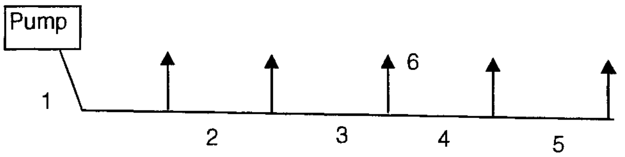
Q = flow rate, m^3/s		
C = roughness coefficient	140	(Veissman and Hammer, 1998)
D = pipe diameter, m		
S = slope of enregy grade line	0.01	

Piping Design

5 headers split from a valve manifold at the pump

Each header has 5 risers

Schematic of one Header



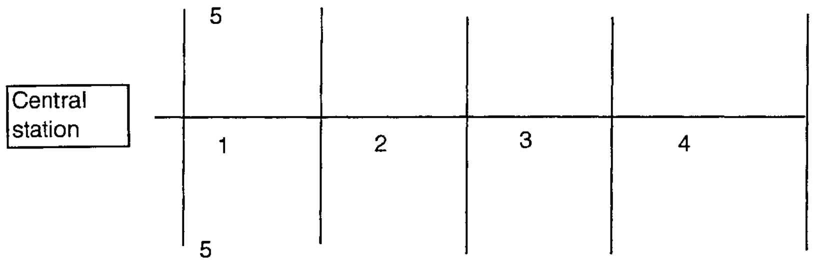
Pipe #	Flow Rate (m^3/s)	Dcalc (m)	Diameter Used (m)	(inches)
1	0.194	0.343	0.350 OD	14 "
2	0.155	0.315	0.350	14 "
3	0.116	0.282	0.300	12 "
4	0.077	0.242	0.250	10 "
5	0.039	0.186	0.200	8 "
6	0.039	0.186	0.200	8 "

Reference.

1. Viessman, W. and Hammer, M.J. 1998. Water Supply and Pollution Control. Addison Wesley Longman, Inc. Menlo Park Californian. pp. 827.

Waste Water Supply Line

Assume that waste water is supplied to a central station at the freezing cells.
From this station the water is dispensed to each of the pumping stations.
Use Hazen-Williams Equation, for circular, steel pressure pipe flowing full.
Requires 1 main feeder pipe
From the main, 10 headers branch out to service the pump stations.
Each header will only supply 2 pumps stations at any given time



Pipe #	X Pump rate	Flow Rate (m^3/s)	Dcalc (m)	Diameter Used (m)	(inches)
1	8	1.550	0.756	0.750	30 "
2	6	1.162	0.677	0.650	26 "
3	4	0.775	0.581	0.550	22 "
4	2	0.387	0.446	0.450	18 "
5	2	0.387	0.446	0.450	18 "

Thaw Flow Rates

Assumptions
Total melting time is 150 days
Based on laboratory scale experiments and Willoughby (2005)
Maximum melt times based on Willoughby's (2005) estimate of 1/3 slowest melt time
Concentrated brine comprises 22 % of initial melt
Treated clean water comprises of the remaining 78 %
Min Brine melt rate based on melt time of 33 days (22 % of total time [150 days])
Max brine melt rate based on melt time of 10 days (1/3 of max melt time)
Min treated water melt rate based on melt time of 117 days (78 % of total time)
Max treated water melt rate time of 40 days (1/3 of max melt time)
Melt rate = volume/ melt time

vol of one freezing zone	312703 m^3
brine volume	68795 m^3
treated water volume	243908 m^3
Brine max melt rate	0.080 m^3/s
Brine min melt rate	0.024 m^3/s
Treated water max melt rate	0.071 m^3/s
Treated water min melt rate	0.024 m^3/s

Effluent Collection System

Use Manning equation for full flowing pipes under atmospheric conditions
1 % grade to follow base slope of freezing cell
Use plastic slotted PVC pipes, manning coefficient of 0.011 (Viessman and Hammer, 1998)
Max brine melt rate will govern the design
Increase diameter by 20 % (factor of safety) since thaw rates are estimate

Manning Equation

$$Q = (R^{0.66}S^{0.5}A)/n, \text{ or}$$

$$r = [(nQ)/(1.979*S^{0.5})]^{3/8}$$

R = hydraulic radius (m) = r/Perimeter
A = cross sectional area (m^2)
S = slope
n = manning coefficient (Ref. 1)
r = pipe radius (m)

