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PII: S0165-232X(06)00183-2
DOI: doi: 10.1016/j.coldregions.2006.12.002
Reference: COLTEC 1166

To appear in: *Cold Regions Science and Technology*

Received date: 26 September 2006
Revised date: 30 November 2006
Accepted date: 4 December 2006

Please cite this article as: Beier, Nicholas, Sego, David, Donahue, Rob, Biggar, Kevin, Laboratory investigation on freeze separation of saline mine waste water, *Cold Regions Science and Technology* (2006), doi: 10.1016/j.coldregions.2006.12.002

Laboratory investigation on freeze separation of saline mine waste water

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ABSTRACT

The extraction and upgrading process for bitumen from oil sand deposits in Alberta, Canada 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 (salt) contaminant concentrations in the recycle water. Using a specially designed flume housed in a cold room, trickle freeze separation was evaluated for contaminant separation of saline solutions used as a surrogate for mine waste water. Experiments were conducted at various ambient temperatures, salt concentrations and mass flow rates. Melting proved to be more effective at concentrating salts than freezing. The trickle freeze/thaw process developed during the experiment was very effective at separating and concentrating the salts into a smaller volume. For source waters frozen at an ambient temperature of -15^{o}C and with 3000 mg/L (NaCl) or less, 80 % removal of salts was possible after melting 9 % of the produced ice. For source waters with higher concentrations (20,000 mg/L), 80 % removal was possible after melting 27 % of the produced ice.

Keywords: freeze separation, freeze concentration, oil sands process water, saline water, impurity separation

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1. INTRODUCTION

Mine waste water management in the Canadian oil sands industry has become a major concern due to increased demand on river water associated with expanding production rates, costs and disturbances associated with limited storage capacity, and treatment costs for the waste water. The extraction and upgrading process for bitumen from these oil sand deposits currently require large volumes of process water. Importing water and recycling/reuse of clarified process water are methods currently used to fulfill the water demand. Consequently, dissolved organic and inorganic (salt) chemical concentrations are steadily increasing in the recycle water due to continuous reuse. Increased concentrations may adversely impact extraction efficiency or lead to scaling, fouling and corrosion (Peng et al., 2004). Conventional treatment methods to remove dissolved salts are considered expensive by the oil sands industry due to the large, diluted volumes requiring treatment and high costs of the technology (Dore, 2005; Szytel, 2005), driving a need for an alternative treatment method. Therefore, natural trickle freeze separation was investigated as a potential alternate treatment method for salt removal from saline mine waste water.

Freeze separation is a process where dissolved solutes in aqueous solutions are concentrated during freezing. Under freezing conditions ice crystals grow from pure water molecules, rejecting impurities ahead of the growing crystal front. As freezing progresses, the impurity concentration in the solution increases while the freezing point of the remaining unfrozen liquid decreases. The purity of the ice and degree of concentration in the fluid reject depends on the freezing rate and how efficiently the fluid is removed from the crystal front (Chalmers, 1959; Gao et al., 2004a and 2004b; Pounder, 1965). Furthermore, due to elution of impurities from ice in the early melt water, the purity of the remaining ice is further enhanced (Cragin et al., 1993; Gao et al., 2004a and 2004b).

Natural freeze separation offers 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. The local climate at oil sands mine sites is suitable for natural freezing and thawing, negating the requirement for complex mechanical freezing systems. Existing mine structures such as ponds may be utilized for storage and ice containment.

Previous freeze separation research by Gao et al. (2004a and 2004b) 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, ice fog produced during spray freezing operations may preclude use of this freeze separation process near existing mine operations.

An alternative to spray freezing is a process called trickle freezing. Conceptually, trickle freezing is a process where saline water flows in thin, laminar sheets over an inclined 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 then drains along the inclined ice mass to the lowest point for collection (Figure 1). Initially, ice will grow from the air/liquid surface downward and from the base ice up into the solution. The base ice will absorb some of the sensible heat from the solution and warm to the freezing temperature (T_f). Once the base ice reaches T_f, heat removal will only occur at the air/liquid interface, thus majority of the ice will grow from the surface downward. Since saline solution is continually added to the system, the air/liquid interface continually rises allowing the thin, successive layers of ice to develop. As long as saline solution is continually added, the ice mass will be almost isothermal at T_f (Lozowski et al., 1991).

The conceptual model for trickle freeze separation is based on the mathematical freeze separation model developed by Otto (2002). Otto's (2002) 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.

Natural trickle freeze separation may produce a small amount of highly concentrated brine solution from a large, diluted source reducing the contaminated volume of water requiring treatment prior to disposal. The purified melt water may also be reused in the extraction and upgrading process, minimizing the demand for fresh, imported river water. The objectives of this study are to: validate the trickle freeze separation conceptual model; investigate the influence of experimental variables including influent flow rate, initial salt concentration and temperature on the trickle freeze/thaw separation processes; and determine the degree of separation and subsequent concentration of salts during the freeze/thaw processes.

2. METHODOLOGY

The current experiment was designed to emulate the conceptual trickle freezing model to investigate the influence of the variables on the freeze separation process. The 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. Specific details of the experimental setup and methodology are available in Beier (2006).

2.1 Experimental Setup and Materials

Saline water consisting of sodium chloride salt (NaCl) and tap water was used as a surrogate for testing. Relationships between electrical conductivity (EC) and various concentrations of NaCl (gravimetric measurement), and Na and Cl (by ion chromatography) were developed to quickly determine concentration by measuring EC. The saline solution to be dispensed into the flume was housed in a cold room adjacent to the cold room housing the flume, to maintain the solution temperature between 1 and 3^{o}C, typical of winter field conditions within a storage pond. Freezing occurred in a specially designed “U” shaped (in plan), transparent flume (0.61 m wide, 0.61 m deep, 12 m long) located in a large cold room (Figure 2). 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 (0.074 to 0.26 kg/s per metre width of the flume). A 0.60 m wide galvanized steel dispenser, suspended from the flume walls, evenly distributed the saline solution into the flume (Figure 2). 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. The base and walls of the flume were insulated with 5 cm thick foam board insulation to induce top down, 1 dimensional freezing and thawing, typical of field conditions.

