Development of an automated ice-block-making system utilizing winter outdoor air

C. VIGNEAULT, M. LEMIEUX, and D. I. MASSÉ

Engineering and Statistical Research Centre, Research Branch, Agriculture Canada, Ottawa, Ontario K1A 0C6. *Agriculture Canada Contribution no. I-922, received 11 March 1987, accepted 24 September 1987.*

Vigneault, C., Lemieux, M. and Massé, D. I. 1988. **Development of an automated ice-block-making system utilizing winter outdoor air**. Can. Agric. Eng. **30**: 77–82. A technique for producing a block of ice using the coldness of outdoor air was developed. Thin layers of water were sprayed on the ice surface, and cold air was blown onto the water to accelerate freezing. A time-temperature integrator was developed and used to control the timing of water application. An ice height sensor, and lifting mechanism were developed to maintain the air and water distribution circuits at an optimal height above the ice surface. Tests were performed to develop optimum design criteria for the components of the automated system. For a large system, the price of the ice was established at $15 per tonne, compared to the current price of $25 per tonne. This system also reduced the energy consumption for ice production 12 times compared to a conventional mechanical refrigeration system.

INTRODUCTION

Low temperatures are used extensively to preserve foods, and use a considerable amount of energy. In gas compression refrigeration systems, 2–4 J of heat are removed per Joule used to operate the compressors. As much as 21 J are removed per Joule used to operate an ice block system (Vigneault and Lemieux 1985).

The Canadian winter offers a limitless source of cold air, but this coldness is available for only a few months and must be stored in some form for warm season uses. In 1982, Agriculture Canada undertook studies aimed at introducing the production of ice as a means of storing winter coldness. The purpose of this research was to reduce the energy consumed in the production of low temperature, for example, in on-farm precooling of fruits and vegetables.

Morofsky (1985) compared energy and capital costs of conventional chilling equipment and seasonal storage. These considerations led to a limit of approximately $150 – $200 per cubic meter of ice produced for capital costs of the system.

Among the different methods presented in the literature (Gorsky et al. 1982; Anonymous 1982), it was found that the layer-by-layer ice formation system was likely the most promising (Vigneault 1985a). All the other ice formation systems reviewed utilized a container filled up with water before ice formation starts. These systems required a structure strong enough to support the hydrostatic pressure caused by a depth total of water equivalent to the height of the final ice block.

With the layer-by-layer formation system, the ice block was formed by adding a new thin layer of water when the previous one froze. The structure only needed to support the hydrostatic pressure of the thin layer of water, and protect the ice block from warm air in the summer. Therefore the capital cost of the structure was much lower than for a system utilizing a container initially filled with water. Also, the rate of ice production was much faster with the layer-by-layer technique since freezing was always near the ice surface. In the container system ice formed on the inside face of the walls. The conductivity was therefore reduced and the freezing rate was slowed down.

The first published work on ice block formation based on the layer-by-layer method was conducted in the winter of 1979–1980 (Morofsky 1979). The block of ice was produced in an insulated storage shed where a ventilation system introduced cold outside air (Fig. 1). Continuous fluctuation of the outside temperature affected the water freezing time during the ice formation period. The layer-by-layer system permitted the adjustment of either the quantity of water sprayed at each spraying cycle or the time interval cycles to optimize the freezing capacity of the system.

The specific objectives of this project were to: (1) develop a water distribution system; (2) evaluate the effect of the air flow uniformity on the ice formation rate and determine the optimal economic cold air distribution system; (3) evaluate the effect of the air flow rate on the ice formation rate and determine the parameters permitting the design of the air distribution system; (4) develop the necessary controls and sensors to automate the ice-making sytem; and (5) evaluate the cost of the ice-making and storing system.

ICE-MAKING SYSTEM

The ice-making system consisted of a water and air distribution system, an ice height sensor, a lifting mechanism, and a control system. The entire system was housed in an insulated storage shed. Thin layers of water were periodically sprayed on the ice surface and were subsequently frozen by blowing cold outside air over the ice surface. A lifting mechanism periodically lifted the air and water distribution systems maintaining them at a constant distance from the ice surface as the ice block built up. A control system adjusted the frequency of water applications to the ice surface according to the outside temperature to maximize the rate of ice production (Vigneault et al. 1987).

