Horizontal Cross Flow Filtration and Rinsing of Ice from Saline Slurries

Continuous filtration of ice slurries (with particles of about 80 μm diameter) to generate potable water was investigated. In the filtration process the ice is driven through a stationary channel with liquid draining through narrow slots in the base. Most of the liquid drained from the slurry at ambient pressure and the residual liquid trapped in the pores of the consolidated ice bed was displaced to a vacuum after downstream rinsing with sprayed or melt water. The cost of this approach may be competitive with reverse osmosis if an automated unit is developed.

On a étudié la filtration continue de suspensions de glace (particules de 80 μm de diamètre) afin de produire de l'eau potable. Dans le procédé de filtration, la glace est amenée dans une conduite statique munie à la base de fentes étroites par lesquelles le liquide se décharge. Le plupart du liquide retiré de la suspension à la pression ambiante ainsi que le liquide résiduel piégé dans les pores du lit de glace consolidé a été déplacé vers un vide après un rinçage en aval avec de l'eau pulvérisée ou de la glace fondue. Le coût de cette méthode peut être compétitif avec celui de la méthode par osmose inverse si on utilise un système automatisé.

Keywords: freeze desalination, filtration.

Clean water is generally in increasingly short supply. Large scale desalination processes have been developed and several companies can design and construct facilities to supply millions of gallons a day or more of water. There remains a need for plants which can supply smaller amounts of water cheaply. Reverse osmosis plants which are often installed in units of only a few m^3/d are the most widely used type of small water plant. Investigations of freeze desalination were funded by the Office of Saline Water in the 1960's but the process was never commercialized despite (potentially) low energy costs. The equipment costs were not low enough, especially the equipment to filter and rinse the ice.

In many areas cleaning up contaminated water is as separating clean water from brine. Lower salinity feeds than seawater are more amenable to freezing because the freezing temperature is not as low and requires less energy to achieve. Where both seawater and a reclaimable contaminated water are available, a blend of the two feeds can provide flexibility of product quantity and cost not available to a single feed source.

For large plants specific capital cost can be reduced (compared to small ones) and investments in energy recovery equipment, such as heat exchangers and fluid transfer loops transferring heat between the ice and freezer, for example, become practical. In small plants the cost of these items is usually greater than the reduction in operating cost warrants and heat rejected from the freezer is not efficiently transferred to the ice during a final, melting step. The small, direct freezer used to provide ice slurries for a milk freeze concentration project has already been described (Dickey, 1995), as have indirect freezers of larger (concentrated beverage) plants.

This report describes separation, using an ice filter developed for milk freeze concentration, of slurries made from approximately 2% (w/w) saline feeds. Ice slurry filtration for water production requires more thorough liquid removal than does feed liquid concentration (assuming the dilute coproduct, made from the ice, can be disposed of easily). However since the feed for water production is cheap, there is no need to filter slurries made of viscous or precipitating concentrates.

In simple batch filtration, the concentrated liquid formed with the ice percolates through an ice bed formed from crystals or particles (larger than about 80 μm) screened or sieved from the slurry. Even though processes like this have been patented (Merle et al., 1984) for fruit juice, the cost of holding ice long enough to achieve potable qualities of ice from most feed water is too high. The most widely used commercial ice filtration method for beverage concentration pumps the slurry to the bottom of a vertical column, expressing the ice upward through a pool of rinse water, while the concentrate is drawn off either through the bottom of the column (Snyder, 1966), perforations in the wall of the column (Brian, 1968) or internal perforated tubes. Ice is continuously scraped from the top of the rising ice plug by a rotating blade. Concentrate displacement rates are limited by permeation of the rinse water through pores partly occluded by frozen rinse water, the small size of the ice crystals and the liquid viscosity.