From the collection gutter, runoff was conveyed through a heat traced, insulated pipe to a flow-through cell equipped with EC and temperature probes to continuously monitor the EC of the collected runoff. Grab samples were also collected from the flow-through cell. Runoff then flowed into a barrel set upon a load cell to provide a measurement of mass of runoff with time.

Platinum resistance temperature devices (RTDs) were positioned above the water/ice surface and at various locations within the two cold rooms (flume and solution storage) to automatically record air temperatures with a data acquisition system during the experiments.

2.2 Experimental Methods

The first step of a typical freezing experiment was to mix the saline solution and cool it to approximately 2^{o}C. During this time the cold room containing the flume was adjusted to the required ambient temperature (T_A) and the dispenser was set into place within the flume. The desired flow rate and pulse rate (if applicable) were set and the saline solution was discharged to the dispenser. The combinations of experimental variables including pumping rate, initial salt concentration (C_o) and T_A used for each of the experiments are listed in Table 1. The original test numbers used in Beier (2006) were reordered for ease of comparison in this paper.

As ice built up and spread along the flume, its elevation and position were documented manually with time. The input flow rate was also manually documented from a flow meter. Temperature, runoff flow rate and EC were recorded regularly during the experiment with a data acquisition system from the flow through cell situated outside the cold room. Grab samples of the runoff were also collected from the flow through cell. Pumping was terminated when the desired input volume was achieved or when no further freezing occurred.

After the saline solution had completely frozen, ice core samples were collected at various points along the flume. The cores were obtained to measure variations of the salt concentration within the ice as well as to examine the ice structure. The core holes were then filled with saline solution from the experiment, and allowed to refreeze.

Melting was induced by increasing the room temperature and then holding it constant at +2^{o}C, either in one step (Test 3 only) or by incrementally increasing the temperature daily until +2^{o}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 the tap water. Ice cores were then collected from the remaining ice to determine salt concentrations and ice structure at various locations along the flume.

3. RESULTS

3.1 Preliminary Tests 1, 2, and 3

Tests 1 through 3 were conducted to determine the optimal freezing and melting procedures for various C_o, T_A, and pumping configurations. All three tests behaved similarly despite the differences in test conditions. Once pumping into the flume began, the solution began to freeze into slush consisting of vertical ice platelets distributed in a random, interlocking arrangement (Figure 3). The slush front advanced to just beyond the bend in the flume and slowed significantly. Input of additional saline solution resulted in thickening of the slush layer rather than significant forward advancement. After approximately 250 L of saline solution were added to the flume, the build up of water in the slush caused a breach at the downstream end of the ice, and channels eroded through the liquid/slush mixture from the dispenser to end of the ice (Figures 4 and 5). These channels allowed the unfrozen liquid in the slush to rapidly drain, and any further solution addition simply flowed rapidly in the channels with little or no freezing taking place. Initial runoff collected before the breach had C/C_o (based on EC) ranging from 1.2 to 2.2, indicating freeze separation was occurring during freezing. The runoff concentration then dropped rapidly after the breach to the value of the incoming solution. After the channels had formed, flow was no longer as a thin sheet across the entire flume width, but rather was concentrated in the narrow, deep channels. Slush build up ceased because the runoff flow rate was too high to freeze the water. The total amount of ice produced during tests 1, 2, and 3 were 240, 250, and 175 kg, respectively.

Ice produced from test 3 was melted to determine the degree of NaCl removal during melting. Melting was induced by increasing T_A in one step from -15 to 2^oC and then holding it constant. The initial runoff had C/Co of 3.0 after 17 hours of melting, indicating significant concentration of salts into the release water. After 42 hours, C/Co had reached 1.0. At this point, 66 % of the salt mass had been collected in 28 % of the initial ice produced. Melting was terminated after 113 hours when the 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. The test results indicated less efficient concentration of the salts than expected, however it was determined that the temperature increase was too rapid, and not likely representative of field conditions where the temperature increase would likely have been more gradual.

3.2 Final Freezing and Melting Tests Revised Method

Based on the preliminary results from tests 1 through 3, slight modifications to the experimental method were introduced, 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 complete freezing trials are available in Beier (2006). The optimum freezing method consisted of pulsed influent flow at 2 minutes on and 6 minutes off with a slightly higher discharge rate than the continuous flow tests (Table 1). Slush fences, consisting of standard vinyl coated polyester window screen, were installed at various locations in the flume to prevent the wash out of slush and subsequent channeling that had rendered previous experiments less effective (Figure 6). Input of saline solution was also limited to approximately 150 to 170 L per freezing event based on the observations from freezing trials. Input of larger volumes in previous experiments had resulted in either erosion channels or caused the slush to float to the surface, freeze solid, and force the influent to flow under the surface. Both scenarios severely reduced heat removal and are therefore undesirable. The slush produced with the modified flow methodology was permitted to just freeze completely (approximately 8 hours) prior to the next freezing event. According to Lozowski et al. (1991), this is an optimal freezing strategy. Allowing the ice to just freeze prior to addition of the next layer will maximize the ice growth as compared to incomplete freezing or freezing and cooling of the ice to below T_f. The above methods virtually eliminated erosion and subsequent channeling of the slush for the remaining tests 4 through 6. However, very little runoff was generated during freezing. Separation and concentration of salts was therefore only observed during melting of the produced ice.

3.3 Final Freezing and Melting Tests 4, 5, and 6

In final tests 4 through 6, T_A was held constant (-15 ^{o}C) and the pumping rate was set to the maximum possible rate while minimizing channeling (0.16 to 0.26 kg/s per metre width of the flume). The EC of test 4 was equivalent to typical oil sands process water (4.6 mS/cm). Electrical conductivity was increased approximately 5 fold for test 5 and reduced approximately 5 fold for test 6 (Table 1). For each test, the saline solution was frozen in the flume over six freezing events at approximately 140 to 160 L per event. Two slush fences were also installed, one, 2 m upstream of the bend and one at the bend, to reduce the erosion of slush during pumping. Random, interlocking ice platelets formed in the slush during each freezing event, as was observed in initial tests described above. The slush layers were built up in thicknesses of 30 to 40 mm, and then allowed to freeze with no further input for a minimum 8 to 10 hours before placement and freezing of the next layer. The produced ice did not extend to the full length of the flume. A total volume of 861, 887, and 911 L were frozen for tests 4, 5, and 6, respectively. Unfrozen liquid was observed as a skim on the ice surface and at the base of the core holes for test 5, which had the highest salt concentration. EC of this unfrozen liquid was approximately 5 times C_o, with a salt concentration of approximately 140 g/L. Ice cores from the frozen mass revealed small brine inclusions were visible within the ice matrix. Once the final layer was frozen, melting was induced. It is important to note that when the room temperature was increased to thaw the ice mass, T_A did not reach 0^oC until 143 hours.

