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The design, fabrication and deployment of an ice boom to protect two hydroelectric power plant water intakes from ice blockages during winter

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ABSTRACT**:** An ice boom was designed, fabricated and deployed on the Ottawa River, in Hull, Quebec, upstream, and at the north end of the Arch Dam. The boom was to protect two hydroelectric power plants, owned and operated by Hydro-Quebec and E. B. Eddy Forest Product Ltd, from ice.

The boom was placed about 200 m upstream of the two intakes and spanned the entire bay width. The boom was justified following field observations carried out during the winter of 1996/97.

The paper describes the procedures followed for the selection of the boom site, the calculation of the ice loads and the selection of the pontoon size, length and number, the span and anchor cable lengths and diameters and the anchor resistance. A comparison between the ice accumulation upstream of the intakes, before and after the installation of the ice boom, and the associated increase in power production is presented.

1 INTRODUCTION

The hydroelectric power production at both plants, Hull 2, of Hydro-Québec, and E. B. Eddy, of E.B. Eddy Forest Products Ltd., are affected by the blockages of their water intakes by ice and frazil. These intakes are located upstream and at the North end of the Arch Dam. The dam was built to spill the excess water of the Ottawa River through its fifty gates and to maintain a constant water level upstream of these intakes. Three other hydroelectric power plants are located at the south end of the Arch Dam.

A study to evaluate this problem and develop solutions was carried out during the winter of 1996/97. The ice and frazil were found to block the trashracks and significantly reduce the power production for a period of up to ten weeks during the winter. Figure 1 shows the ice accumulation upstream of the intakes following the break-up of the river ice, (Abdelnour, 1997).

Figure 1: Accumulation of ice upstream of the Hull 2 and E.B. Eddy water intakes, April 7, 1997.

It has also been observed by operators of these power plants that the formation of a stable ice cover immediately upstream of the water intakes, and in the bay, reduced the incidence of trashrack blockages by frazil and slush and improved the production of electricity in winter.

The type of ice drifting toward the intakes depends on conditions of the ice cover formation upstream. When the ice drifts from Chats Falls, about 40 km upstream of the intakes, it is relatively thick and exceeds 10 cm, especially when the air temperature is below -15°C. However, when a stable ice cover forms at about 3 km upstream of the intakes, most of the ice that reaches the intakes becomes very thin and consists of very low concentrations of pancake ice, slush and frazil. This type of ice, particularly with low concentrations, breaks-up on impact with the stationary ice, then submerges and becomes entrained in the currents under the ice until it reaches the trashracks. Solutions to control this ice are difficult to succeed especially when the current speed exceeds 0.6 m/sec.

This paper details the design procedures and the ice observations during the winters of 1996/97 and 1997/98, before and after the installation of the Hull 2 and E.B. Eddy Ice Boom.

2 OBJECTIVES

The overall objective of this work was to develop a solution to improve the power production and reduce the cost of labour for de-icing the trashracks at Hull 2 and E.B. Eddy power plants.

An ice boom was considered the most appropriate solution. The project objective was to design, fabricate, build and monitor the performance of the boom after its installation. The ice boom was designed to retain the drifting ice and to produce a stable ice cover upstream of the boom as early as possible, thus reducing the amount of ice, slush and frazil drifting into the intakes.

3 ICE BOOM DESIGN

The design procedures have been based on several years of experience in the concept and operation of ice booms. It included the recent re-engineering of the Lake Erie Ice Boom, (Crissman et al., 1995), the construction and observation of the Yamachiche ice boom in Lac St. Pierre, (Morse, 1993-1995) and the re-engineering of the Lavaltrie ice boom in the St. Lawrence River, (Abdelnour et al., 1993). The design procedures included the following steps:

3.1 Define the layout of the ice boom

The obvious location for the ice boom was immediately upstream of the Hull 2 and E.B. Eddy water intakes. However, due to the relatively high current velocity in this area a more appropriate location for the boom was to be found. The criteria observed for the layout of the ice boom was as follows:

1) It must be deployed in an area where the water current velocity is below 0.6 m/sec.
2) It must provide an area, upstream of the ice boom, to allow the ice to accumulate and form a solid and resistant ice cover where the greater part of the frazil and slush can be deposited under the ice. This area should be relatively deep and should have a current velocity below 0.6 m/sec.
3) None of the boom components should interfere with the operation of any of the fifty Arch Dam floodgates and no anchoring of the boom cables to the dam wall was allowed.