Air was distributed uniformly over the ice surface to avoid the production of unfrozen pockets of water and to create turbulence in the air layer at the ice surface to maximize heat transfer. The system was automated to minimize the manpower required to make the ice, but the technology used also minimized the production cost of the ice. Because the system included water transportation below the freezing point of water the system was designed to avoid any pipe freezing problem.

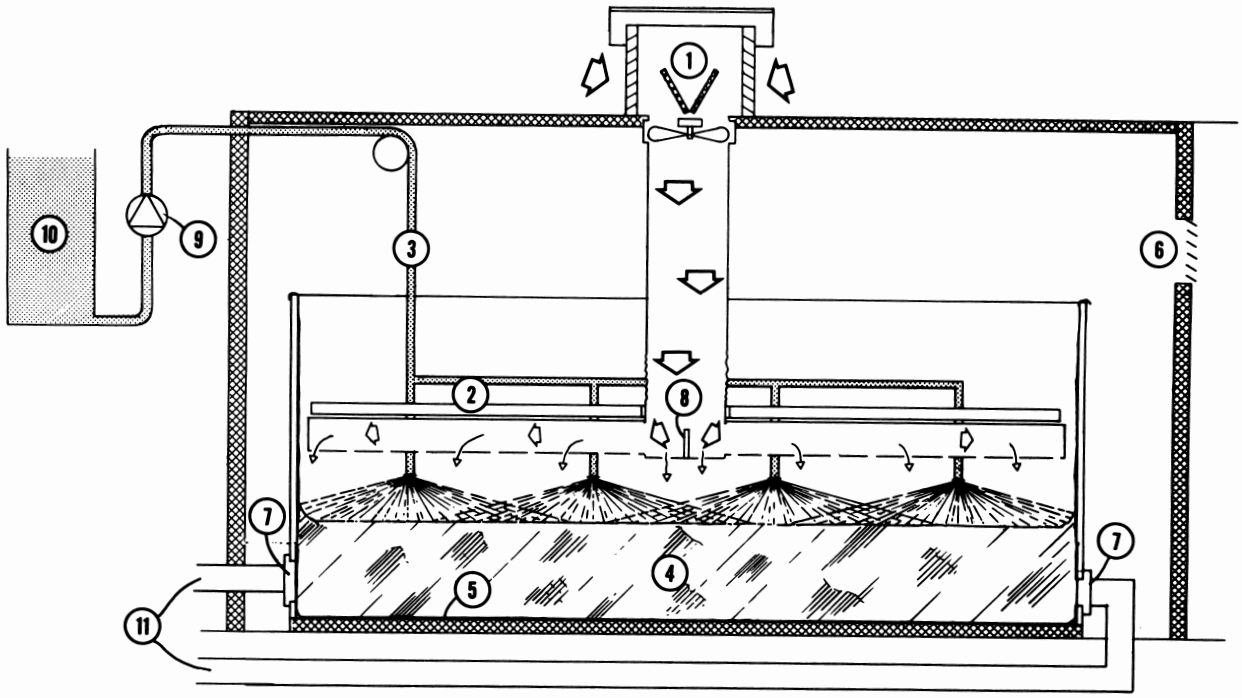

Figure 1. Ice production system. (1) air system intake; (2) air and water distributions systems; (3) water supply line, the water flow is a function of the outside air temperature; (4) ice; (5) plastic liner used to form a watertight reservoir; (6) air outlet; (7) ice reservoirs; (8) integrator sensor; (9) pump; (10) water tank; (11) melting water output and warm water input (deactivated during the winter).

WATER DISTRIBUTION SYSTEM

The water was distributed uniformly to ensure that the freezing time was uniform over the ice surface to maximize the efficiency of the system. The following criteria were considered in the search for the water distribution system: (1) uniform water distribution over the largest possible area to minimize the number of nozzles required; (2) low water flow rates to reduce the total flow rate required to supply all nozzles simultaneously; (3) no splashing of water above the nozzles to prevent the accumulation of ice on the air distribution system; (4) minimal pressure loss through the nozzles to reduce the total pressure required in the water flow distribution system; (5) drops of water large enough that they would not be swept up by the air continuously circulating above the ice; and (6) optimum vertical distance of 600 mm allowed for the air distribution outlets above the ice surface.