Q collection	Qmax melt/8	0.010 m^3/s
Q header	Qmax melt/2	0.040 m^3/s
Q main to sump	Qmax melt	0.080 m^3/s

Collection Pipes		Header Pipes	
8 pipes		2 pipes	
n =	0.011	n =	0.011
Slope	0.01	Slope	0.01
max r	0.060 m	max r	0.101 m
max Dia	0.120 m	max Dia	0.202 m
DIA	**0.150 m**	**DIA**	**0.250 m**

Main Pipe to Sump

1 pipe		
n =	0.011	
Slope	0.01	
max r	0.131	m
max Dia	0.262	m
DIA	**0.300**	**m**

Collection Sump

Collection sumps located at the corners of each freezing cell
9 sumps collect melt from 4 freezing zones
12 sumps collect melt from 2 freezing zones
4 sumps collect melt from 1 freezing zone
Base must be a minimum of 9 m below the berm crest to allow gravity drainage from the base of the freezing cell to the sump
allow 1 m of collection before pumps are activiated

Height	9 m
Diameter	3 m
Fluid level	1 m
volume	7.1 m^3

Sump pumping rates
Use pumps from freezing cells (1 pump = 0.160 m^3/s)
Use level actuators to turn pumps on and off

Sump inflow rate for sumps with 4 freezing zones

Q max melt	0.080 m^3/s
Q max sump	0.318 m^3/s

therefore two pumps required to empty sump

Sump inflow rate for sumps with 2 or less freezing zones

Q max melt	0.080 m^3/s
Q max sump	0.159 m^3/s

therefore one pump required to empty sump

References:

Viessman, W. and Hammer, M.J. 1998. Water Supply and Pollution Control. Addison Wesley Longman, Inc. Menlo Park Californian. pp. 827.

Appendix 7: Pumping Scheme

The waste water placement system was designed to simulate the pumping scheme utilized in the laboratory bench scale experiments. Waste water is pulsed pumped into a freezing cell for an hour, three times a day. There are four separate pumping zones in each of the sixteen freezing cells. One pump is utilized for each zone. Pumping zones from adjacent freezing cells share the use of a single pump. Each pumping zone has 5 header pipes. To ensure adjacent freezing zones are not in operation at the same time the following pumping scheme is required (Figure 7.1):

1. Pumping will initiate in an unattached pair of freezing cells (*i.e.* 1 and 9).
2. All four freezing zones will operate at the same time in both freezing cells.
3. The pump from each freezing zone will supply one header pipe at a time.
4. A series of automated valves will cycle pumping to each of the five header pipes in one freezing zone at 120 s intervals.
5. After 1 hour of operation, each header pipe will have received six, 120 s pulses.
6. Pumping into the freezing cell pair will stop. Pumping into the next pair of cells (*i.e.* 2 and 10) will initiate.
7. A reverse cycle will be initiated in the previous cell pair to drain the header pipes to prevent freezing.
8. Repeat steps 1 through 7 until freezing season has ended. One complete cycle will take 8 hours to complete.

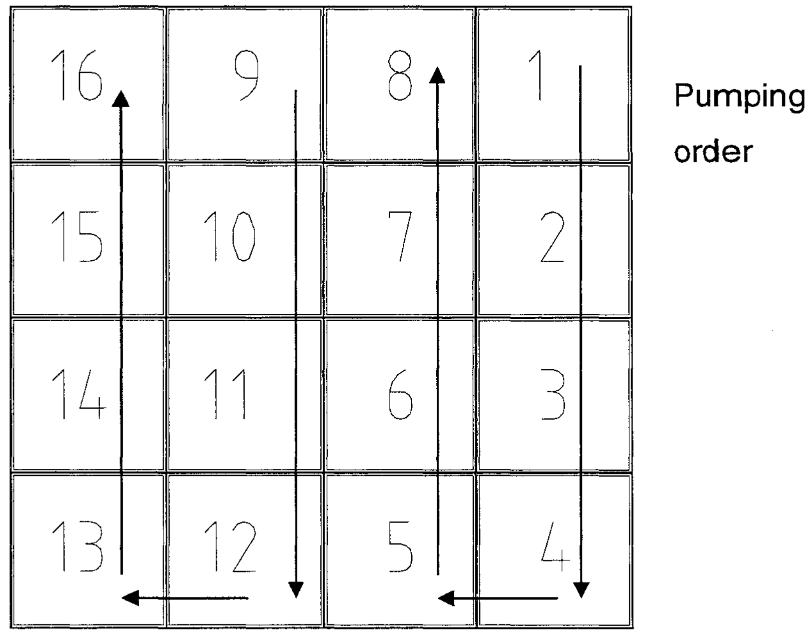


Figure 7.1 Schematic of the pumping order for each of the freezing cells.