Based on the above conditions, the boom was placed about 200 m upstream of the intakes and spanned the width between the North end of the Arc Dam and the north shore. The width of the river in this area is 240 m. Figure 2 shows the layout of the ice boom as deployed.

The ice boom was built in two sections, north and south, to minimise the pull force on the anchors and to reduce the north-south displacement caused by wind. The ice boom covered a width of 225 m or 94% of the 240 m river width at this location. It should be noted that moving the south end of the ice boom further upstream would have exposed the boom's buoy and pontoons to the relatively high currents which may interfere with the operation of the Arch Dam gates.

3.2 Current Distribution in the Bay

The bottom of the bay is rocky and with relatively no sedimentation. Only at the north end of the boom, at the entrance of a small creek, sediments exceeded 1.5 m in thickness. The bottom of the bay had a relatively uniform depth of about 6 m since it was levelled during the construction and the rehabilitation of the dam.

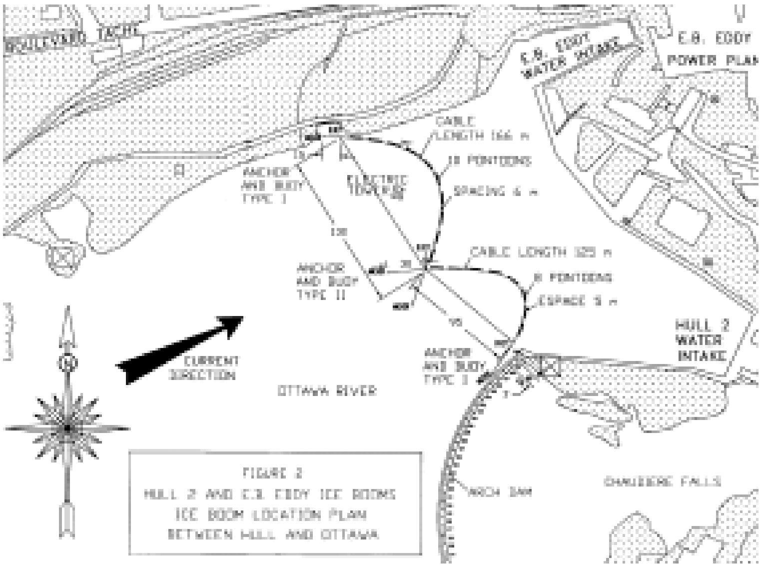


FIGURE 2
HULL 2 AND E.B. EDDY ICE BOOMS
ICE BOOM LOCATION PLAN
BETWEEN HULL AND OTTAWA

A constant water level in the bay is maintained year round by the Chaudière Dam Corporation by opening and closing the Arch dam gates. Fifty floodgates are available to evacuate the excess discharge required by the five power plants (the two power plants on the city of Hull side and three on the city of Ottawa side). Therefore the discharge of the Ottawa River does not affect the discharge through the bay where the boom is located.

The water discharge through the bay is equal to the flow through the water intakes of the two plants, Hull 2 and E.B. Eddy. An additional discharge is used for ice evacuation immediately upstream of the intakes. The discharge at the bay consists of:

1) The discharge through the Hull 2 turbines can reach a maximum of 340 m3/sec
2) The discharge through the E. B. Eddy turbines can reach a maximum of 170 m^3/sec.
3) The discharge used for ice evacuation by the 2 plants was estimated at 285 m^3/sec (maximum).