Several commercial nozzles were tested but none gave the desired results (Vigneault 1985b) because splashing induced ice formation on the air and water distribution system. A nozzle (Fig. 2) satisfying all the requirements was therefore developed. The pressure-flow characteristics are given in Fig. 3. The nozzles were operated at 20 kPa, and 500 mm above the ice, and covered an area of 9 m^2 each. The water flowed evenly on the ice before freezing which provided a uniform surface.

The optimal thickness of the layer of water was determined by comparing the uniformity of the ice surface for different thicknesses of the water layer. When the water layer was too thin, the water did not have time to flow onto the ice surface to form a uniform surface prior to freezing. This happened mainly when the air temperature was relatively low (below $-15°C$) and the thickness of the layer of water was under 1.25

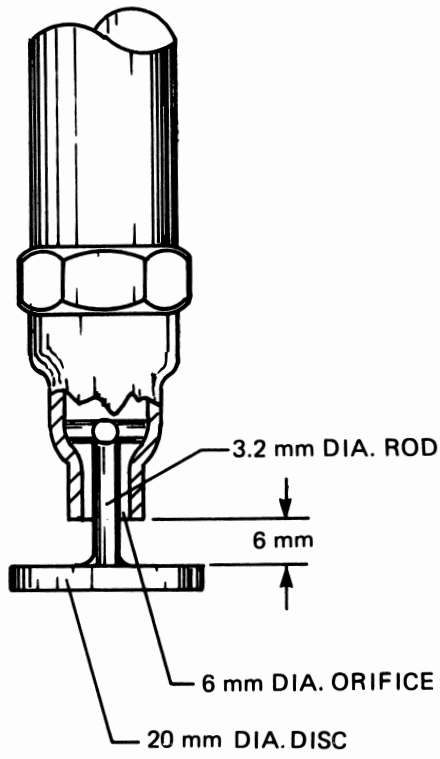

Figure 2. Nozzle developed to meet the requirements of the ice production system.

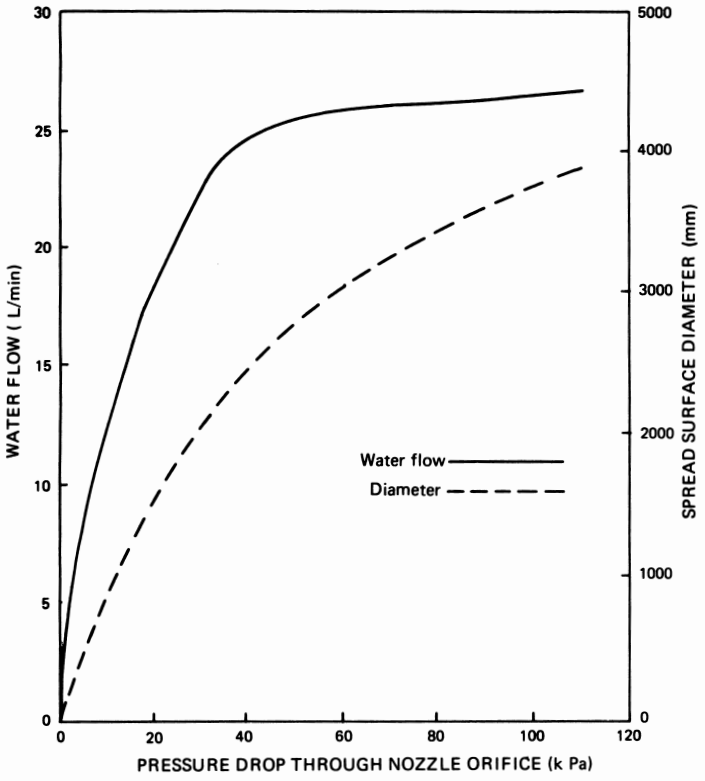

Figure 3. Flow and spread surface diameter of water layer versus pressure drop through water distribution nozzles, located 500 mm above the ice surface.

mm. When any large low spot appeared on the ice surface, a thick layer of water (thicker than 3.0 mm) caused water migration to this spot and formed water pockets which had insufficient time to freeze before the next spray. This situation was corrected by operating the system manually; the water in the pockets was allowed to freeze completely before applying the next layer of water. This slowed the rate of ice formation but when this was not done, some pockets of water remained entrapped between successive layers of ice and damage was caused to the structure when the water subsequently froze and expanded. A 1.5-mm layer of water was found to be the minimum thickness which yielded a uniform ice surface.