Although it seems likely that the ice slurry filtration rate could be increased by using a paper machine type moving web, thereby reducing processing cost, the equipment would be too expensive for a small plant. Filters based on ice flow between concentric tubes have been built and tested by the authors, and an annular suspension treating design was patented (Wilson, 1983). The main advantage of this design, compared to the vertical tube design is that a thin particle layer can be filtered and rinsed more rapidly since the longest liquid path out of the layer is shorter. Although the symmetry of the annular design promotes bed uniformity in the (circumferential) direction perpendicular to both ice flow and filtrate flow, with reduced drag on the moving ice associated with channel edges, the ice layer thickness is hard to change and rinsing is complicated. To fill the annular space fully, the tube assembly has to be essentially vertical, which adds the weight of the ice to the flow resistance.

A bed of ice, with the desirable thin cross section which recommends the annular design, can be formed and driven through a rectangular channel. The rectangular design is simpler and thus less expensive than the annular design and allows variation of the bed thickness. This report describes a rectangular channel filter and describes measured relations between bed thickness, rinsing parameters and thoroughness of filtration performance.

Removing liquid from the slurry feed to the filter proceeds in two steps: filtration of 70-90% of the feed liquid, using a relatively low suction, low flowrate pump such as a peristaltic tubing pump and removal of 93-99% of the remaining liquid (the higher% with water rinsing), that is, sweeping the ice bed with a relatively high flow rate of air and/or water to displace liquid from finer pores. The cost of removing the free liquid is much lower than the rinsing filtration, but rinsing is necessary to remove enough remaining liquid to obtain a potable product.

One objective of this study was to determine whether filtration parameters, particularly those descriptive of the free liquid drainage could be identified which have an influence on the amount of rinsing that needs to be done. Slurries of particles will consolidate as liquid is withdrawn, and form a fixed bed at the maximum packing fraction, which is the fraction of the bed volume filled with solid (ice) particles. A generalized equation relating the suspension and suspending medium viscosity with suspension particle volume fraction includes a maximum particle packing fraction (Sudduth, 1993); for fairly uniform particles this maximum fraction is somewhere above 0.64. It is also known that in some circumstances flowing suspensions will generate a particle structure (Hoffman, 1991). When the volume fraction of solid particles is above a certain value, about 0.16, some structuring of the particles is expected from percolation theory (Campbell and Forgacs, 1990). These known relations suggest that the parameters of the drainage process that control the uniformity (and hence permeability) of the consolidated bed can be identified. Without rinsing, saline ice slurries typically can be filtered down to about 0.45 weight fraction ice; adding a rinsing step downstream reduces the output of the initial filtration to about 0.25 mass fraction ice. It has been noticed that ice filtration improves with reduced ice feed rate, presumably due to an increase in residence time of the ice bed which allows the liquid trapped in finer pores more time to be rinsed into the percolation network formed from the larger pores. A very small amount of solute may be trapped within ice particles formed by the coalescing of ice crystals during their compression, during pumping; this solute content should be below that of potable water.

Equipment

Ice slurries were produced continuously using a vigorously agitated freezer which creates ice particles by evaporative chilling at the slurry triple point. The ice slurry is constantly pumped out of the bottom of the freezer with a progressing cavity product pump (1FG3 Moyno®, Robbins & Myers Inc., Springfield, OH), which seals the vacuum in the freezer. The slurry mass in the freezer is kept steady by pumping a feed solution at a rate controlled by a sensor sensitive to the pressure difference between the top and bottom of the freezer. The freezer and associated equipment are shown schematically in Figure 1.

The progressing cavity product pump, basically a continuously sealed auger for conveying liquid slurries, supplies the pressure to drive the ice through the filter, which is shown in Figure 2. The filter is comprised of a stainless steel channel, closed on one end, 25 cm wide and 125 cm long, through which the slurry, and after consolidation, the ice, flows. The smooth base plate contains eight rows of slots in two banks as shown in Figure 2. Each row has 15 or 16 slots parallel to the long axis of the channel with 1.27 cm between slots; rows are offset 3.2 mm from the immediately preceding row. The slots are 5.08 cm long and 0.25 mm wide, connected to low pressure receivers which collect liquid drawn through the slots and return it, through pumps, to the freezer feed tank.