The total discharge without the discharge for ice evacuation is equal to 510 m^3/sec. Assuming the cross section under the ice boom is 240 m wide and 6 m deep, the average current velocity would be less than 0.35 m/sec. The total discharge, including the discharge used for the evacuation of ice, is equal to 795 m^3/sec. This corresponds to an average velocity of 0.55 m/sec or an increase of 53%.

The current distribution using a numerical model showed that the current speed at the south side of the bay was twice as high as the current speed at the north side. This was due to the larger discharge through the Hull 2 power plant than the E.B. Eddy plant. This shows that the maximum current speed, without the discharge for ice evacuation, will be through the south end of the ice boom close to 0.6 m/sec. This is the maximum speed for the ice floes to be retained by the boom and to progress upstream of the ice boom. The use of water for ice evacuation will increase the current velocity to much more than the critical velocity of 0.6 m/sec, and will present difficulties to form an ice cover.

3.3 *Ice Forces on the Boom*

The ice forces on the boom have been calculated using a numerical model developed by Abdelnour et al., 1993. The calibration of the model was made using data obtained from the Lavaltrie, Yamachiche and the Lake Erie ice booms (Crissman et al, 1995, Cowper et al., 1997). The variables, including the current and wind velocities and the effective area, used to calculate the ice forces on each of the two boom sections are shown in Table 1.

Table 1

Define the Ice Loads on the Ice Boom Anchors and Cables

Input of the environmental factors

Section	Width	Angle Triangle	Distance to Ice Boom	Effective Area	Wind Speed	Current Speed		Mean Speed
						Boom	Upstream	
#	(m)	(Deg.)	(m)	(m2)	(km/hr)	m/sec	m/sec	(m/s)
North	**130**	**20**	**369**	**23961**	**100**	**0.50**	**0.35**	**0.45**
South	**95**	**20**	**269**	**12796**	**100**	**0.80**	**0.40**	**0.67**

Results

Section	Width	Force on the Boom	Line Load on the Boom	Force on the Boom	Number of Anchors	Force on one Anchor	Number of Pontoons	Load on each Pontoon
#	(m)	(kN)	(kN/m)	(tonnes)		(kN)		(kN)
North	**130**	**175.9**	**1.4**	**17.9**	**2**	**88.0**	**10**	**17.6**
South	**95**	**155.9**	**1.6**	**15.9**	**2**	**77.9**	**8**	**19.5**

The model calculates the line load applied on the ice boom for the design current, wind speed and their directions. The wind speed considered is 100 km/hr with a direction perpendicular to the ice boom.

The calculated line load on the north section of the boom, where the mean current velocity is 0.45 m/sec, is 1.4 kN/m. The calculated line load on the south ice boom, where the mean current velocity is 0.67 m/sec is 1.6 kN/m. The width of each of these two sections was defined to ensure that the applied total force on each boom section and each of the four anchors are almost equal. The north section of the ice boom would be 130 m wide and the south section would be 95 m wide as shown in Figure 2. The total force applied on the north section of the ice boom is 176 kN and on the south section is 156 kN. As there are two anchors for every ice boom section, each anchor will resist half the total force. This means the anchors at the north section of the boom will have to be designed to resist a force of 88 kN and the anchors at the south section of the boom, 78 kN.

3.4 *Selection of boom pontoons*

The boom type and method of attachment to the span cable used at the Lake Erie, Lavaltrie and Yamachiche ice booms was followed (see Figure 3). This method allows the ice to run-over when the ice resistance capacity of the pontoon is exceeded. The pontoons are designed to submerge then resurface when the load drops. This guarantees that the impact of a large ice floe, with sufficient kinetic

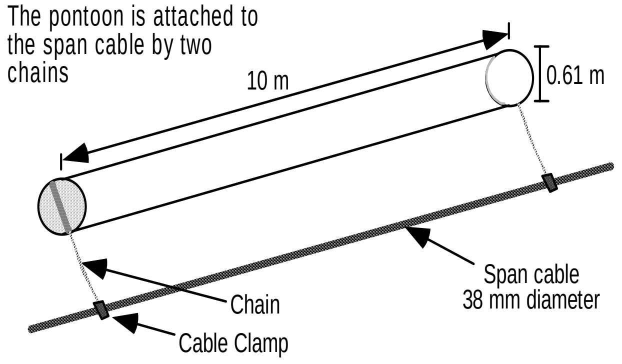


Figure 3 : The method the pontoon is attached to the span cable to allow the ice to run-over when the load exceeds the resistance capacity

energy, will not cause structural damages to any of the boom components.