The water was spread in a short time (1 min or less) to ensure it flowed uniformly onto the ice before freezing. Because fluctuations occured in the water line a reservoir was provided in a heated insulated area and contained sufficient water for one spraying cycle.

A pump controlled by a timer supplied water from the reservoir distribution circuit for the length of time required to add a 1.5-mm layer of water to the ice surface. The reservoir level was controlled by a float valve. The water distribution system was completely emptied between sprayings or heated to avoid freezing. System draining was accomplished by adding a valve to allow air in, and all the water to drain out. The nozzles were very susceptible to freezing. Some drops of water remained in the orifices and froze between spraying, thus, plugging the nozzles. The installation of a heating cable avoided this problem.

AIR DISTRIBUTION SYSTEM

The optimization of the capital cost investment required a forced-air distribution system which produced a higher block of ice than a natural circulation system. A freezing index was utilized to compare the performance of the different air distribution systems. The freezing index is the number of the degree minutes below 0°C required to freeze a layer of water of unit of thickness (°C min mm^{-1}) assuming constant air-flow.

A time-temperature integrator was developed to control the spraying system (Vigneault et al. 1987). This integrator accumulated the number of degree minutes below 0°C, and could be preset to generate a control signal at any even number of degree minutes between 2 and 510. Test runs of at least 4 h were performed to obtain the freezing index. Visual observations determined whether the water was completely frozen or not. When the ice surface was frozen, the freezing index was reduced by ten °C min and a new test was started. This procedure was followed up to the minimal freezing index which resulted in a solid ice surface. The vertical distance of the air outlets above the ice surface was adjusted at intervals of 100 mm between 300 and 800 mm to determine the position which provided the lowest freezing index.

Three air distribution systems, with 1, 5 and 25 outlets with outlet areas of 162 000, 18 300 and 3800 mm^2, respectively, were compared. The same total air flow (46 L m^{-2} s^{-1}) and total ice surface of 9.29 m^2 were utilized. The extrapolation of the results obtained in the comparison of the three systems demonstrated little advantage to increase the number of the air outlets with this ice surface and large increase in the costs of the system. Using these systems, Vigneault et al. (1987) recommended 2.7 outlets of 3800 mm^2 per square meter of ice surface and at a vertical distance of 600 mm above the ice surface as the optimal economic system.

The same procedure was used to determine the effect of the air flow on the freezing index with the recommended outlet position. It was obvious that when air flow increased, the freezing index decreased because of the increase in air turbulence at ice level and corresponding increase in heat transfer.

Figure 4 shows the relationship between freezing index and air flow. These data are useful in selecting operating parameters

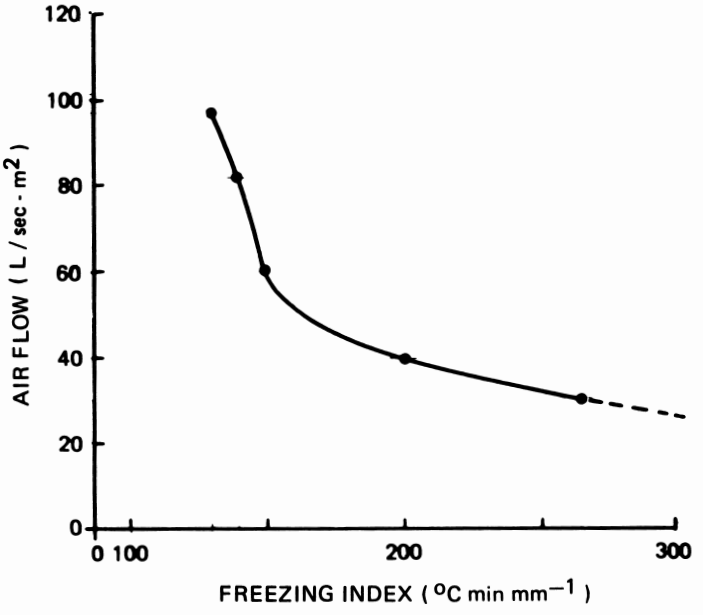

Figure 4. Ratio of the air flow and freezing index of the ice formation system.

