CGU HS Committee on River Ice Processes and the Environment
19th Workshop on the Hydraulics of Ice Covered Rivers
Whitehorse, Yukon, Canada, July 9-12, 2017.

Ice Boom Design Challenges in a Very Large, High-Latitude, North-Flowing River

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Many challenges were encountered during the design and installation of multiple ice booms on the lower Nelson River that were utilized to develop a stable ice cover upstream of the Keeyask Generating Station construction site from 2013 freeze up to 2017 breakup. Without the ice booms (and the stable ice cover), a large ice dam would form downstream of the construction site and would create significant river management challenges by way of elevated water and ice levels at the cofferdams. To the best of the author's knowledge, these ice booms were installed at the highest latitude of any previous ice boom installations and in this case, where the winter coldness factor can reach 3,600 freezing degrees-days (FDD). The Nelson River also has a relatively high flow with very limited regulation control options during flood conditions. Adding to this challenge, the river flows from south to the far north, meaning that the snow and ice starts to melt in the south early in the spring season which can increase the northern flows while the ice conditions near the site are still firmly frozen to the boom and the shores.

1. Introduction

This paper presents the results of four years of design and operation of the Keeyask Ice Booms (Figures 1 and 2). The first ice boom, referred to as the Test Ice Boom, was built during the fall of 2013 on the Nelson River in Northern Manitoba, near the town of Gillam. In 2015, the Test Ice Boom was moved upstream, and split into two separate booms (identified as Boom A and Boom B) on either side of Caribou Island. The boom was to be in place until the year 2019/2020 when the construction of the new hydroelectric dam at Gull Rapids will be nearly complete and the forebay will be impounded.

During above average to high flow conditions, portions of the stretch of river between Split Lake and Gull Rapids often remains as open water for a very long period of time before a solid ice cover forms in winter. If this stretch of open water upstream of Gull Rapids does not freeze entirely, it generates a significant quantity of frazil ice over the 50 km reach. This frazil ice forms a hanging ice dam downstream of the falls against the stable ice cover of Stephens Lake, resulting in higher upstream water levels throughout the vicinity of the construction site. Without a stable ice cover, this phenomenon increases the height requirements of the construction cofferdams and presents numerous other river management challenges (Figure 3, Bonin et al, 2011).

Figure 1: The boom is located in Northern Manitoba, 3 km Upstream of Gull Rapids.

Figure 2: The Test Ice Boom Installed on the Nelson River, Northern Manitoba, in 2013.

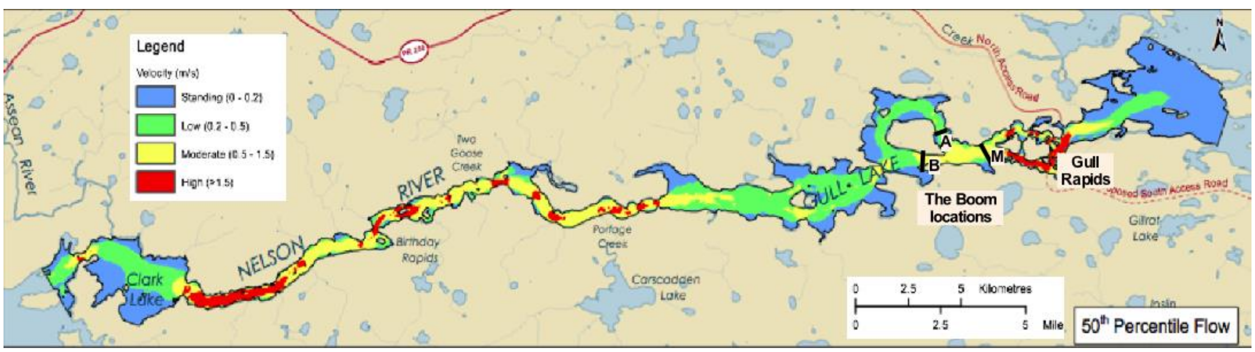

Figure 3: Velocity Grid of the Nelson River upstream and downstream of the Ice Boom Site.