The design load and the breaking resistance for each of the components of the boom has either been calculated or defined based on previous experience. The design load and the breaking resistance of various components of the boom are shown in Table 2.

Table 2
Calculated and breaking resistance of the ice boom components

Components	Calculated Force	Breaking Resistance	Safety Factor
	kN	kN	(-)
Anchor	125	2000	16
Span &anchor cables	125	850	7
Center junction plates	250	1000	4
Ends junction plates	125	800	6
Cable clamp	50	510	10
Shackles	50	510	10
Chain	50	200	4
Attachment bar	50	300	6
Pontoon	100	1000	10

3.5 Anchor Design and Breaking loads

To keep the ice boom in place, four anchors are required. The design load of each anchor is 125 kN and the breaking resistance is 2000 kN. This is a safety factor of 16. The cost associated with a failure of any of the anchors is offset by the small increase in cost for the anchor construction. Other factors, such as uncertainty in the type of the rock and the existing faults within the rock, corrosion and wears of the anchor components, make this safety factor more than adequate.

3.6 Anchors, Span Cables and Boom final configurations

The anchor cables were 30 m in length and only the one deployed at the north end was 15 m. This is equivalent to about 12 degree angle with the river bottom when the ice boom is loaded and the anchor cable fully stretched. This anchor cable length is considered adequate to minimise the uplift force on the anchors. The use of a longer cable will affect the stability of the ice when a crosswind parallel to the axis of the ice boom direction occurs.

The length of the span cables must be at least 25% longer than the desired boom width to achieve the target boom section width. The span cable length of the north boom section was chosen to be 166 m or 28% greater than the 130 m desired width. The span cable length of the south boom section was chosen to be 125 m or 32% greater than the 95 m desired width.

The location of the anchors were drilled to allow the anchor cables to spread under the tension load applied by the water current and ice forces to form a 37^{o} angle with the water current direction. The final configuration of the boom is shown in Figure 2.

The design tension load of the span and anchor cables was 125 kN and the breaking resistance of the installed cables is 850 kN.

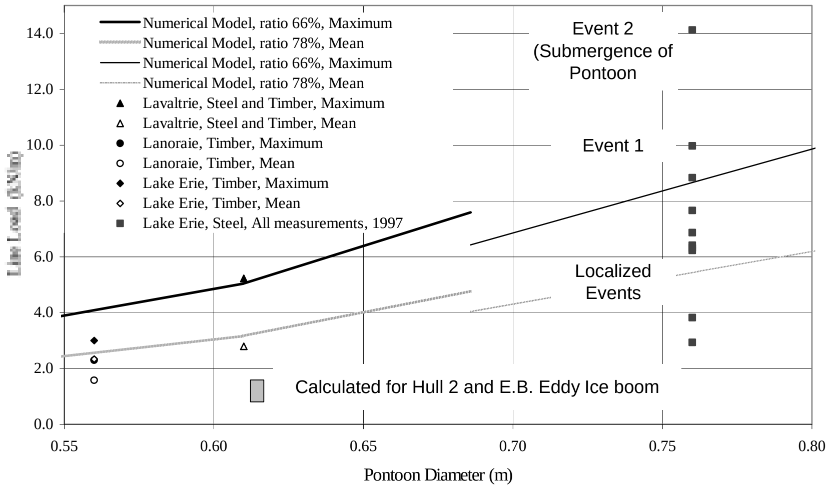
3.7 Boom Hardware

Three junction plates were used to connect the anchor cables to the span cables. These plates were held just below the water surface with buoys. The end junction plates have a breaking resistance slightly less than the breaking load of the cables and are considered a fuse so they would fail before any other components of the boom. Two cable clamps were required to join the chain of each pontoon with the span cable. The cable clamp was designed to resist to a sliding force of up to 75 kN. However, its breaking resistance is 510 kN. The design and the breaking loads of all the other components are shown in Table 2.