The profiles of C/C_o (EC based), melt water mass runoff, and salt mass removed for tests 4, 5, and 6 are contained in Figures 7, 8, and 9, respectively. Data collection began after the first increment of temperature increase (*i.e.* -15 to -10^oC). The left axis corresponds to the C/Co data. The right axis corresponds to the melt water and salt mass data and represents the percentage collected in the runoff of the total available frozen in the flume.

Runoff was generated during freezing only for test 5. In tests 4 and 6, runoff was not collected until after the ambient temperature was increased. The initial runoff EC for tests 4 and 5 was approximately 170 mS/cm (~230 g/L of NaCl at 1.5 ^oC), and was 100 mS/cm (~100 g/L of NaCl at 1.7 ^oC) for test 6, indicating that salts were being flushed from the ice at high concentrations in the fluid. Melting was terminated when the salt mass removal rate began to level off. Test 6 was terminated prematurely due to expiration of laboratory access. For test 4, 100 % of the NaCl mass was removed in 22 % of the initial ice volume during melting. In test 5, 92 % of the NaCl mass had been concentrated into 53 % of the melted ice. In test 6, 86 % of the NaCl mass was concentrated into 11 % of the initial ice volume. The average EC (measured at 1.5 ^{o}C) in core samples from the remaining ice when melting was terminated was either slightly greater or less than tap water: test 4 = 0.5 mS/cm, test 5 = 0.1 mS/cm, and 6 = 0.3 mS/cm, versus 0.34 mS/cm for tap water.

3.4 Mass Balance

To ensure the salt concentration and volume measurements were accurate, a mass balance was performed at the completion of melting for each test. Salt mass was calculated by multiplying the volume of ice, runoff or remaining ice after melting with the associated salt concentration determined 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 EC-[ion] relationships. Concentrations of Na^+ and Cl^- in the ice cores after melting were based on the results of ion chromatography laboratory analyses. The mass of dissolved solutes associated with the tap water were assumed negligible. If measurements and calculations were reasonable, the mass of salt in the influent (concentration x volume) should equal the sum of the salt mass in the runoff and ice remaining after melting. Table 2 summarizes the mass balance analyses. In most cases the mass balance was within 14%. The Cl^- mass balance gave an error of 21 % for test 4. Mass and volume measurements were based on grab samples collected during melting leading to averaging of the actual values between measurements. Small leaks in the flume joints may have contributed to the loss of mass in test 5. Additionally, due to low concentrations in test 6, and in the final runoff and remaining ice cores from all tests, small analytical errors may lead to larger errors in the mass calculations determined in this test program.

4. DISCUSSION

The freezing mechanism observed during the laboratory experiments was considerably different from the expected conceptual model. The conceptual model assumed ice crystals would not grow throughout the entire flow field, but rather only as thin successive layers below the continually rising liquid surface, allowing the rejected brine to flow along the ice mass. The model also assumed the flowing fluid would only contain brine and travel as laminar flow across the base ice surface. Instead the saline solution partially froze as slush. The slush, comprised of vertical platelet ice crystals, grew from the liquid surface and the ice base as the saline solution cooled (Figure 3). The platelets then grew throughout the entire solution within minutes of formation. The freezing mechanism observed is analogous to the solidification of binary alloys and freezing of sea ice (Wettlaufer et al., 1997; Kovacs, 1996). During solidification of alloys, the solid forms a "mushy layer" consisting of a porous medium filled with residual melt. In the case of freezing sea ice, the mushy layer is comprised of vertical platelets of ice with rejected brine in between the platelets. The development of vertical platelet slush from salt water was also 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 using freshwater, comparable to the present set up. Due to the presence of slush ice, flow actually occurred through the porous ice. The development of vertical platelets resulted in anisotropic permeability with vertical permeability much greater than the horizontal direction, impeding horizontal flow (Wettlaufer et al., 1997). This anisotropy was exacerbated as the growing platelets commingled, grew wider, and stacked one against another with time. Lateral flow was ultimately retarded forcing the upstream thickness to increase, increasing the head behind the leading edge of the slush. The build up of head subsequently lead to breaching, erosion, and channeling of the slush as seen in tests 1, 2, and 3. With flow in narrow, deep channels, heat removal and consequently ice production was significantly reduced. Therefore, the initial conceptual model for trickle freeze separation (Figure 1) is not valid because it did not accurately describe the freezing mechanism. However, an effective trickle freeze/thaw separation technique was developed.

The final freeze/thaw process was quite successful at separating and concentrating the salts into a smaller volume. Tables 3 and 4 summarize both the NaCl concentrations and the volumes of purified water and concentrated brine runoff for 80 % NaCl mass removal and at the end of each experiment for tests 4 through 6. Removal efficiencies are expected to be greater in the field because thawing in the field is generally slower than in the laboratory (Gao et al. 2004a). For source waters with 3000 mg/L (NaCl) or less, 80 % removal of salts was possible after melting 9 % of the produced ice. For source waters with higher concentrations (20,000 mg/L), 80 % removal was possible after melting 27 % of the produced ice.

Brine drainage during melting proved to be more efficient at concentrating salts than during 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. As the slush mixture cooled, the brine became more concentrated, which then developed vertical melt 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 5 during coring. As the ice sheet thickened and became colder, the drainage pathways were partially blocked by newly formed ice and isolated brine pockets formed. Evidence of brine inclusions were observed in ice cores collected after the ice mass had completely froze. Increased temperatures at the onset of the melting cycle caused melting at the crystal boundaries forming brine pockets within the ice. These pockets contained highly concentrated brine which subsequently melted the ice and reopened the old drainage channels, allowing brine to flow from the ice to the collection gutter. Brine drainage observed in these experiments has been observed and documented during the warming of sea ice (Untersteiner, 1968; Kovacs, 1996; Oetling and Watts, 2004; and Widell et al., 2006).