Appendix 8 Cost Estimate

Material Estimates

Earthwork			*1 cell*	*16 cells*
	Area (m2)	**Depth (m)**	**Volume**	**Volume**
Material			**(m3)**	**(m3)**
Stripping	321205	0.3	96362	1541784
excavation and berms	-	-	252800	4044800
Compact Clay	302500	1	302500	4840000
20 mm Gravel	302500	0.3	90750	1452000

Feed main Pipe HDPE for salts, burried)			
pipe	**length/unit**		
30 "	567	m	
26 "	567	m	
22 "	567	m	
18 "	567	m	
18 "	11335	m	
total trench	13.603	km	install pipe prior to excavating for base and berms
4 way tees	5	units	

Water Placement system				
	1 string (m)	**1 freezing cell**	**all cells**	
pipe		**(m)**	**(m)**	
Header 14 "	110	2200	35200	50 m burried in berm, else below clay surface
14 "	50	1000	16000	just below compact clay surface
12 "	50	1000	16000	just below compact clay surface
10 "	50	1000	16000	just below compact clay surface
8 "	50	1000	16000	just below compact clay surface
8 "	30	600	9600	riser
14 " tees	1	20	320	
12 " tees	1	20	320	
10 " tees	1	20	320	
8 " tees	1	20	320	
14 " elbow	1	20	320	
8 " elbow	1	20	320	
pipe in berms	200	800	12800	burried in berm as construction progresses
14 " header pipe install			5040	pipe trench shared for header and sump lines
14 " header pipe install			7760	pipe trench for header line only
Bedded on clay liner surface			86400	bedded 600 mm below clay surface
	1 string units	**1 cell units**	**total units**	
riser supports	5	100	1600	
install supports			1600	includes installing silt screen
plunge pool ring	30	600	9600	metres of silt screen
pump			**40**	
	valve per pump	**# pumps**	**total units**	
valves 14 " automatic single zone	10	16	160	
valves 14 " automatic multi zone	15	24	360	
total valves 14 " auto			**520**	

Automated control system	**single zone units**	**multi zone units**	**total**	
single zone - start stop valves	160	360	520	
control unit	16	24	40	
pump control unit	16	24	40	
host computer			1	

Collection System				
	1 zone length (m)	**1 freezing cell**	**total (m)**	
pipe				
6 " slotted PVC	390	1560	24960	install on clay base, put gravel over top
10" solid PVC header	120	480	7680	install on clay base, put gravel over top
12 " suck line from sump	140	315	5040	burried with placement header pipe
pipe install			37680	total length of pipe to install
sump (3 m dia by 9 m culvert)			25	
sump install			25	install prior to berm construction, 3 m deep
valves (10 " ball)			50	for collection to sump isolation
suck line valve (12 " check)			25	check for pump prevent lose prime
actuators			50	(two pumps per sump)

System Operation				
Freeze cycle	Units	Duration (weeks)	total	
Field engineer	3 shifts/day	22	66	weeks to monitor system during operation and collect samples
EC meter	25		25	conituous EC meter at each sump
Pumping	Power (kW)	Hours	kWhr	
1 pump	112	3600	403200	8 pumps will run continuously during the freeze
8 pumps	**896**	28800	**25804800**	cycle
Diesel generator	2		2	500 kW units
Fuel consumption	120 L/hr	2880 L/day	432000	L diesel per 1 unit
		5760 L/day	864000	L diesle for 2 units

System Operation				
Thaw cycle	Units	Duration (weeks)	total	
Field engineer	3 shifts/day	22	66	weeks to monitor system during operation and collect samples
Analytical			1	analyse for inorgancis (major ions)
EC meter	25		25	conituous EC meter at each sump
Pumping	Power (kW)	Hours	kWhr	
1 pump	112	3600	403200	Average of 8 pumps will run continuously during
8 pumps	**896**	28800	**25804800**	the thaw cycle
Fuel consumption	120 L/hr	3600 hr	432000	L diesel per 1 unit
			864000	L diesle for 2 units
Yearly maintenance	5 % of mechanical and electrical			