for an ice-making system. The final height of the block of ice is set by economic and structural considerations (e.g., cost of land, site available, etc.) and the air flow required can be determined from the height of ice to be made and the climatic conditions. For example, the mean number of degree minutes below 0°C available during an average winter over 20 yr in Ottawa is 1.47×10^6 °C min (Vigneault et al., 1987). Thus with an air flow of 60 L $m^{-2}s^{-1}$ which corresponds to a freezing index of 150°C min mm^{-1}, it is possible to make an ice block of $(1.47 \times 10^6$ °C min)/(150°C min mm^{-1}) = 9.8 m in height.

At the end of the ice-formation period, when the maximal height of the ice was obtained, the air entrance and exit of the storage were closed and air sealed to minimize ice melting caused by natural convection air circulation.

CONTROLS AND SENSORS

To automate the ice-making system, the three following control systems were installed: the air distribution control system; the water distribution control system and a lifting system which maintained the air and water distribution system at a constant distance above the ice surface as the ice builds up.

The air distribution system was controlled by a thermostat which shut down the fan when the outside temperature rose above −3.0°C; under these conditions, the time required to freeze a layer of water was 45 min or more, and the efficiency of the system was considered too low. At this air temperature, the total energy required to make ice was approximately the same as with a compression refrigeration system.

The water distribution system was controlled by the time-temperature integrator. When the preset freezing index was accumulated, the integrator initiated a timer which turned on the water pump to supply a 1.5-mm layer of water. The integrator was controlled by the same thermostat as the air distribution system and did not operate when the outside temperature was above −3.0°C. The integrator probe was placed in the air distribution system downstream of the fan, which permitted the