The purpose of the ice boom was to accelerate the formation of a stable ice cover soon after the freezing temperatures begin and the frazil ice formation in the river starts to occur. As soon as an ice cover forms, it insulates the water and prevents the formation of frazil during the winter. The boom was designed to form an ice cover during every winter of the Keeyask project construction from 2014 to 2020. The boom should also resist the ice during the freeze up, the winter and the ice breakup.

The Test Ice Boom was installed in the fall of 2013 and successfully formed an ice cover by December (Figure 2). The winter of 2013/2014 was the coldest on record in 50 years. The freeze up occurred and an ice cover formed by December 2013. At the end of the winter, the flow was relatively high during the breakup, about 4,600m^3/s (above the 75% percentile). The load on the boom was already high. Ice drifting from far upstream accumulated behind the solid ice cover, which increased the load significantly on the anchors and resulted in their release.

In 2014/2015, the number of anchors was increased and the span width decreased. A relatively rare event occurred on November 9, 2014, during the freeze up. Cold weather combined with high flow conditions as well as wind and snow precipitation resulted in the formation of a very weak ice cover that was comprised largely of slush and snow, that under pressure generated by the current drag compacted and partially blocked the river. Six anchors on the north side of the boom started to release, one each hour, which resulted in the opening of 1/3 of the total boom width and left a gap that was large enough to leave this portion of the river open for the entire winter. The average current velocity was relatively high compared to the 1.2 m/s obtained for the same flow during the summer. This event was described in detail in Abdelnour et al, 2016.

In the fall of 2015, the boom was relocated about 2.5 km upstream where the currents are about 30% less. The boom was redesigned with independent spans to ensure a large scale freeze up anchor release would not occur. It was installed at the two branches of the Nelson River just downstream of Gull Lake (south and north branches, see Figure 4), on either side of Caribou Island. When the freeze up occurred, both booms successfully held the ice the entire winter. In the spring, it was discovered that some of the boom spans opened due to the release of some anchor chains. This indicates that significant loading occurred during the winter (due to possible thermal pressure) or during the spring breakup.

In the fall of 2016, fuse hammerlocks were installed to protect the anchor chains, well below the water surface so they would not be encased by ice and would therefore break before the anchor chains. The addition of the fuses was expected to raise the odds of having more spans release during the breakup than the previous year but in a more controlled fashion. Observations during and after the breakup period in Spring 2017 have indicated that a number of boom spans did release. Engineering assessments are ongoing to determine the mechanism of anchor release. Also, during the 2017 breakup, the Nelson River flow exceeded 7000 m^3/s, which was well above the 5,600 m^3/s design flow. This exceptionally high flow applied load that is higher than the design load on the boom and contributed to the release of the boom spans.

Figure 4: Booms A (right) and B installed in the fall of 2015, 6 km Upstream of Gull Rapids.

2. The Ice Boom Site Conditions

2.1 The Bathymetry

The bathymetry at both boom sites is shown in Figure 5. The water depth at the boom site ranges from 2m to 15m at 153.43m water level elevation. The width of the river at the location of the Test Ice Boom was about 800m at this elevation. The width at Boom A was 484m and at Boom B was 530m.

2.2 The Flow, Currents at the Site

The historical outflow at Split Lake, upstream of Keeyask GS for data collected from 1977 to 2012 for 0 to 100% percentile is shown in Figure 6. The flow in the past four years varied from approximately 3,500 m^3/s to over 7,000 m^3/s in 2017 (Note: spring 2017 inflow values are still under review by Manitoba Hydro).

The current velocity distribution was obtained from a simulation of the river with an inflow of 5,600m^3/s and an ice thickness of 1m (Figure 8). A flow split of 60% south channel / 40% north channel was considered appropriate for this simulation. The average current velocity upstream of the booms ranges from 0.7 to 0.9 m/s.