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 4 (3000 mg/L) and 5 (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 5) at -15^{o}C, the concentrated brine drained more readily at temperatures less than 0^{o}C than when Co was 3,000 mg/L (test 4).

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 advancing ice front had not slowed just beyond the bend, more saline solution may have been added to the flume before the critical slush thickness was achieved and channeling started.

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 (in plan) 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 slush fences (Figure 6) to reduce slush erosion may be required at the field scale. 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 by decreasing the heat removal to the atmosphere thereby reducing the freezing rate (Ashton, 1980).

5. CONCLUSIONS

The laboratory experiments have shown that the initial conceptual model for trickle freeze separation is not valid because it did not accurately describe the freezing mechanism. However, an effective trickle freeze/thaw separation technique was developed based on the fact that brine drainage during melting proved to be more efficient at concentrating salts than during the freezing process. The revised experimental methods were quite successful at separating and concentrating the salts into a smaller volume. For source waters with 3000 mg/L (NaCl) or less, 80 % removal of salts was possible after melting 9 % of the produced ice. For source waters with higher concentrations (20,000 mg/L), 80 % removal was possible after melting 27 % of the produced ice. The initial salt concentration of the saline solution did not significantly affect the ice production rate in the tests conducted. An order of magnitude difference in concentration resulted in only 7 % difference in the daily production rate, at an ambient temperature of -15^{o}C.

6. ACKNOWLEDGEMENTS

The authors would like to thank Steve Gamble and Christine Herygers of the University of Alberta. Their technical support was paramount to the successful completion of this study. Additional thanks are extended to Natural Sciences and Engineering Research Council of Canada Discovery Grant program and Luscar for financial support.

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Tables

Table 1. Experimental Variables

Test Number	Input Salt Concentration Co (mg/L [mS/cm][a])	Ambient Temperature T_A (°C)	Mass Flow Rates[c] kg/(s m)
Test 1	500 [1.00]	-30	0.15
Test 2	20,000 [26.80]	-30	0.15
Test 3	20,000 [26.80]	-15	0.074
Test 4	3,000 [4.63][b]	-15	0.22-0.26[d]
Test 5	20,000 [26.80]	-15	0.16-0.19[d]
Test 6	500 [1.00]	-15	0.23-0.25[d]

a - measured at approximately2 °C

b - concentration determined by calculating the mass of NaCl required to produce an equivalent EC of typical oil sands mine waste water

c – mass flow rates are calculated per metre width (flume width = 0.61 m)

d - flow was pulsed at intervals of 2 min on and 6 min off; for pulsed tests the rate is the average equivalent flow rate.

Table 2. Calculated mass balance of salts for tests 4, 5, and 6.

Test Number	Species[a]	Analyte Mass			Difference
		Produced ice (g)	Runoff (g)	Remaining ice (g)	({runoff + ice}-Influent) (%)
Test 4 3000 mg/L	NaCl	2570	2591	76	4
	Na^+	960	980	90	11
	Cl^-	1250	1374	142	21
Test 5 20000 mg/L	NaCl	17740	16260	0[b]	-8
	Na^+	6580	6100	9	-7
	Cl^-	8980	8630	12	-4
Test 6 500 mg/L	NaCl	456	393	0[b]	-14
	Na^+	189	154	41	3
	Cl^-	257	215	57	6

a – NaCl concentration determined by the EC-[NaCl] relationship, Na^+ and Cl^- concentrations determined by the EC-[ion] relationships or by ion chromatography laboratory analyses (remaining ice cores only).

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

Table 3. Water balance at 80 % NaCl removal

	Runoff		Purified Ice		
Co (mg/L)	Volume (L)	Average Concentration[a] (mg/L)	Volume (L)	%	Average Concentration[b] (mg/L)
3000	76	26370	785	91	720
20000	243	58350	644	73	5530
500	71	5130	840	92	110

a - Average concentration based on cumulative salt mass/runoff volume

b - Concentration based on (input mass - runoff cumulative mass)/remaining purified ice volume

Table 4. Water balance at thaw termination

Runoff			Purified Ice		
Co (mg/L)	Volume (L)	Average Concentration[a] (mg/L)	Volume (L)	%	Average Concentration[b] (mg/L)
3000	188	13650	673	78	0
20000	471	34530	416	47	3550
500	101	3890	810	89	77

a - Average concentration based on cumulative salt mass/runoff volume

b - Concentration based on (input mass - runoff cumulative mass)/remaining purified ice volume

Figure Captions

Figure 1. Conceptual schematic of trickle freeze separation. (Colour web only)

Figure 2. Photo of the freezing flume in the cold room. (Colour web only)

Figure 3. Picture of platelet slush ice. (Colour web only)

Figure 4. Preferential flow path in the produced slush ice preceding channel formation. (Colour web only)

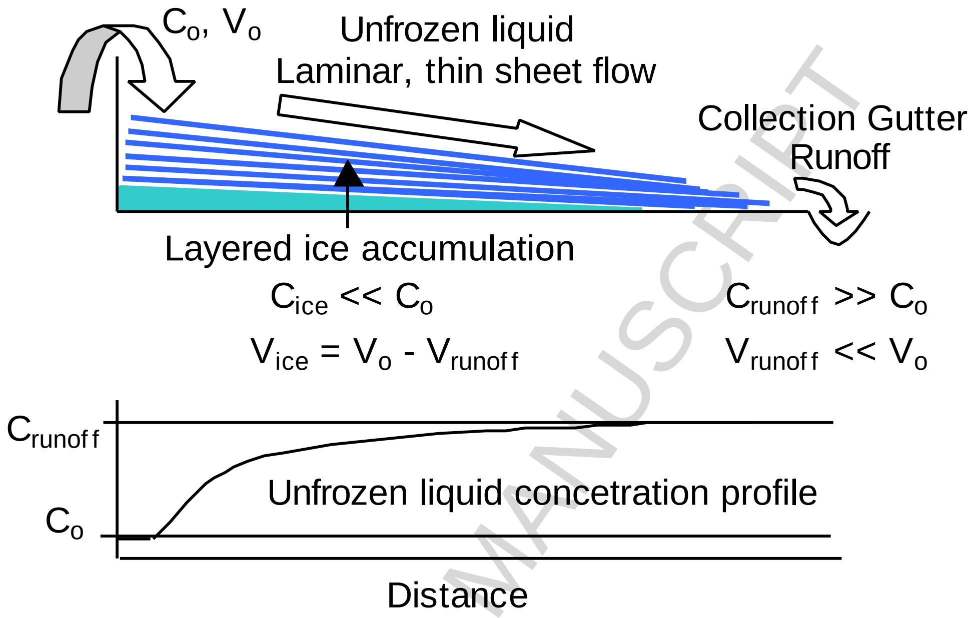
Figure 5. Erosion channels formed during freezing. (Colour web only)