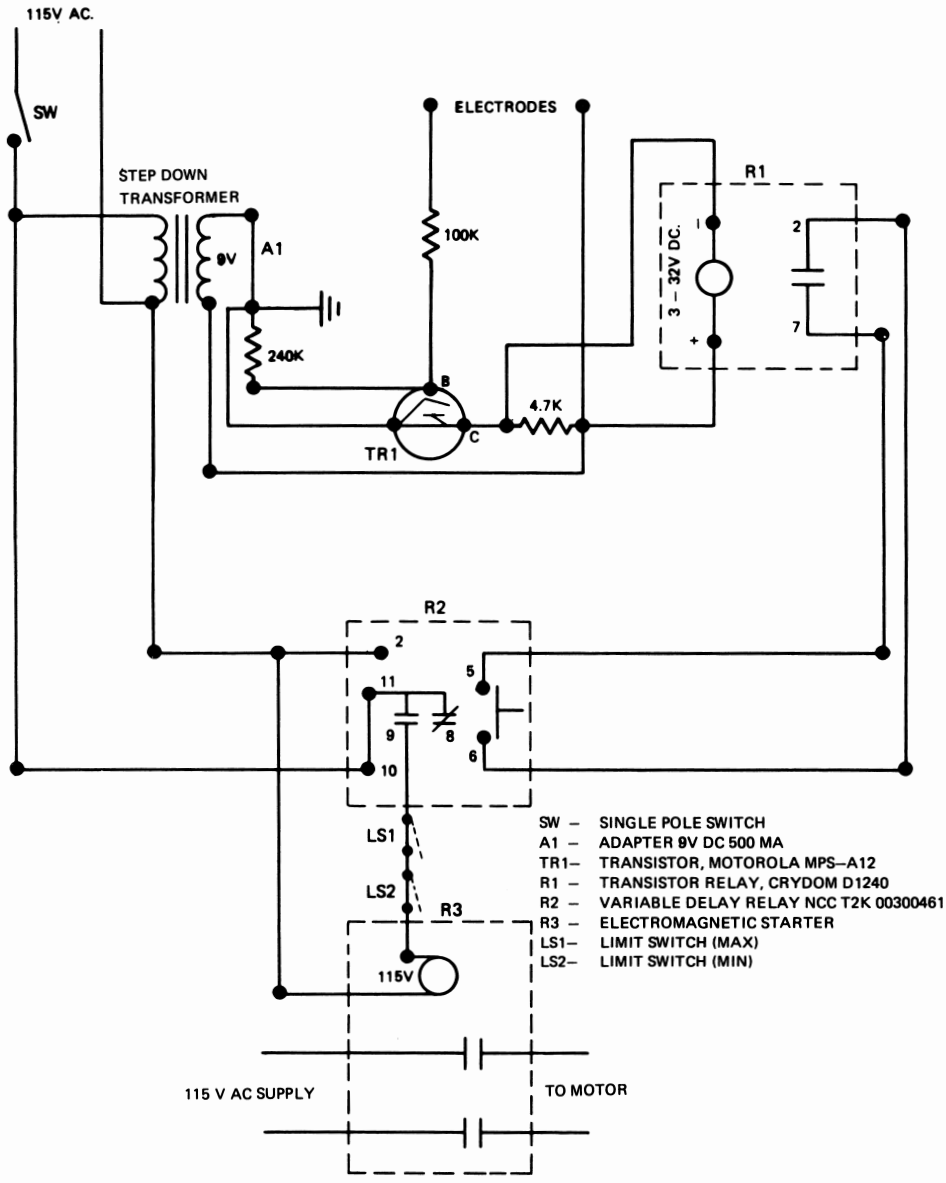

Figure 5. Automatic filling system controlled by a sensor utilizing two electrodes to detect the ice surface level.

integrator to measure the air temperature of the air blown on the ice surface.

The air and water distribution systems were mounted on a frame. The lifting system maintained this frame at a constant distance above the ice surface. An ice height sensor was developed to control the lifting system (Fig. 5). The sensor consisted of two electrodes fabricated from copper pipes 10 mm in diameter and 800 mm long. Electric heating cables were inserted into the electrodes to prevent ice formation on their surface. When a layer of water was added to the ice surface, the electrode tips became immersed in water and an electric circuit was completed. A timer was initiated, which activated the lifting sytem raising the frame by a 5-mm increment.

INSULATION

Since ice made in the winter months melts in warm weather, insulating the storage shed reduces the loss due to melting.

The optimum amount of insulation is reached when the cost of extra insulation equals the production cost of ice (including variable costs and capital cost of equipment and storage facilities) saved by adding extra insulation.

A computer simulation was carried out to determine the optimum amount of insulation of the storage shed to yield the minimum cost per tonne of ice available for vegetable cooling in the month of September (Vigneault 1983). The results were plotted against quantity of ice required (Fig. 6).

STRUCTURE

A 300-t ice block building (Vigneault and Lemieux 1983) was utilized to develop the structural criteria and performed satisfactorily during the three seasons of use. The outside structure was built to support the climatic loads, such as wind and snow. The inside structure was made with 38 × 89-mm wooden studs 400 mm on center; horizontal 25 × 100-mm wooden girths 400 mm on center completed the frame. A 25-mm white styrofoam was installed inside this frame and covered by a 0.1-mm polyethylene sheet. A pool was built to gather the melting water. A layer of 50-mm blue styrofoam SM was installed under the pool between the 38 × 89-mm wooden studs installed at 400 mm on center. This frame was covered with 18-mm plywood to support the ice load. This frame was not strong enough and punctured the pool liner with its sharp edges. It was suggested to use the Styrofoam SM directly to support the ice. The maximum compressive stress recommended for the styrofoam SM is 207 kPa m^{-2} (Dow Chemical Co., Data Sheet BCI 5.13) which corresponds to a 17-m high column of ice.

COST AND OPERATION

Based on the technology developed and the commercial structure assembled as recommended, the design of a 2000-t ice block system was accomplished to air condition a secondary school. The investment for this complete system located in the Ottawa region was evaluated at $150 000 or approximately $80 per tonne of ice produced which is approximately half the price suggested by Morofsky (1985). With a 20-yr depreciation for the building and equipment and 10% interest, the cost of the ice is approximately $15 per tonne compared to current price of $25 per tonne for delivered ice for use in on-farm postharvest vegetable cooling operations (Morofsky 1983).