3.8 Number and Size of the Ice Boom Pontoons

The total length of all the steel pontoons used for the Lake Erie Ice Boom is 66% of the span cable length. The value used for the north section was 60% and the south section was 64%. The proposed number of pontoons, would be 10 for the north and 8 for the south sections of the boom. The calculated ice boom resistance capacity is 1.6 kN/m. This resistance capacity can be achieved by using a 0.61 diameter pontoon, as shown in Figure 4 (Cowper et al., 1997).

Figure 4
Effect of Pontoon Diameter on the Ice Resistance Capacity



These pontoons are capable of resisting a line load of at least 3 kN/m. The selected pontoon wall thickness to resist ice impact was similar to other ice booms at 9.5 mm.

4. INSTALLATION OF THE ICE BOOM

The ice boom was installed in November 1997. The installation started by drilling holes in the rock bottom and was later followed by placement of the anchor, the anchor cables and the buoys. The two boom spans were later deployed after all the pontoons were attached on shore. The operation took about two weeks.

The anchors were placed in the rocky bottom using a drill installed on a barge. The diameter of every hole was 152 mm and its depth was 6.0 m. With the help of a diver, every anchor, shown in Figure 2, was placed in the hole after concrete was poured. Each anchor was positioned in the direction of the pull of the anchor cable as shown in Figure 2. The concrete compression strength was 40 MPa after 28 days, well above the target strength.

The pontoons and the span cables were transported to the site provided by E. B. Eddy for the deployment of the boom components. The site was on the North shore of the boom site. After placing the cable clamps on the span cables and the attachment of the pontoons, a boat was used to attach the ends of the spans to the junction plates below the three buoys.

5. ICE OBSERVATION DURING WINTERS OF 1996/97 AND 1997/98

The bay upstream of the intakes was observed during the winters of 1996/97 and 1997/98. A video camera and a time-lapse video recorder were used for the period between December and April. Photos were also taken using a 35 mm still camera.

The video camera was placed on the twentieth floor of the "Les Terrasses de La Chaudière" building in Hull, about 200 m North of the intakes. The view of the camera covered a distance of about 1 km upstream and 100 m downstream from the ice boom site.

5.1 Observation of the winter of 1996/97 (without an ice boom)

During the freeze-up: The ice started to grow on the Ottawa River on December 31, 1996. The freezing degree-days was about 40°C (the cumulative sub-zeros air temperature since the start of the winter). The ice started to form the Chats Falls Dam, and drifted a distance of about 40 km before the relatively thicker ice started to reach the intakes. During this period, the thickness of the ice averaged about 10 cm, considering the average air temperature was about -15°C.

The ice cover in the bay began to form slowly starting from the North shore (see Figure 5).