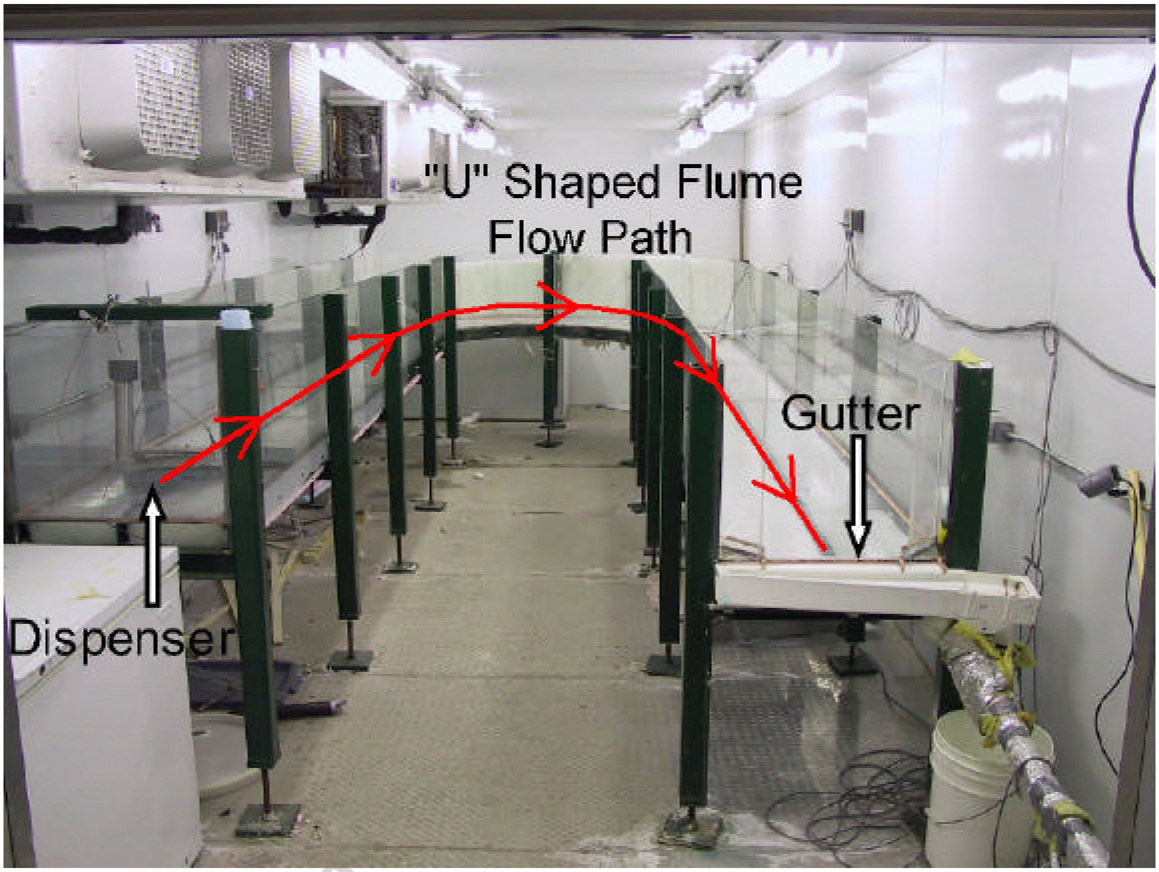
Figure 6. Ice fence and position in flume. (Colour web only)

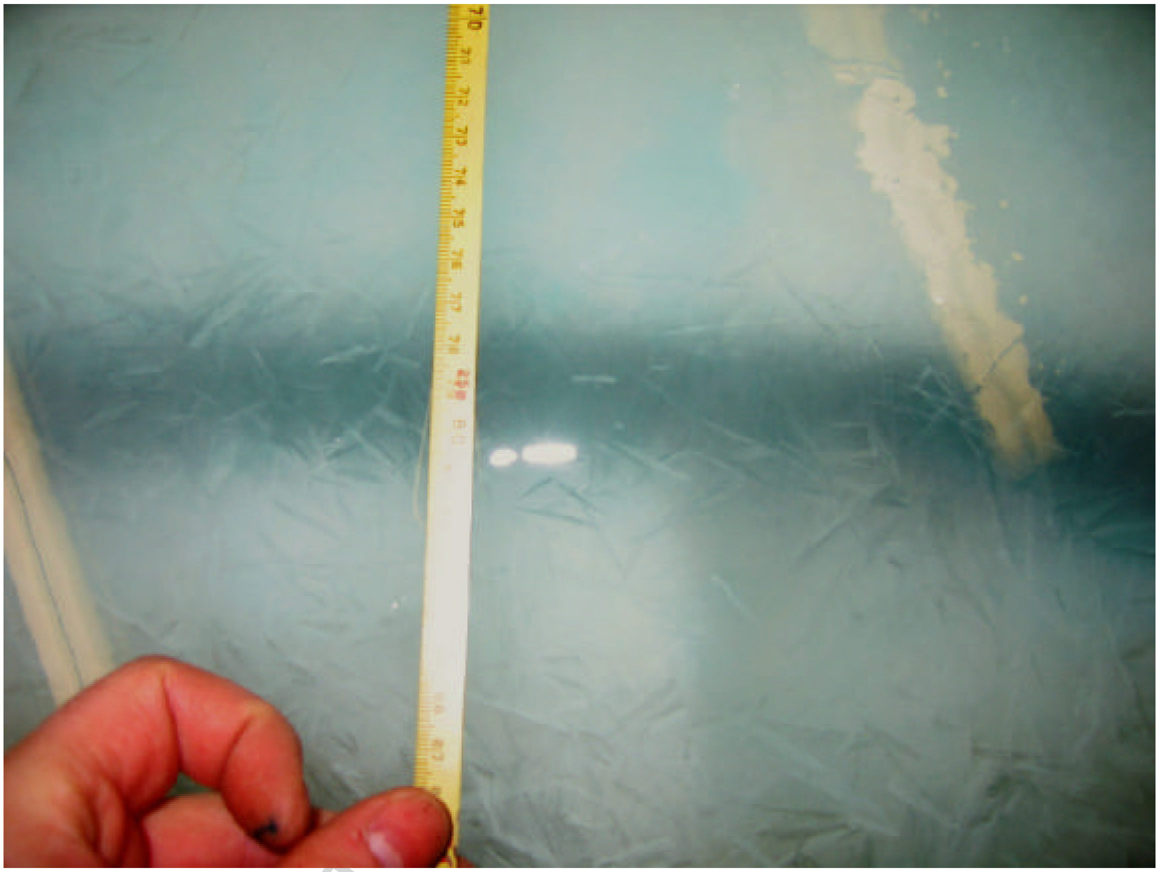
Figure 7. Cumulative percent removed of NaCl and melt water and relative concentration (C/Co) during melting of Test 4 ice (3,000 mg/L NaCl). (Colour web only)