Suction for the first three rows of slots was provided by peristaltic tubing pumps with a maximum pumping rate of 8 L/min. Two acrylic upper plates were used: one covered only the upstream half of the filter, which includes the first four rows of slots, the other covered the entire filter. The lower surface of these cover plates is the top boundary of the channel through which the consolidated ice bed is formed and, in the case of the full length cover, moves. The plates have fittings allowing connection to a 3.87 cm diameter hose which delivers the ice slurry to the filter. The height of the channel was reduced for some tests by adding plates to the bottom of the cover plate.

Suction for the last five rows of slots was provided by a vacuum tank held between 50 and 80 kPa by two mechanical vacuum pumps (MicroVac 140H10, Stokes Vacuum Inc., Philadelphia, PA). Suction to any of the five last rows of slots can be controlled with butterfly valves on the hoses between the receivers and the vacuum tank. Measurements with a flowmeter confirmed the expectation that air flow to the vacuum tank, A, was directly proportional to the steady pressure in the tank, P:

$$A = [P/P_0]\,A_0$$
$$= 0.016\,[P/P_0]{-}0.001 \qquad (1)$$

where A and A_0 are in m^3/s and P_0 is atmospheric pressure.

Rinse water was sprayed on the top of the moving ice bed from a single fan, low flow (nominal 7 L/h) spray nozzle mounted at the downstream end of the cover plate. The height of the nozzle was adjusted so that the spray just spanned the ice bed for the selected rinse water flow rate. When rinse water was sprayed at 15-20 kg/h, it was applied at about the same ratio of rinse to ice slurry (1:25) reported for the Colt process (Snyder, 1966).

Pressure upstream of the slots is measured with a pressure gauge (Ashcroft Duragauge, Dresser Corp., Stratford, CT accurate to 3.45 kPa. Vacuum pressure on the tank supplying suction to the last five rows of slots was measured with a gauge (Danton, Duro Instrument Corp., Oceanside, NY, U.S.A.) accurate to 0.8 kPa. Ice and filtrate flow rates were measured by weighing a timed sample when the process was running steadily. NaCl concentration of filtrate and melted ice slurries was determined from measurement of solution conductance using a temperature compensated meter with resolution to 0.1 TS/cm in the range from 0 to 200 and 0.001TS/cm from 0 to 2.

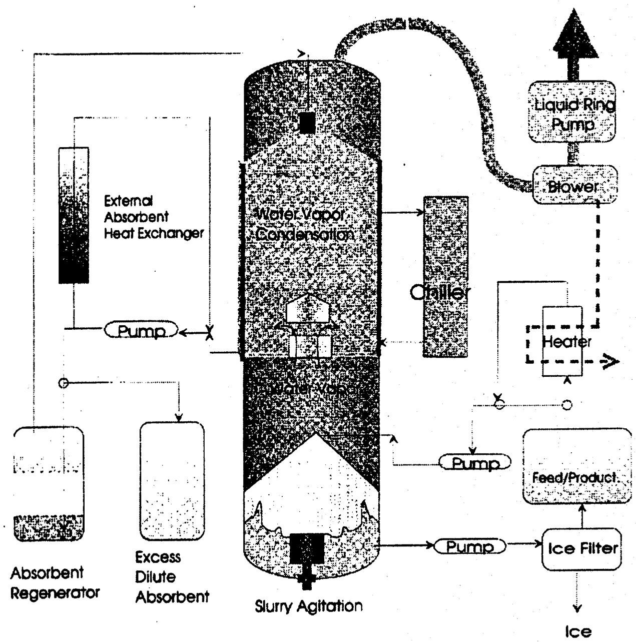

Figure 1 — Direct contact freezing equipment.