Unit Price Estimates

Cost data estimated from RS Means Cost Data Manuals and Local suppliers
Unit costs include overhead and profit as per RS Means format
Material costs (*i.e.* pipe, tees, valves, etc.) include labour for assembly (*i.e.* joining pipe sections) and equipment
Install costs are for excavating and backfill of pipe bed and or trench (labour and equipment)
Fort McMurray adjusted costs estimated from Alberta 2003 Wage and Salary Survey (average of various construction position wages and ratio of labour to unit cost for each item)

Labour wage ratio	2003 Average Hourly Wage		Ft.Mac/Edmonton
Position	Edmonton	Fort McMurray	Ratio
Heavy equip opeator	21.06	20.47	0.97
Heavy equip Supervisor	21.76	25.42	1.17
Pipefitter	25.24	35.09	1.39
Labourer	16.16	25.40	1.57
Industrial Electrician	27.50	28.08	1.02
Average			1.22

Labour Ratio to Unit Cost			
Item	Bare Cost	Labour	*Ratio*
Pump	23925	5025	*0.210*
24" HDPE pipe	174	36.5	*0.210*
12" HDPE pipe	55.05	14.1	*0.256*
24" Line Install	77.5	51	*0.658*
Header pipe Install	8.45	5.4	*0.639*
10" HDPE Tees	353.5	32	*0.091*
14" valves	1165	350	*0.300*

Average Cost of Labour Ratio to Unit Cost	*Ratio*
Pipe, tees, valves labour ratio of cost	*0.213*
Pipe line install labour ratio of cost	*0.649*

Fort MacMurray adjusted cost from Edmonton Unit Costs	**ratio**
Minimum increase in cost for mob/demob, shipping	**1.1**
Pipe, tees, valves cost (0.213*1.22+(1-0.213)*1.1)	**1.13**
Pipe line install (0.649*1.22+(1-0.649)*1.1)	**1.18**

References:
Government of Alberta, 2003. 2003 Wage and Salary Survey. Alberta Learning Information Service. http://www.alis.gov.ab.ca/main.asp, accessed September 8, 2005.
Martin, S., 2002. Environmental Remediation Cost Data - Unit Price. RS Means, 8th Edition.
Mossman, M., 2002. Mechanical Cost Data. RS Means, 25 th Edition.
Spencer, E., 2004. Heavy Construction Cost Data. RS Means, 18th Edition.
Statistics Canada, 2005. Construction union wage rate index table. Government of Canada. http://www40.statcan.ca/cbin/fl/cstprintflag.cgi, accessed September 8, 2005

Earth Work

Material	Rate	Unit	Cost Assumption
Stripping	5.25	$/m^3$	based on personal communication with Syncrude
excavation and berms	5.25	$/m^3$	based on personal communication with Syncrude
Compact Clay	1.06	$/m^3$	based on RS Means national average
	1.15	$/m^3$	Edmonton, AB adjusted cost (1.083)
total	1.26	$/m^3$	Fort McMurray, AB adjusted cost (1.1)
drainage layer	5.25	$/m^3$	earth moving cost as per personal comm. w/ Syncrude
20 mm Gravel	30.00	$/m^3$	Gravel cost, local Supplier
	7.17	$/tonne	Hauling Costs, local firm
	10.76	$/m^3$	Hauling Costs (1.5 tonne/m^3^)
total	40.76	$/m^3$	material costs