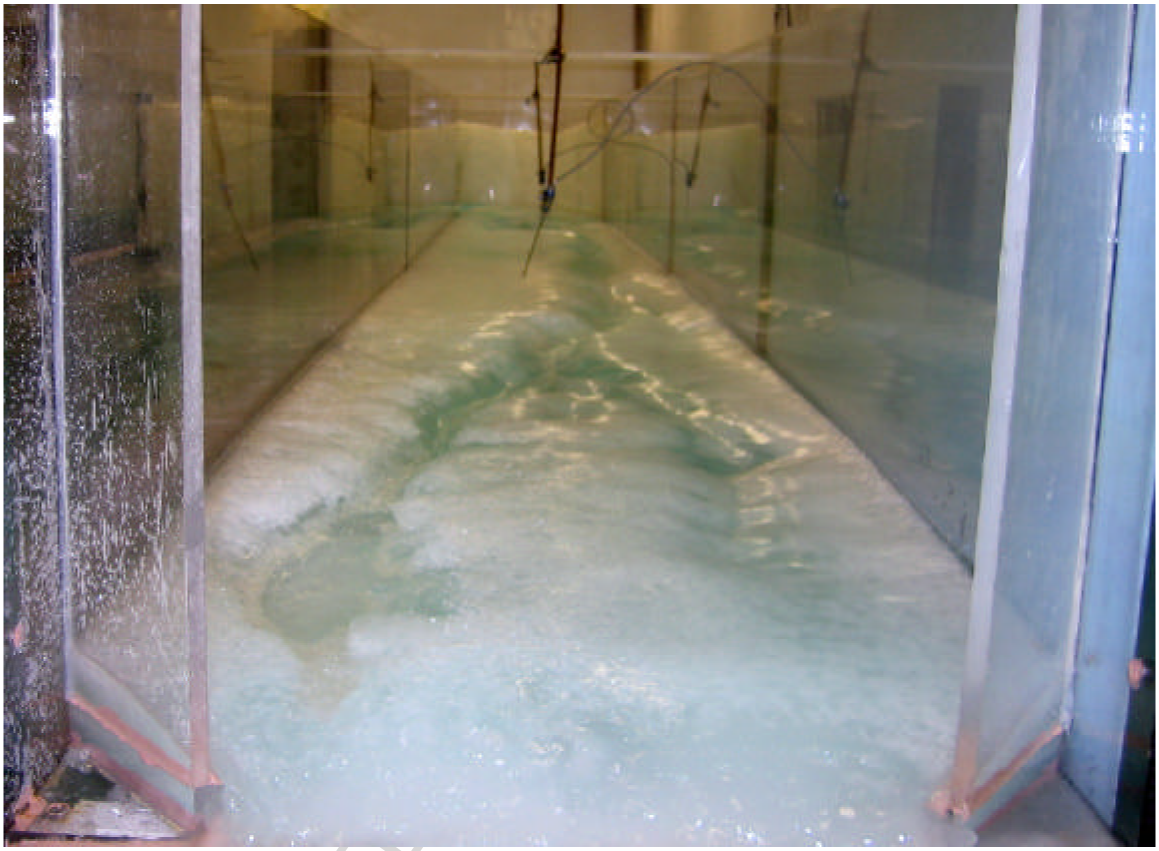
Figure 8. Cumulative percent removed of NaCl and melt water and relative concentration (C/Co) during melting of Test 5 ice (20,000 mg/L NaCl). (Colour web only)