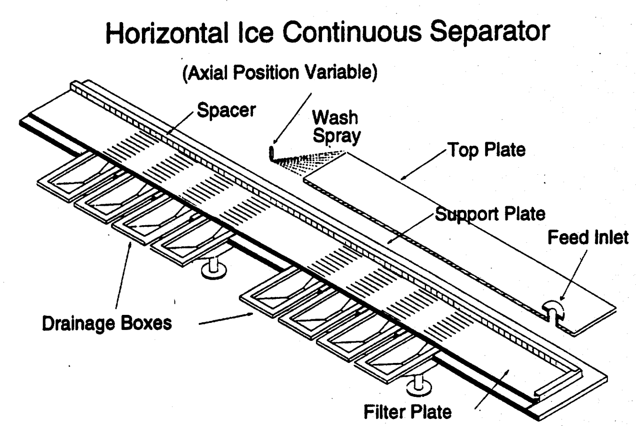

Figure 2 — Horizontal, continuous ice filter.

The last five rows were particularly vulnerable in earlier unheated equipment. Fouling of the filter slots with ice was minimized by heating the slotted base plate with a water stream running through a channel in an acrylic plate clamped to the bottom of the plate. The water was heated by a steam heated heat exchanger and held a steady inlet temperature (± 1°C in the 50-60 degree range, at a flow rate around 3.8 L/min). Melting (ice particles trapped in slots in the filter base plate) provides an alternative to intermittent backflushing as a way to determine the fouling contribution to the overall flow resistance. The lack of effect on filtration performance of intermittent suction at the downstream rows of slots, at frequencies as low as 1 cycle/s, confirmed the expectation that fouling was not significant under our usual operating conditions.

Procedure

The first filter was designed to provide a 1.27 cm channel height. This thickness was reduced in 0.32 cm increments to study ice 1/2 and 3/4 of the standard thickness. After tests

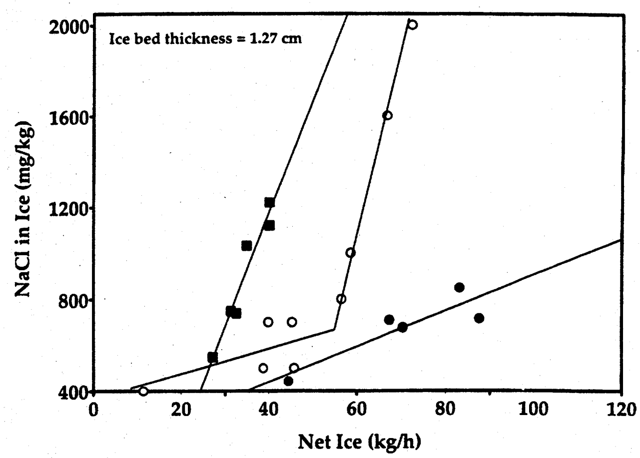

Figure 3 — Ice purity vs. production rate.

TABLE 1
Effect of Ice Bed Thickness on Projected Production Rate of Pure Ice*

Bed Thickness (cm)	Production Rate (kg/h)
2.54	32
1.27	45
0.95	28
0.63	43

*The production rates listed in the second column were determined by extrapolating the linear ice production rate vs. ice purity plots to pure ice (0 NaCl content).

with these thicknesses indicated the possibility of improved performance with greater bed thickness, a 2.54 cm spacer was made to provide a channel of that height. Slurries were formed from feeds of 454 kg/h of a 1.9 to 2.2 (w/w)% NaCl solutions. Slurry ice content varied, depending on the run, from 20 to 8 (w/w)%, as determined from the slurry density measurement. The ice crystals were suspended in a liquid of from 2 to 3 (w/w)% NaCl. The ice content decreased during a run but not enough to affect the filtration significantly.