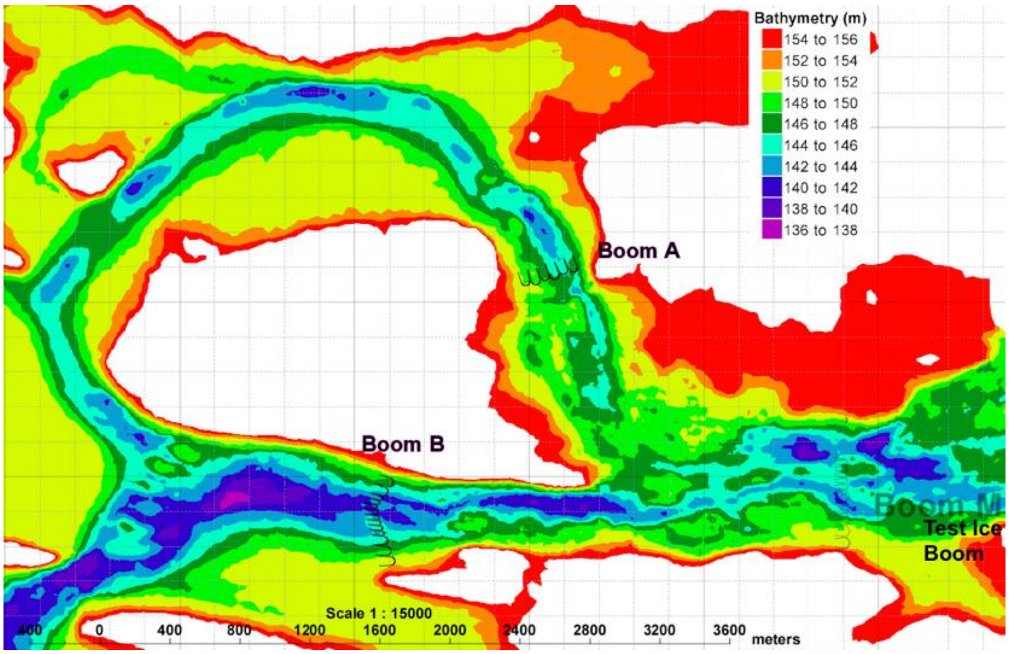

Figure 5: The Bathymetry at the Ice Boom Sites.

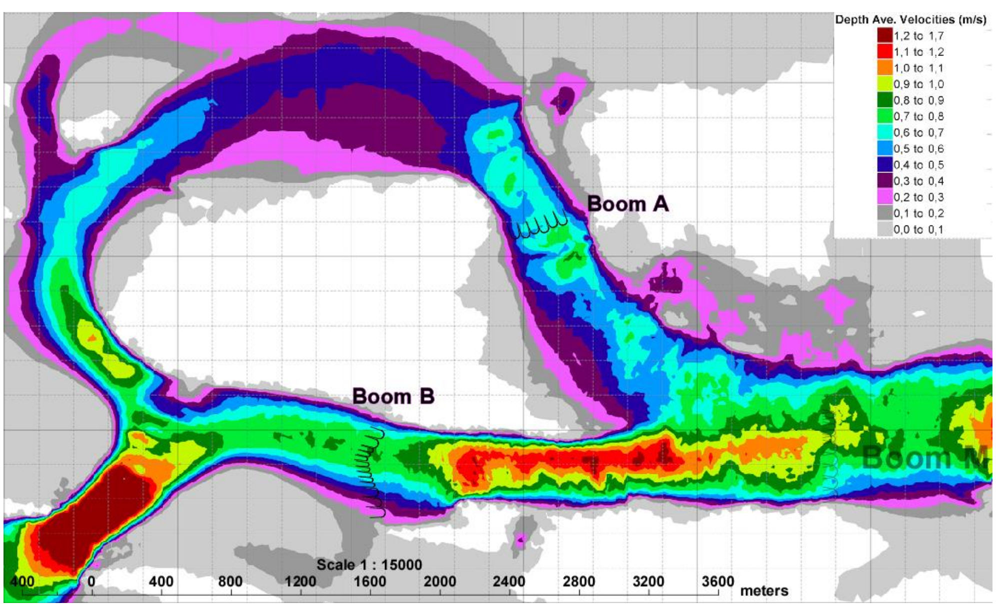

Figure 6: Ice Booms A and B, Current distribution for an inflow of 5,600 m^3/s.