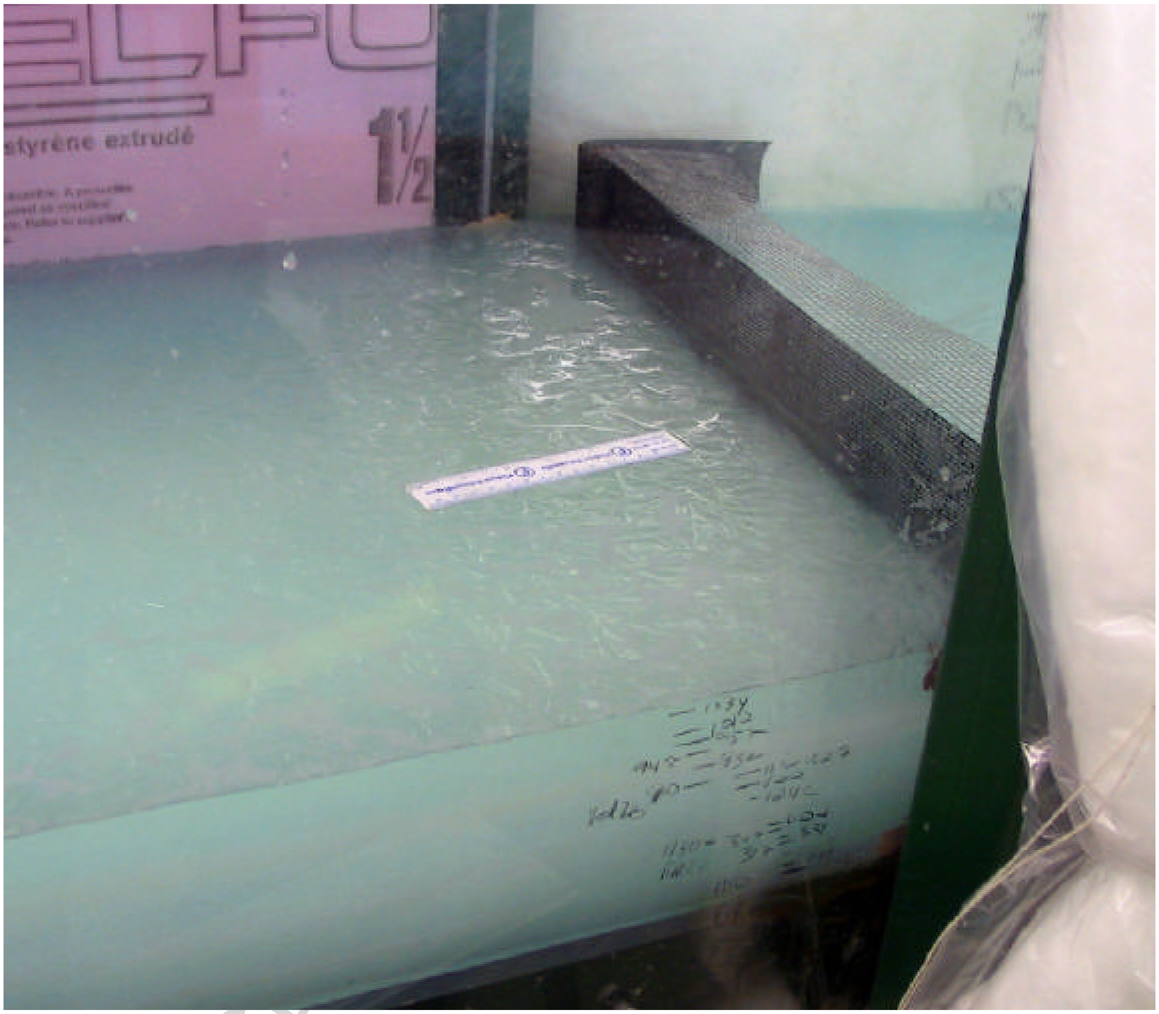
Figure 9. Cumulative percent removed of NaCl and melt water and relative concentration (C/Co) during melting of Test 6 ice (500 mg/L NaCl). (Colour web only)

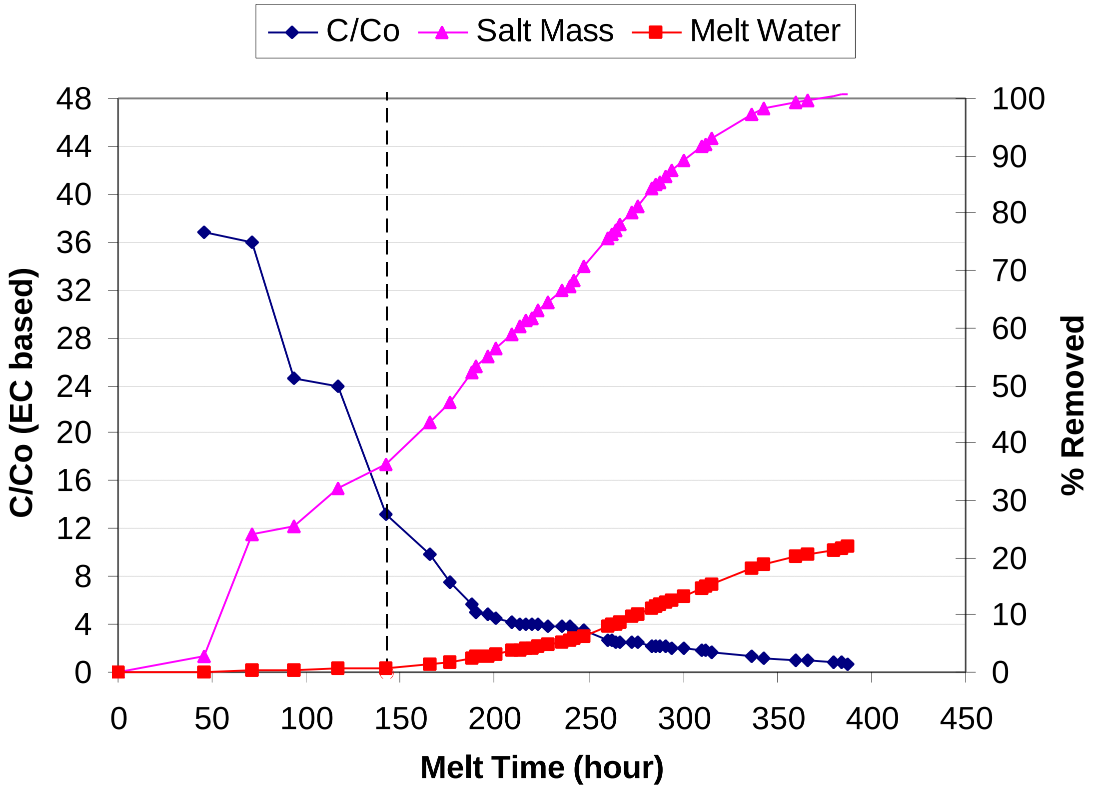

C_o, V_o
Unfrozen liquid
Laminar, thin sheet flow
Collection Gutter
Runoff
Layered ice accumulation
$C_{ice} << C_o$
$V_{ice} = V_o - V_{runoff}$
$C_{runoff} >> C_o$
$V_{runoff} << V_o$
C_{runoff}
C_o
Unfrozen liquid concetration profile
Distance