Waste Water Placement

Main Feed Lines (AVG 24 " HDPE)	208.00	$/m	based on RS Means national average
	225.26	$/m	Edmonton, AB adjusted cost (1.083)
total	253.78	$/m	Fort McMurray, AB adjusted cost (1.13)
Main Feed Lines (AVG 18 " HDPE)	129.00	$/m	based on RS Means national average
	139.71	$/m	Edmonton, AB adjusted cost (1.083)
total	157.39	$/m	Fort McMurray, AB adjusted cost (1.13)
Main Feed Tees (AVG 24" HDPE)	2300.00	$/unit	based on RS Means national average
	2490.90	$/unit	Edmonton, AB adjusted cost (1.083)
total	2806.25	$/unit	Fort McMurray, AB adjusted cost (1.13)
Main Feed Line Install (24 ")	77.50	$/m	based on RS Means national average
	83.93	$/m	Edmonton, AB adjusted cost (1.083)
total	99.11	$/m	Fort McMurray, AB adjusted cost (1.18)
Main Feed Line Install (18 ")	61.00	$/m	based on RS Means national average
	66.06	$/m	Edmonton, AB adjusted cost (1.083)
total	78.01	$/m	Fort McMurray, AB adjusted cost (1.18)
Header (14 " HDPE)	80.00	$/m	based on RS Means national average
	86.64	$/m	Edmonton, AB adjusted cost (1.083)
total	97.61	$/m	Fort McMurray, AB adjusted cost (1.13)
Header (12 " HDPE)	67.50	$/m	based on RS Means national average
	73.10	$/m	Edmonton, AB adjusted cost (1.083)
total	82.36	$/m	Fort McMurray, AB adjusted cost (1.13)
Header (10 " HDPE)	52.50	$/m	based on RS Means national average
	56.86	$/m	Edmonton, AB adjusted cost (1.083)
total	64.06	$/m	Fort McMurray, AB adjusted cost (1.13)
Header (8 " HDPE)	42.00	$/m	based on RS Means national average
	45.49	$/m	Edmonton, AB adjusted cost (1.083)
total	51.24	$/m	Fort McMurray, AB adjusted cost (1.13)
Header (14 " Tees)	670.00	$/unit	based on RS Means national average
	725.61	$/unit	Edmonton, AB adjusted cost (1.083)
total	817.47	$/unit	Fort McMurray, AB adjusted cost (1.13)
Header (12 " Tees)	565.00	$/unit	based on RS Means national average
	611.90	$/unit	Edmonton, AB adjusted cost (1.083)
total	689.36	$/unit	Fort McMurray, AB adjusted cost (1.13)
Header (10 " Tees)	405.00	$/unit	based on RS Means national average
	438.62	$/unit	Edmonton, AB adjusted cost (1.083)
total	494.14	$/unit	Fort McMurray, AB adjusted cost (1.13)
Header (8 " Tees)	305.00	$/unit	based on RS Means national average
	330.32	$/unit	Edmonton, AB adjusted cost (1.083)
total	372.13	$/unit	Fort McMurray, AB adjusted cost (1.13)
Header (14 " elbows)	640.00	$/unit	based on RS Means national average
	693.12	$/unit	Edmonton, AB adjusted cost (1.083)
total	780.87	$/unit	Fort McMurray, AB adjusted cost (1.13)
Header (8 " elbows)	224.00	$/unit	based on RS Means national average
	242.59	$/unit	Edmonton, AB adjusted cost (1.083)
total	273.30	$/unit	Fort McMurray, AB adjusted cost (1.13)
Header Line Install with sump line (burried in berms)	39.00	$/m	based on RS Means national average
	42.24	$/m	Edmonton, AB adjusted cost (1.083)
total	49.88	$/m	Fort McMurray, AB adjusted cost (1.18)

Header Line Install (burried in berms)	29.00	$/m	based on RS Means national average
	31.41	$/m	Edmonton, AB adjusted cost (1.083)
total	37.09	$/m	Fort McMurray, AB adjusted cost (1.18)
Header Line Install (on clay liner)	8.45	$/m	based on RS Means national average
	9.15	$/m	Edmonton, AB adjusted cost (1.083)
total	10.81	$/m	Fort McMurray, AB adjusted cost (1.18)
Riser Support with install	1000.00	$/unit	esimated cost depends on support design
Plunge pool Ring (Geotextile Silt Fence)	40.00	$/30.5 m roll	Local distributor
	4.00	$/roll	Shipping Fort McMurray (10 %)
total	1.44	$/m	
8 " vertical riser flow control valves	825.00	$/unit	based on RS Means national average (2 x manual valve cost)
	893.48	$/unit	Edmonton, AB adjusted cost (1.083)
total	1006.59	$/unit	Fort McMurray, AB adjusted cost (1.13)
14 " Automated Shut off Valves	2850.00	$/unit	based on RS Means national average (2 x manual valve cost)
	3086.55	$/unit	Edmonton, AB adjusted cost (1.083)
total	3477.31	$/unit	Fort McMurray, AB adjusted cost (1.13)
Pump (112 KW, 252 L/s 150 HP with install)			
	28400.00	$/unit	based on RS Means national average
	30757.20	$/unit	Edmonton, AB adjusted cost (1.083)
total	34651.06	$/unit	Fort McMurray, AB adjusted cost (1.13)
Pump House	5000.00	$/unit	Double Willoughby's (2005) cost
Pump House Heater	100.00	$/unit	Double Willoughby's (2005) cost
Automated Control System			
start/stop control for valves	326.40	$/unit	based on RS Means national average
	353.49	$/unit	Edmonton, AB adjusted cost (1.083)
total	398.24	$/unit	Fort McMurray, AB adjusted cost (1.13)
Controller Unit	5000.00	$/unit	based on RS Means national average
	5415.00	$/unit	Edmonton, AB adjusted cost (1.083)
total	6100.54	$/unit	Fort McMurray, AB adjusted cost (1.13)
Pump Control Unit	1552.50	$/unit	based on RS Means national average
	1681.36	$/unit	Edmonton, AB adjusted cost (1.083)
total	1894.22	$/unit	Fort McMurray, AB adjusted cost (1.13)
Host Computer	10000.00	$/unit	based on RS Means national average
	10830.00	$/unit	Edmonton, AB adjusted cost (1.083)
total	12201.08	$/unit	Fort McMurray, AB adjusted cost (1.13)