Establishing a steady ice content in the product stream usually takes about an hour after starting the freezing process; the product slurry flows through the filter and cools it to the operating temperature during this period. Ice content of the product stream was determined using an in-line densitometer in a loop formed using two automatic valves which divert a slurry sample to, and melts it while recirculating it through, the meter, every 7 minutes (Dickey et al., 1989).

As an alternative to rinsing, the cover plate and spacer bar between plates were heated by spraying 75 kg/h of ambient temperature water on top of the last half of the coverplate. This increased ice melting and reduced the flow resistance of the bed as indicated by slurry feed pressure but consumed an impractically high fraction of ice. The resistance reduction was primarily attributed to melting of ice jammed in the corners between the spacers and baseplate.

Results

The right hand leg of the unheated filter curve in Figure 3, which is similar to most of the early runs, shows that the ice purity is inversely related to net ice production. This is

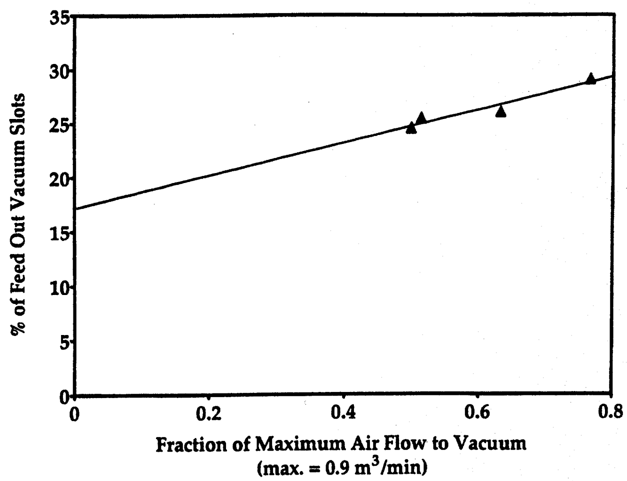

Figure 4 — Vacuum liquid filtration rate vs. air flow rate.

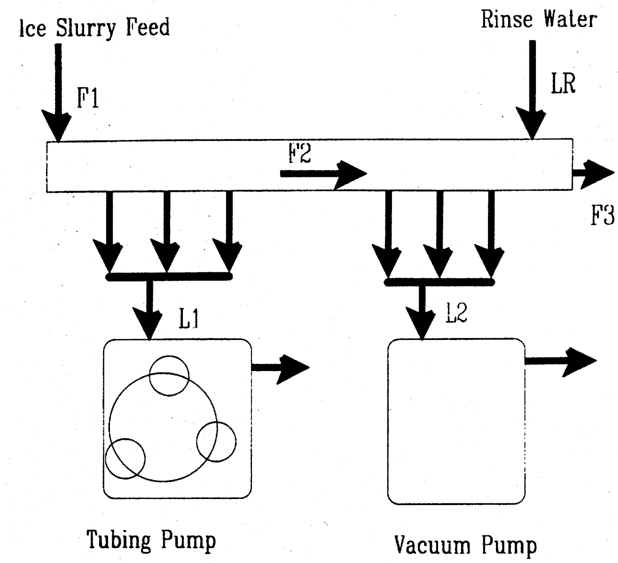

Figure 5 — Vacuum filtrate fraction of liquid fed to vacuum section vs. fractional ice loss.

consistent with the effect of changes to the basic operating procedure meant to improve purity: spraying water, heating the base, or operating at a lower initial ice production rate; they all reduce production rate. The ice slurry fed to the filter was kept at a constant rate, near the maximum our freezer could supply for a given salt concentration. The unheated filter curve in Figure 3 shows the lowered salt content due to rinsing at the higher ice yields (about 1 mass unit of salt solution at its original concentration removed per 3.5 units of rinse water lost) and a lesser effect at lower yields as the additional sprayed rinse water (the ratio of rinse to residual solution used becomes 44:1) removes less salt solution.