To evaluate the recommended system, a 300-t ice block system was installed in an existing building and operated for 3 yr. The mean coefficient of performance (COP, the ratio of heat

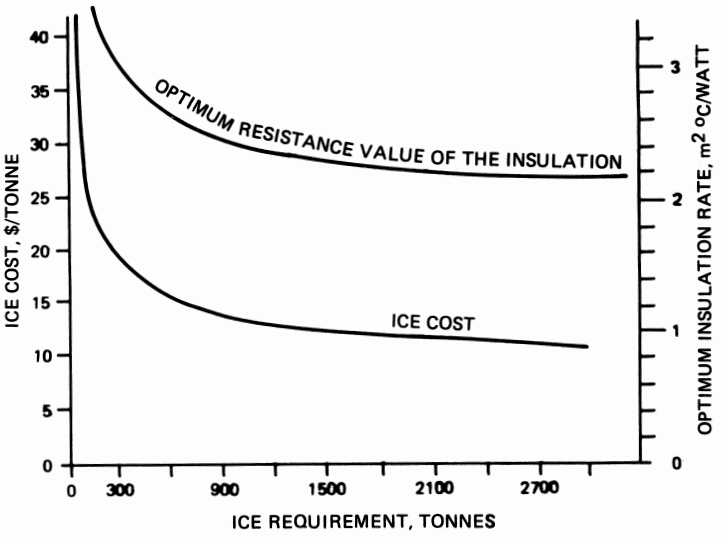

Figure 6. Ice cost and optimal insulation rate as a function of ice production requirements.

removed from the water to electrical energy used to operate the system) of the system during the last winter of the test was 25 when it was controlled by the integrator. Production of ice with a conventional mechanical refrigeration system requires approximately 12 times more energy.

The manpower required to operate this sytem was low because the system was automated; a half hour daily check was required to ensure the system was operating properly.

Design of a system requires careful study to evaluate the needs of coldness before the construction of the system. The fabrication of excess ice would result in a waste of energy and capital expenditure for the building and equipment.

CONCLUSION

All the components required to design a winter coldness ice-storage system were developed and tested on a 300-t ice system. The tests conducted for 3 yr resulted in an automated system. For a system as large as 2000 t of ice, the cost of the ice was found to be much lower than commercial ice. The goal of $150 to $200 per cubic meter of ice for the construction cost of the system was surpassed.

REFERENCES

ANONYMOUS. 1982. Abstracts of presentations. Second annual workshop on ice storage for cooling applications. Argonne National Laboratory, Argonne, Ill. 20 pp.

DOW CHEMICAL CO. Styrofoam and styrospan plastic foam insulation for wall, ceiling and perimeter applications. The Dow Chemical Company. Leaflet No. BCI 5.13. 4 pp.

GORSKY, A. J., W. W. SCHERTZ, A. S. WANTROBA, A. E. McGARITY, and E. H. BUYCO. 1982. Ice production and storage for seasonal application utilizing heat pipe technology. Argonne National Laboratory, Argonne, Ill. Report No. B-B5248-A-0. 102 pp.

MOROFSKY, E. L. 1979. Project ICEBOX — A Public Works Canada experiment in seasonal energy storage. Public Works Canada, Ottawa, Ont. November. 14 pp.

MOROFSKY, E. L. 1985. Cooling with ice — Canadian progress. Proceedings of the Third International Conference on Energy Storage for Building Heating and Cooling. The Westin Hotel, Toronto, Ont. September. pp. 337–340.

VIGNEAULT, C. 1983. Seasonal ice storage for agricultural use. Proceedings of the Third International Workshop on Ice Storage for Cool-

ing Applications. Argonne National Laboratory, Argonne, Ill. 10 pp.
VIGNEAULT, C. 1985a. Ice making from winter coldness: Agricultural applications. Engineering and Statistical Research Centre, Agriculture Canada. Ottawa, Ont. Report no. I-710. 33 pp.
VIGNEAULT, C. 1985b. The production of ice using winter coldness. Engineering and Statistical Research Centre, Agriculture Canada, Ottawa, Ont. Report no. I-759. 19 pp.
VIGNEAULT, C. and M. LEMIEUX. 1985. Ice production using ambient winter temperature. Proceedings of the Third International Conference on Energy Storage for Building Heating and Cooling. The Westin Hotel, Toronto, Ont. September. pp. 341–344.
VIGNEAULT, C., G. ST. AMOUR, and D. J. BUCKLEY. 1987. Use of a temperature integrator to control ice making using cold outside air. Engineering and Statistical Research Centre, Agriculture Canada, Ottawa, Ont. Report no. I-901. 6 pp.