Collection System			
6 " perforated PVC	29.00	$/m	based on RS Means national average
	31.41	$/m	Edmonton, AB adjusted cost (1.083)
total	35.38	$/m	Fort McMurray, AB adjusted cost (1.13)
10 " solid PVC (buried)	43.00	$/m	based on RS Means national average
	46.57	$/m	Edmonton, AB adjusted cost (1.083)
total	52.46	$/m	Fort McMurray, AB adjusted cost (1.13)
6 " PVC wyes	130.00	$/unit	based on RS Means national average
	140.79	$/unit	Edmonton, AB adjusted cost (1.083)
total	158.61	$/unit	Fort McMurray, AB adjusted cost (1.13)
6 " Collection Pipe (on clay liner)	2.52	$/m	based on RS Means national average
	2.73	$/m	Edmonton, AB adjusted cost (1.083)
total	3.22	$/m	Fort McMurray, AB adjusted cost (1.18)
10 " Collection Pipe (on clay liner)	5.71	$/m	based on RS Means national average
	6.18	$/m	Edmonton, AB adjusted cost (1.083)
total	7.30	$/m	Fort McMurray, AB adjusted cost (1.18)
12 " HDPE Sump Line	67.50	$/m	based on RS Means national average
	73.10	$/m	Edmonton, AB adjusted cost (1.083)
total	82.36	$/m	Fort McMurray, AB adjusted cost (1.13)
10 " shut off valve	1200.00	$/unit	based on RS Means national average
	1299.60	$/unit	Edmonton, AB adjusted cost (1.083)
total	1464.13	$/unit	Fort McMurray, AB adjusted cost (1.13)
12 " check valve	3200.00	$/unit	based on RS Means national average
	3465.60	$/unit	Edmonton, AB adjusted cost (1.083)
total	3904.34	$/unit	Fort McMurray, AB adjusted cost (1.13)
Sump	20000.00	$/unit	Double Willoughby's (2005) cost
Sump Install	3000.00	$/unit	Double Willoughby's (2005) cost
Level actuators	50.00	$/unit	Willoughby's (2005) cost
System Operation			
Field Engineer	1360.00	$/week	based on AB 2005 Wage and Salary Info
EC meter	4000.00	$/unit	
EC probe/solutions	500.00	$/unit	
Ec data logger	500.00	$/unit	
EC monitoring total	5000.00	$/unit	
Generator	102500.00	$/unit	based on RS Means national average
	111007.50	$/unit	Edmonton, AB adjusted cost (1.083)
total	125061.05	$/unit	Fort McMurray, AB adjusted cost (1.13)
Fuel	1.20	$/L	delivered cost ($1.09/L, + 10 % delivery)

* Data from RS means 2002 Environmental Remediation Cost Data - Unit Price
** based on Conststruction union Wage rate Index, Statistics Canada
http://www40.statcan.ca/l01/cst01/econ144b.htm

Distribution of investment over the project life

Use equal payment series capital recovery factor (Madwar and Tarazi, 2002)

$$A = P(1+i)^n \{ i / [(1+i)^n - 1] \}$$

A	yearly cost of project over the investment period	
P	present worth ($)	127,200,000
i	interest rate	
n	investment period (years)	

20 years,	7%	A =	$ 12,007,000	per year
			$ 0.60	/m³
10 years,	7%	A =	$ 18,110,000	per year
			$ 0.91	/m³
30 years,	8%	A =	$ 11,299,000	per year
			$ 0.56	/m³