2.3 Ice conditions

Based on observations made over a 5 year period, it was found that the ice at the selected boom sites does not form every year. The ice thickness depends on the air temperature, the current velocity and the snow precipitation. The winter of 2013/14 was the coldest on record since 1969 and reached 3,700 freezing degrees-days. The winters of 2015/16 and 2016/17 were the warmest years on record and reached less than 2,500 freezing degrees-days. The calculated maximum ice thickness in the river reach for all years should be between 0.75 and 1.00 m but is expected to vary significantly due to a number of environmental factors (namely, water velocity and weather).

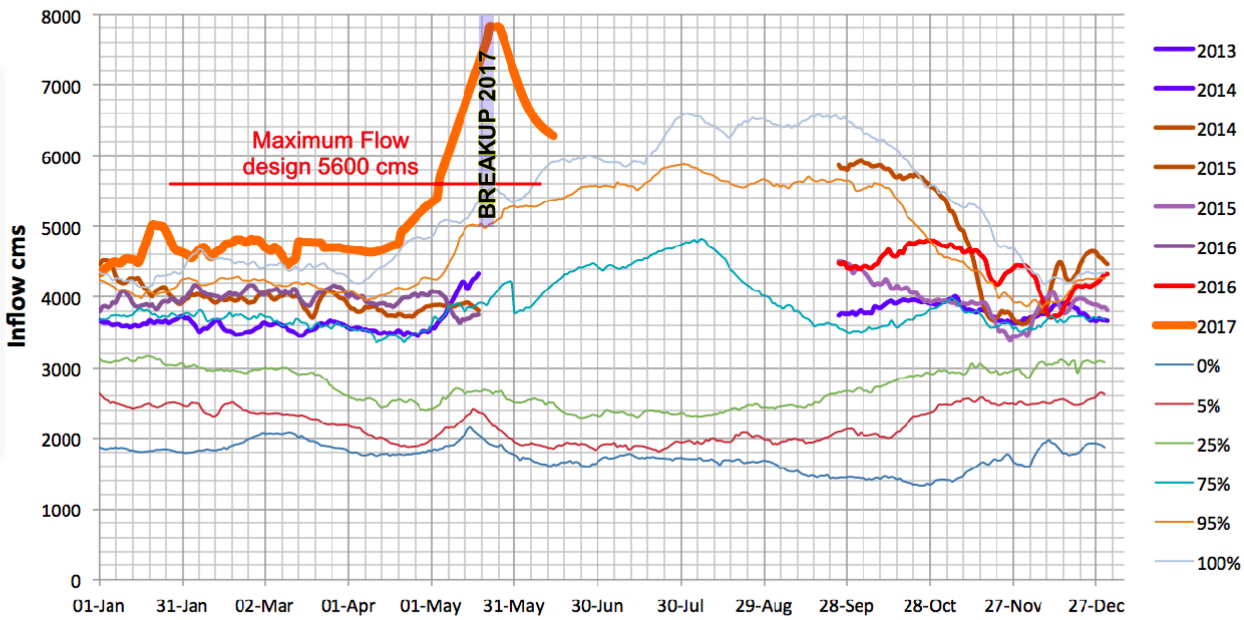

Figure 7: Historical Split Lake Daily outflow for the Nelson River (between 1977 to 2012) for 0 to 100% percentile and during the ice seasons from 2013 to 2017 (flow values are under review and not final).