Spraying clean water on the top of the ice bed to rinse the consolidated ice has a low net production cost as long as only a small amount of the rinse water is sucked through the slots. If the rinse water moves slowly through the ice bed and does not mix with the residual salt solution it can freeze in the bed, ideally the rinse will reach the base plate after displacing the salt solution to the bottom of the bed. A design objective for rinsing a porous bed is clearly to create a sharp rinsing front that reaches the row of slots as the ice bed reaches the slots. Prior to rinsing, the ice bed should be as dry as possible to minimize melting as the bed slides along the (heated) base plate. Ice filtration has the unusual feature that the rinse water will solidify if it goes through the bed slowly. The tendency for this to occur increases as the ice temperature, original ice particle size (and resulting bed pores) and filtration rate drop. When the rinse water is unevenly distributed feebly rinsed portions of the bed can be sealed off by frozen rinse water, forming practically unrinsable conglomerates.

Table 1 shows the results of runs using different channel heights. The production rates listed in the second column were determined by extrapolating the linear ice production rate vs. ice purity plots to pure ice (0 NaCl content). Later runs, all made with the 1.26 cm bed thickness, often showed a reduced ice content/production rate slope for operation under conditions producing low ice contents, and thus a bilinear plot, such as the unheated curve in Figure 3.

The bed must be thick enough to overcome the compressive forces that result from the braking of the suction boxes and the hydraulic force driving the bed through the channel. Tests with coverage of only the upstream half of the bed showed that beds 0.635 cm thick were marginally rigid enough for filtration, since they would fold sporadically at the end of the covered section of channel. If the ice bed is rigid enough to resist the compression, then enough force must be applied to overcome the drag created by the suction at the drainage slots. When there is resistance to solid motion in the channel the slurry feed pressure rises to match it. With no suction at the slots the pressure is less than 3.4 kPa, but rises to measurable levels as the valves below the vacuum boxes are opened to allow significant amounts of liquid to flow through the slots. With hot water heating the channel, there is no measurable resistance of the ice motion from the channel *per se*, without flow through the slots. However there is resistance due to a clamping of the solid against the plate by liquid, and air in the downstream section, flowing through the bed to the slots. The force behind the bed is roughly equal to the product of the bed cross section and the upstream pressure, for typical runs this was measured to be 10-11 kg. Resistance to ice motion is also evident in the measured slurry flow rate to the filter; rates will drop as much as 10% due to incipient slot occlusion which in turn is seen from a decrease in vacuum tank pressure (since there is a reduced flow of air and brine into the tank).

Since it is desirable to have the rinse water front just reach the slots as the motion of the ice bed moves away from the last row (so the rinse displaces nearly all of the remaining saline solution but does not leave with it) it is preferable to spray the rinse water at the outlet end of the filter. We have shown this gives less salt in the product ice than the partly covered configuration with rinse application at various locations above the vacuum slots. As shown in the Figure 4, the rate of liquid (calculated by difference) withdrawn through the rows of vacuum slots is roughly proportional to the air flow through the ice— for the range plotted; this indicates a conservative use of the vacuum equipment. Although vacuum is expensive, it is necessary to get acceptable ice purity with this equipment; water rinsing is also necessary, but cheaper. A study of dewatering box systems for paper machine operation has recently been reported (Neun, 1993). They found, as here, that the box efficiency decreases with number (in series) and increased filtration suction is desirable as the substrate stream becomes drier.