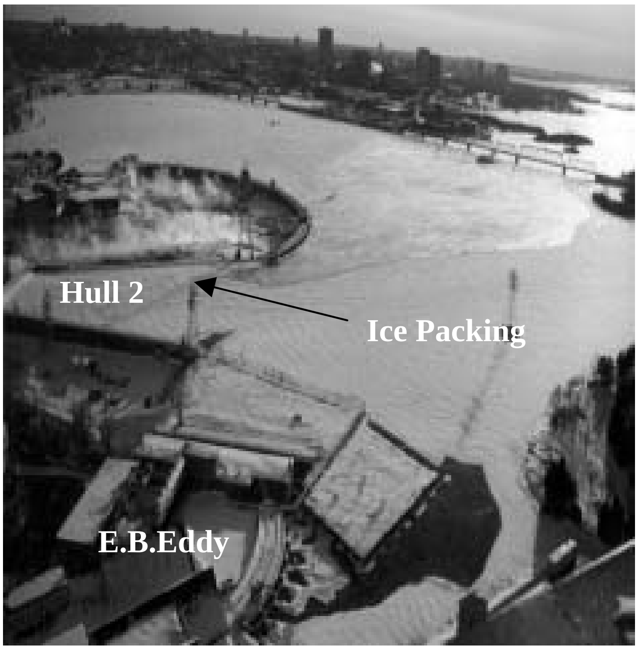


Figure 5 : Ice cover without an ice boom (Mid-winter 1996/97).

Immediately upstream of the intakes, the current velocity is well above 1 m/sec. At this velocity and considering the ice is very thin, ice packing occurs. The pack ice deepens and blocks the flow, thus resulting in significant headloss at the power plants. The ice also drifts into the trashracks causing blockages and additional local headloss.

The current velocity was less (below 0.6 m/sec) about 200 m upstream of the intakes. Therefore, as soon as the pack ice progressed upstream and reached this area, combined with cold air temperature, a relatively thin ice cover formed. This occurred on January 30, 1997, subsequent to leaving the intakes without protection for several weeks where ice problems were frequent and costly. Despite the formation of a cover, slush and frazil continued to reach the Hull 2 intake due to the continued erosion of ice by the current flow. In the past, only once every few years did an ice cover form early in the winter with minimal ice problems.

When an ice cover formed on January 5, 1997, 3 km upstream of the boom location (at the Champlain Bridge), the ice volume that drifted toward the boom was reduced by more than 90%. Following this event, only thin pancake ice with relatively low concentration and discharge frequencies drifted into the bay. As soon as this ice cover formed, it became very difficult to get sufficient volume of ice to form a cover, which prevented the formation of an ice cover for most of the winter. The presence of a partial ice cover forced the water to pass through the south side thus significantly increasing the average water velocity to well above the critical velocity of 0.6 m/sec. This allowed the slush and the frazil to reach the water intakes for the most part of the season resulting in frequent ice blockages of the trashracks.

During the break-up: The ice cover in the bay started to melt slowly and most of the south side melted by March 15 when the air reached above freezing temperatures. The ice started to break from the Arch Dam walls, on the south end of the bay, then from the north shore of the bay. Large floes then drifted downstream and melted away rapidly due to the combination of high current velocity and relatively warm water. The ice covering the bay melted away completely by late March.

However, ice floes continued to drift toward the intakes due to multiple river ice break-ups that occurred on the river from Chats Falls to Hull. One of these ice break-up events occurred on April 7, 1997 and presented significant performance problems to the power plant due to significant ice ingestion and packing, ridging and grounding within the bay, and in the channels immediately upstream of the intakes. The event of 7 April is shown in Figure 1.

5.2 Observation During the Winter of 1997/98 (with an ice boom)

The actual discharge during the winter of 1997/98 was about 270 m^3/sec including the discharge for ice evacuation (Mr. H. Bertrand, Hydro-Quebec). The ice boom was designed for a maximum discharge of 340 m^3/sec. This is an equivalent reduction in the current velocity of about 20%. Therefore, the ice boom is expected to perform more effectively in controlling the ice compared to a maximum discharge.

First Freeze-up: The ice started to grow on the Ottawa River during the evening of December 1, 1997. The freezing degree-days (the cumulative sub-zeros air temperature since the start of the winter) was about 40^{o}C. The ice started to form at the Chats Falls Dam, and drifted a distance of about 40 km before the relatively thicker ice started to reach the intakes. Assuming an average drift velocity of 0.5 m/sec, the total time required is about 20 hours. During this period, the thickness of the ice may have reached about 15 cm, considering the average air temperature was about -5^{o}C

On December 2, the overnight air temperature remained below -5^{o}C and was colder, -8.5^{o}C, on December 3. During the early morning of December 3, and within about ten hours after the start of significant ice drifts into the bay, the ice boom helped form an ice sheet that quickly covered the bay, an area up to 1 km long and 400 m wide upstream of the boom. Figure 6 shows the ice

Figure 6 : December 4, 1997, first ice cover formation

accumulation upstream of the boom on December 4, 1997. It is believed that most of the thicker ice that formed the ice cover had drifted all the way from Chats Falls.