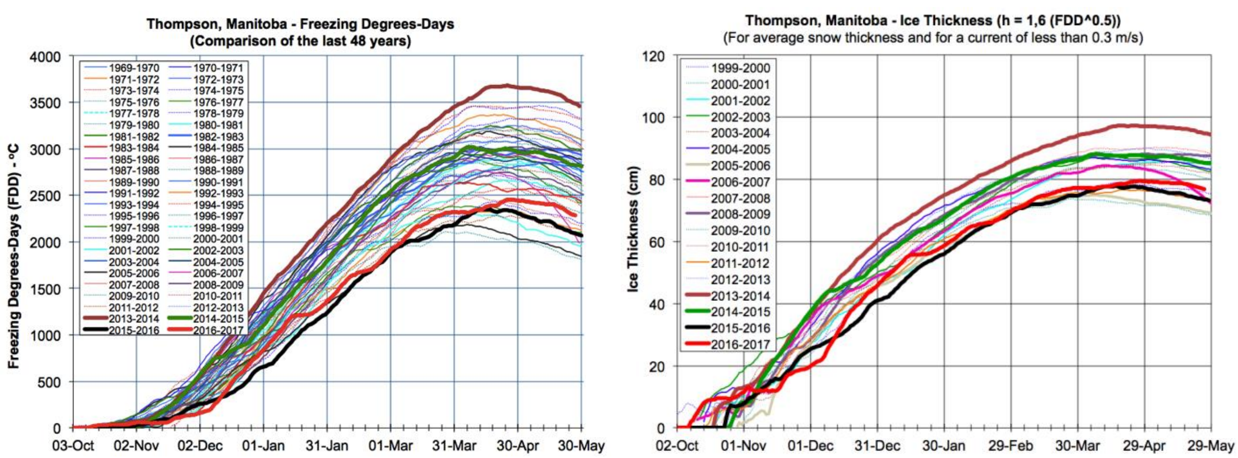

Figure 8: The Freezing Degrees-days 1969 to 2017 and the calculated ice thickness 1999 to 2017 (Thompson, Manitoba.)

3. Final Ice Boom Design in 2015

Ice Booms A and B were redesigned in the summer of 2015. Ice Boom A was installed in the north channel and B in the south channel. The site selection was optimized to minimize the river width (and the associated contributing cross-sectional area) and also minimize the average water velocity upstream of the boom locations.

3.1 Ice Boom A

Ice Boom A had 6 spans; all were 56m wide between the anchors (Figure 9a). The span had a 70m long cable and seven pontoons on each span. The ice boom spans were installed side by side to ensure coverage of most of the river width. To avoid any contact between the anchor cables of each span, and to ensure that the anchors are not at the same location, a 10m distance separated each two anchor points in the direction of the currents. Each span has two anchors that are completely independent from the adjacent spans. The span cables are 1.75” in diameter and are 50 m long. . The anchor chains are grade 80 and 1.25” in diameter.

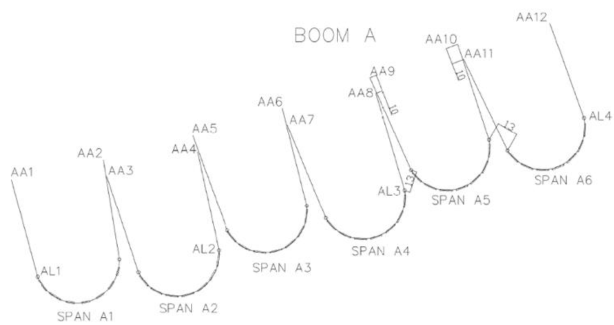

Figure 9a: Ice Boom A – All boom span widths are 56 m between the anchors.

The load on Ice Boom A was calculated for an inflow of 5,600m^3/s (Table 1). The average current velocity would be 0.65m/s (see Figure 6). This assumes that 40% of the Nelson River flow, 2,240m^3/s of the 5,600m^3/s, will pass through this stretch of the river. The calculated loads for three levels of ice roughness are shown in Table 1. The maximum load on each anchor is 608kN (for the highest roughness) and the minimum safety factor before the fuse will break is 1.83 (770 kN fuse strength used).

Table 1: Calculated Load on Ice Boom A

Options	Ice Roughness	Span Width	Max River Discharge	Apex Angle	Effective Area	Wind Speed	Current upstream	Force on the Boom	Line load on Boom	Number of Spans	Load on the Span	Number of Anchors	Load on the Anchors	Safety factor Anchor chain	Safety factor Fuse
		(m)	m^3/s)	(Deg.)	(m^2)	(km/hr)	(m/s)	(kN)	(kN/m)	(-)	(KN)	(-)	(KN)	(1.25")	(1.00" mod)
															770 KN
Boom A	Smooth	484	5600	20	318100	74	0.65	3261	6.7	6	544	12	272	4.68	2.83
Breakup	Average	484	5600	20	318100	74	0.65	5277	10.9	6	880	12	440	2.89	2.52
40/60 split	Rough	484	5600	20	318100	74	0.65	7293	15.1	6	1216	12	608	2.09	1.83

3.2 Ice Boom B

Ice Boom B has 13 spans; eight spans are 28m wide between the anchors and five outer spans are 56m wide between the anchors (Figure 9b). The 28m wide spans had a 35m long span cable and four pontoons on each span. The 56m wide span has a 70m long span cable and seven pontoons on each span.