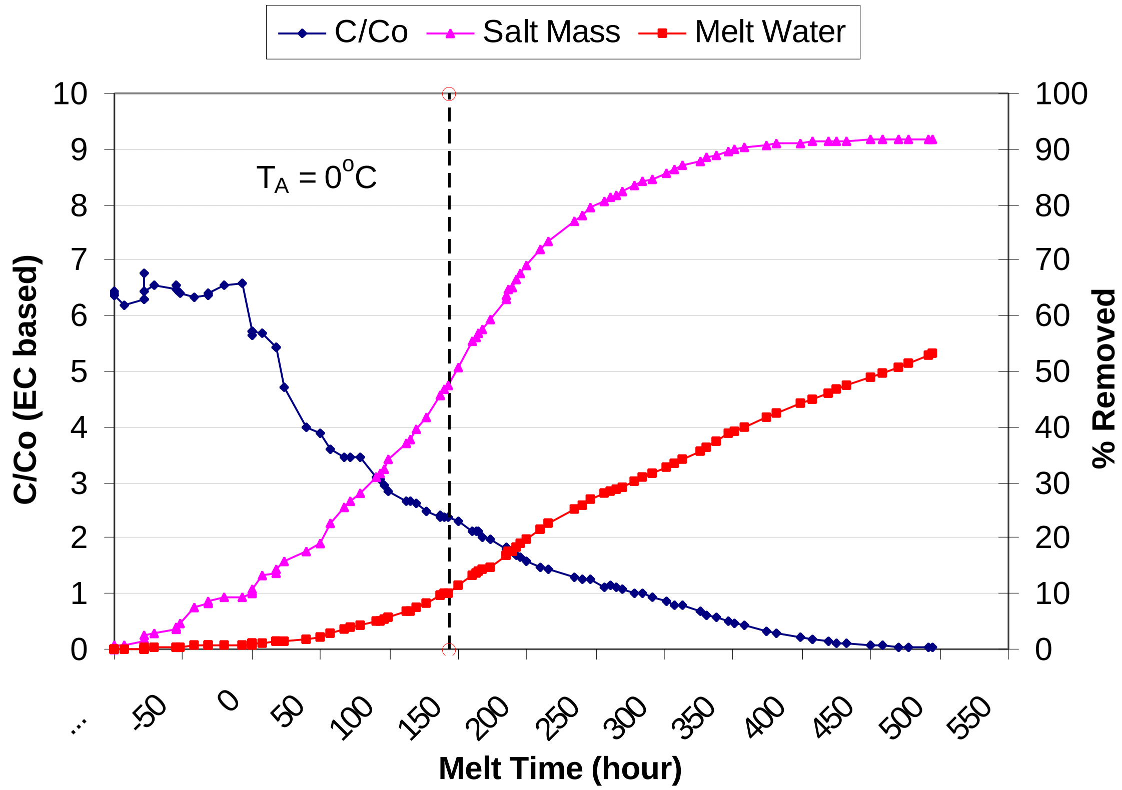

"U" Shaped Flume
Flow Path
Gutter
Dispenser

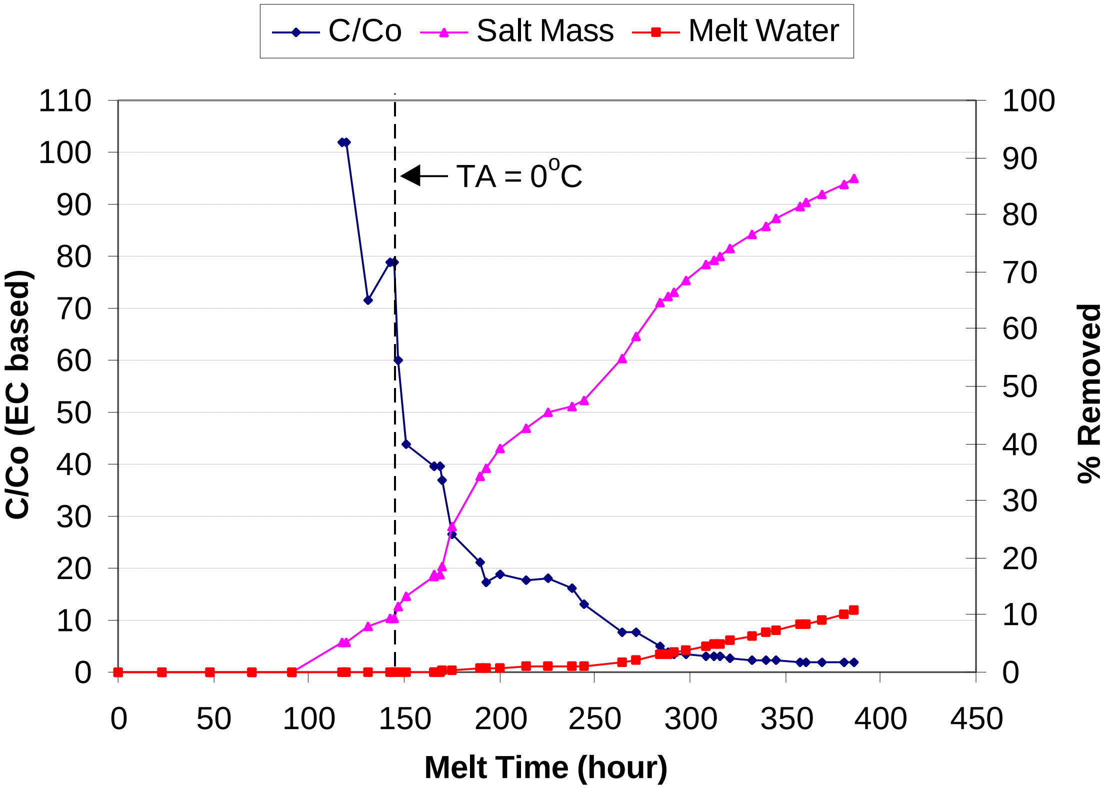





styrène extrudé
1½


C/Co
Salt Mass
Melt Water
C/Co (EC based)
% Removed
Melt Time (hour)
0
4
8
12
16
20
24
28
32
36
40
44
48
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450


C/Co
Salt Mass
Melt Water
$T_A = 0^oC$
C/Co (EC based)
% Removed
Melt Time (hour)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
100
...
-50
0
50
100
150
200
250
300
350
400
450
500
550



C/Co
Salt Mass
Melt Water
TA = 0°C
C/Co (EC based)
% Removed
Melt Time (hour)
0
10
20
30
40
50
60
70
80
90
100
110
0
50
100
150
200
250
300
350
400
450