The ice completely melted away when the air temperature rose to above freezing temperature and ranged between –2°C to +2°C from December 4 to 8, 1997.

Subsequent Freeze-up: On December 9 to 12, a cold air resulted in the formation of ice on the north side of the bay. All melted on December 14 and remained open to December 21st. During the period of December 9 to 12, 1997, an ice cover formed about 3 km upstream of the bay and remained there until the end of March 1998. This prevented any thick ice from reaching the ice boom after this date.

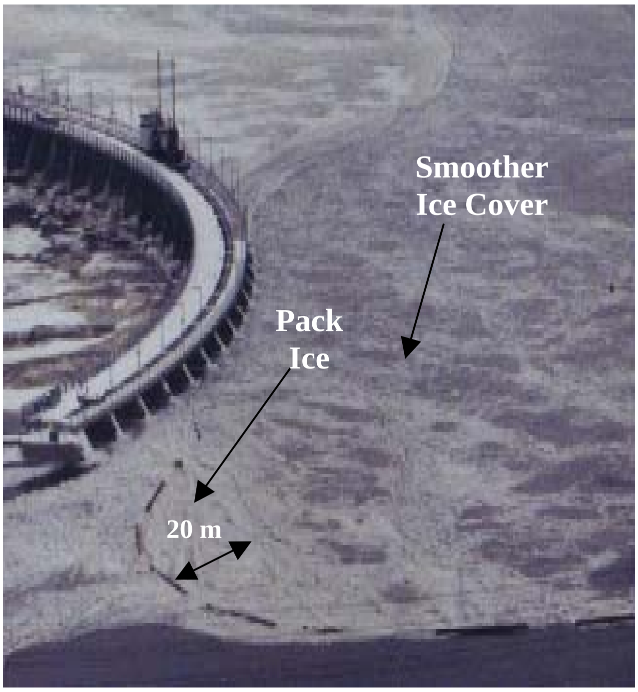


Figure 7 – Ice cover formation on the south side of the boom in relatively high current.
Photo taken on January 1, 1998

On December 17, 1997 the air temperature fell to -22°C and the ice started to grow again in the river. Only thin pancake ice was drifting toward the boom, with very low ice concentrations. The ice formed a relatively stable ice cover on the north side, while on the south side, at least 25% of the boom width remained open.

Thin ice combined with a higher current velocity and low ice concentration presented difficulties for the ice boom in retaining the ice on the south side. The current velocity was obviously much higher at the boom site than a few meters upstream. Figure 7 shows the ice interaction with the boom and the thick pack ice that formed about 20 m upstream of the boom. This situation remained for two days where ice frazil and slush continued to drift into the Hull 2 water intake channel. The E.B. Eddy water intake, being situated at the North end of the bay was relatively well protected and minimal ice drifted into the intakes, causing no blockages and minimal reduction in power generation. The ice cover finally formed on December 29, 1997, and remained stable until February 26, 1998 when open leads started to form due to an above normal temperatures of about 10°C during the day.

During the break-up: Large ice floes were pushed past the boom as soon as they detached from the sides of the bay. These floes were pushed slowly over the pontoons, driven mainly by the high current at the south side of the boom. This was not observed to occur on the north section of the boom where almost complete melt down of the ice upstream of the ice boom was observed. These ice runs did not have an effect on power generation since most of the ice remained in the channel upstream of the trashracks without causing any major ice blockages.

No major ice break-ups upstream of the ice boom occurred in 1997/98. Most of the ice melted in place along the river between Chats Falls and Hull.