The ice boom spans are installed side by side to ensure covering the entire river width. To avoid any contact between the anchor cables of each span, and to ensure that the anchors are not at the same location, a 10m distance separated these anchor points in the direction of the currents as shown in Figure 9b.

Each span has two anchors that are independent from the adjacent spans. The span cables are 1.75” in diameter and 50 m long. The anchor chains are 1.25” diameter, grade 80 steel.

The load on Ice Boom B was calculated assuming the total inflow is 5,600m^3/s. The average current velocity under the contributing area for this inflow is 0.62m/s. This assumes that 60% of the Nelson River flow, 3,360m^3/s of the 5,600m^3/s, will pass through this stretch (main channel) of the river. The loads on Ice Boom B are calculated as shown in Table 2.

The load on Ice Boom B is also calculated assuming the current velocity will increase due to a higher share of the flow splitting from 60% to 70% through the south channel due to the ice formation in the north channel. The current velocity for this inflow is calculated to be 0.73m/s. The loads on Ice Boom B for this case are also calculated in Table 2.

For both cases, the ice loads for the worst ice roughness would not exceed 423kN/anchor. The safety factor before the fuse would fail (770 kN fuse strength) is 2.62 for the 70/30-split scenario.

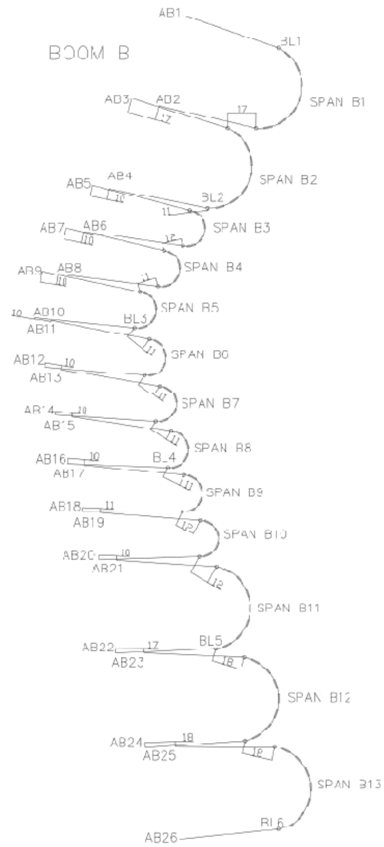

Figure 9b: Ice Boom B – 8 spans, 28m wide, and 5 spans, 56 m wide between the anchors.

Table 2: Calculated Load on Ice Boom B

Options	Ice Roughness	Span Width	Max River Discharge	Apex Angle	Effective Area	Wind Speed	Current upstream	Force on the Boom	Line load on Boom	Number of Spans	Load on the Span	Number of Anchors	Load on the Anchors	Safety factor Anchor chain	Safety factor Fuse
		(m)	m^3/s)	(Deg.)	(m^2)	(km/hr)	(m/s)	(kN)	(kN/m)	(-)	(KN)	(-)	(KN)	(1.25")	(1.00" mod)
															770 KN
Boom B3	Smooth	530	5600	20	391747	74	0.62	3733	7.0	13	287	26	144	8.85	5.36
Inflow	Average	530	5600	20	391747	74	0.62	6003	11.3	13	462	26	231	5.51	3.34
60/40 split	Rough	530	5600	20	391747	74	0.62	8273	15.6	13	636	26	318	4.00	2.42
Boom B3	Smooth	530	5600	20	391747	74	0.73	4826	9.1	13	371	26	186	6.85	4.15
Inflow	Average	530	5600	20	391747	74	0.73	7916	14.9	13	609	26	304	4.18	2.53
70/30 split	Rough	530	5600	20	391747	74	0.73	11005	20.8	13	847	26	423	3.00	1.82