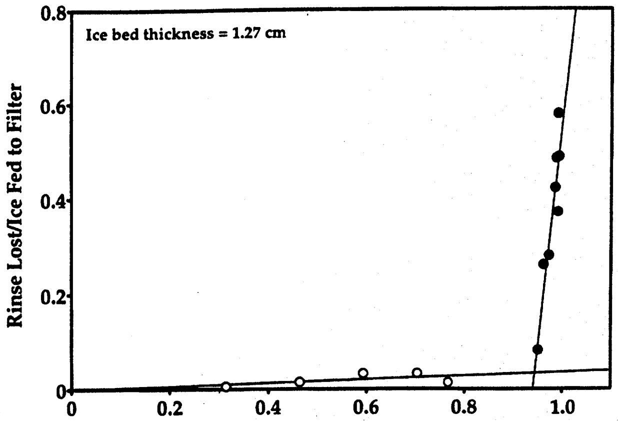

Figure 6 — Fractional ice loss and vacuum filtrate fraction vs. low suction filtrate fraction.

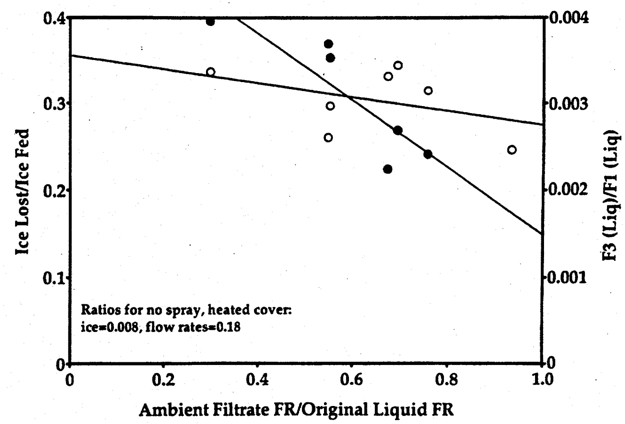

Figure 7 — Schematic drawing of ice filter.

Figure 5 is a schematic diagram which represents the streams and blocks pertaining to the process. $F1$ is the slurry from the freezer, $F2$ is the slurry from which liquid has been filtered using a low flow rate pump and $F3$ is the product slurry after rinsing filtration. $L1$ and $L2$ are the filtrates to ambient and vacuum receivers, respectively, and LR the water rinse, which can be either sprayed water or melting of the ice by bed heating (or both). Mass and solute balances can be made over sections of the process to provide calculated flow rate values for entities such as $F2$ and $L2$ which cannot be easily measured. For example,

$$F2 - F1 - L1 \quad (2)$$

$$L2 = (L2)/(F3_{liq})\ [F1_{liq} - L1 - F3_{liq}] \quad (3)$$

The subscript *liq* means only the liquid portion of the slurry streams and values in parentheses are solute mass fractions of liquid streams.

The effectiveness of the rinsing filter can be described in terms of the relation between the filter's ability to separate the liquid in the ice fed to it and the cost, in terms of ice lost to the product. Figure 5 shows a linear fit of measurements of liquid fraction removal $(L2/(L2 + F3_{liq})$ and ice loss $(F2_{ice} + LR - F3_{ice})/(F2_{ice} + LR)$. The liquid fraction separated was calculated from the liquid drawn through the rinsing filter and the liquid left in the ice. The fraction of product ice lost is the ice fed to the rinsing filter and rinse water used, less the clean product ice. The clean product ice is the product ice stream less the weight of a liquid stream at the concentration removed by the pumped filter which would produce the measured product salinity. The dependence of the ratios shown in Figure 6 on the ambient pressure liquid fraction removed $(L1/F1_{liq})$ is shown in Figure 7. Both curves, no spraying — only melting was used for the runs shown in Figure 7, indicate that increasing the amount of liquid initially removed is advantageous.