6. CONCLUSIONS

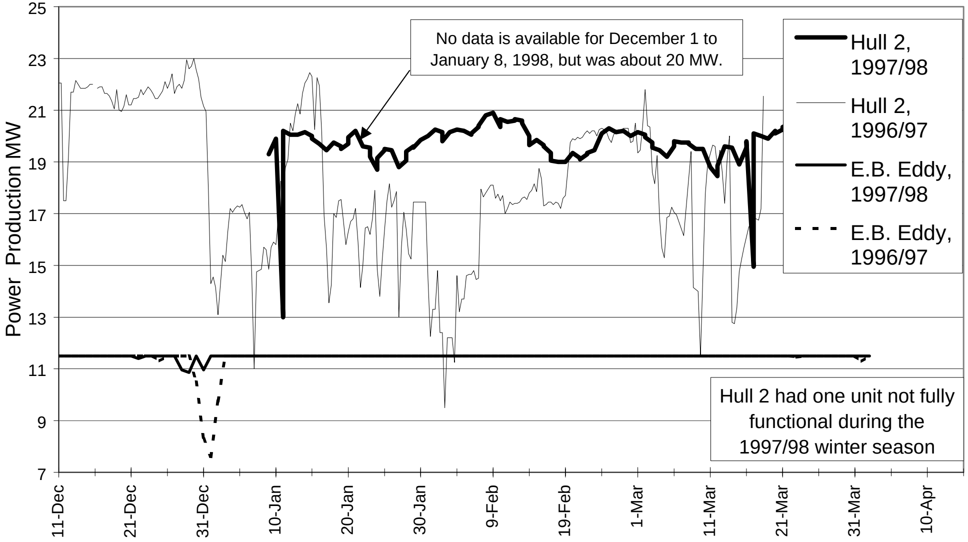
One year is not sufficient to evaluate the benefits of an ice boom. However, power production data obtained from the two power plants were positive.

Figure 8 shows the production before and after the installation of the boom. At the Hull 2 plant, the normal power production, without the presence of ice, was 22 MW in 1996/97 and 20 MW in 1997/98. The average power production during the 1996/97 ice season was 18.1 MW, an average power loss of 3.9 MW. The average power loss during the 1997/98 ice season, with the ice boom in place, was 19.7 MW, an average power loss of 0.3 MW. This is equivalent to an improved power production of more than 3 MW for the full winter season.

At E.B. Eddy, an 80 % reduction in power generation loss was achieved during the winter of 1997/98. E.B. Eddy plant is located downstream of the North section of the boom where a more stable ice cover formed for most of the winter.

The ice conditions during the winter of 1997/98 were more likely to cause ice blockages than

Figure 9 - Power Generation losses of Hull 2 and E.B. Eddy Power Plants, Before and After the Installation of the Ice Boom



1996/97 because of the higher number of freeze-ups that occurred due to the relatively warm winter.

As expected, the ice boom doesn't retain all the frazil and slush from reaching the water intakes. However, when an ice cover formed upstream, significantly lower volumes of slush and frazil were found to reach the intakes and affect the performance of the plants.

7. RECOMMENDATIONS

A more favourable condition to form an ice cover at the south boom section is considered for winter 1998/99. This should be done by:

a) Moving the boom 20 m upstream from its present position. The current is lower due to deeper water. The buoy will interfere with the last two flood gates operations (flood gates 49 and 50 are rarely opened, Mr R. Guévremont, 1998). This will require the approval of the Chaudière Water Power Incorporated, the corporation responsible for control of the river water level.

b) The discharge used by the operators of the two power plants to evacuate the ice should be reduced to close to zero for the entire period of ice formation. This will reduce the current speed at the south end of the ice boom and provide an opportunity for the ice cover to form upstream of the boom as quickly as possible.

c) More pontoons should be added to the south span to improve its retention of slush and large ice floes at the end of the winter.

8. ACKNOWLEDGEMENTS

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