Cost Estimate

Operating costs for the test facility, run 350 days a year, 24 hours per day are shown in Table 2. Two significant cost elements, labor and salt, could be reduced drastically, if not eliminated in exchange for a modest increase in capital cost if most of the process steps are automated. The dilute absorbent could be continuously recycled at fully effective salt content using heat from the chiller to evaporate the absorbed water. This change would require an extra heat exchanger, tank and pump. This would cut the cost to about 0.05 \$/lb of water at the 100 lb/h scale. Current desalination costs of 600 gallon per hour Reverse Osmosis Water Purification Units (Shalewitz, 1996) are reported to be 0.005 \$/lb. The capital cost of the plants is \$75,000 with 8 replaceable elements (\$440 each and a 2000 hour life). With a 20 year life for the plant, the annual capital cost is half the estimated cost of a 600 gallon per hour freeze desalination plant (with a 10 year estimated life). Labor is the greatest cost element of these small reverse osmosis plants, which includes training since the units are designed for intermittent use by the US Army; this cost should be much lower for a fixed, continuously operating, process.

The processes differ most significantly in their energy costs. Both processes use electric power to drive the separation, and it might be expected that freeze desalination, using fixed power from the electric grid, would have lower energy cost than the cost for a portable, small generator-powered package unit. The freeze desalination cost is high because

TABLE 2
Operating Costs for 100 lb/h and Estimated Costs for 600 gal/h Freeze Desalination Plants, $US

	Unit cost-rate	Annual cost	$US/lb of water	Est. Ann. cost	$US/lb
Electric power	18 kW @ .05/kWh	7,560	0.009	380,000	0.009
Labor	2100 h @ 20/h	42,000	0.05	50,000	0.001
Salt*	0.11/h	7,390	0.009	–	
Maintenance	2% of capital	4,760	0.006	50,000	0.001
Capital	$238,000	23,800	0.028	250,000	0.005
Total		85,510	0.102	730,000	0.016

*A larger plant would evaporate the dilute salt solution absorbent.

the 100 lb/h unit is too small to include power use reduction methods used in larger plants (Fleming, 1983). The 20,000 gallon per day AFVC freezing desalination plant, ancestor to the process discussed in this article, was reported to consume of 104 kWh/1000 gal in 1983. This is almost the same power cost as the reverse osmosis plant (0.0006 \$/lb). Modifying the direct freezing process to reduce power consumption would increase capital cost, possibly significantly. Development of an inexpensive way to use the chilling capacity of the product ice to drive the freezing end of the process will be needed before freezing desalination plants can be generally cost competitive with comparable reverse osmosis plants.

Conclusions

Most of the salt solution remaining on the ice after the ambient filtration, provided by the peristaltic liquid pumps, ~90%, can be removed with loss of 5% or less of the ice or its equivalent in rinse water drained with the salt solution. Removing the last 5% is much more costly in terms of production and to achieve pure ice could take as much as an impirical 60% of the ice. Melting some of the ice is preferable to spraying pure water as a rinse source because it is easier to distribute the rinse uniformly across the width of the ice bed and thereby rinse effectively using less water. Both melting and rinsing are necessary to obtain the purest ice product. To reduce the ice salt content below 1000 mg/L by melting along, 30% of the original ice has to be melted. Freeze desalination by the method described in this study does not appear to be attractive for small scale plants, however an automated plant with improvements in ice rinsing may be competitive with reverse osmosis, for feed water that is especially difficult to purify with membranes.

Acknowledgements

The direct freezer used to produce ice slurries for the experiments was operated by E. Richard Radewonuk. Neil Goldberg designed and built the filter. James Martel, Ronald D. Grose and Geoffrey White reviewed the manuscript and provided many constructive suggestions.

Nomenclature

A = air flow rate, m^3/s
F = ice slurry flow rate, kg/h
$F1$ = ice slurry from freezer, kg/h
$F2$ = drained ice slurry from low suction section, kg/h
$F3$ = ice slurry product from vacuum filtration, kg/h
L = liquid flow rate, kg/h
$L1$ = filtrate to low suction pump, kg/h
$L2$ = filtrate to vacuum pump, kg/h
LR = rinse water, kg/h
P = pressure, kPa

Subscripts

ice = ice component of an ice slurry, kg/h
liq = liquid component of an ice slurry, kg/h
o = ambient condition

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