3.3 The Pontoon Size

The pontoons were 7.5m long for Boom A and 5m long for Boom B. The buoyancy force of both pontoons, is almost equal as the Pontoons of Boom B are 36” in diameter while the Boom A pontoons are 30” in diameter. However, the shorter pontoons will provide more space between them to allow the slush and snow-ice to pass through more easily and prevent a blockage similar to the event of September 9, 2014 (Abdelnour et al, 2016). Figure 10 shows a sample of the 5m long pontoon drawing. These pontoons when installed on a 28m wide span, with 35m long span cables will produce 16.8kN/m of ice resistance during the freeze up period. The resistance of each 28m wide span is calculated to be 470kN.

Three pontoon chains were used for the 5m long pontoon and four pontoon chains were used for the 7.5m long pontoon. Attachment points on the top of the pontoons were added for handling purposes.

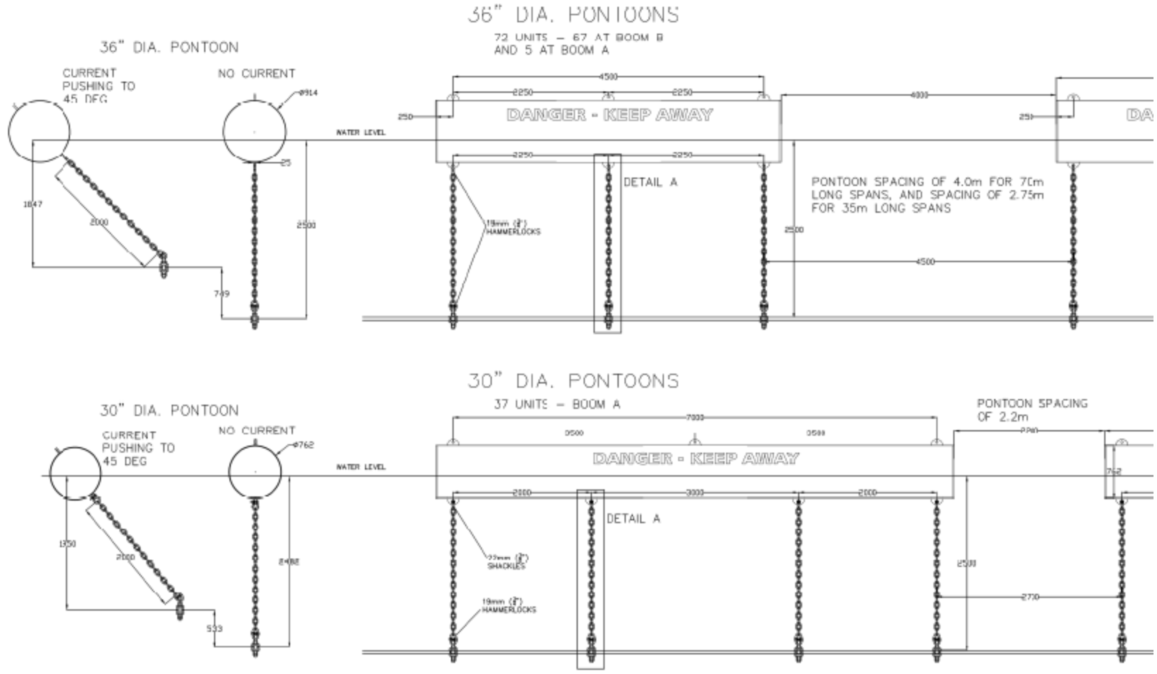

Figure 10: Boom A: Pontoons, 7.5m long, 30" diameter & Boom B: Pontoons, 5m long, 36" dia.

3.4 Other Ice Boom Components

Four junction plates are used to connect the span cable and the two anchor cables. A buoy is used to hold the span junction plates close to the water surface. The two junction plates serve to connect the each two spelter sockets installed on each end of the span cable to the two anchor cables (Figure 11).

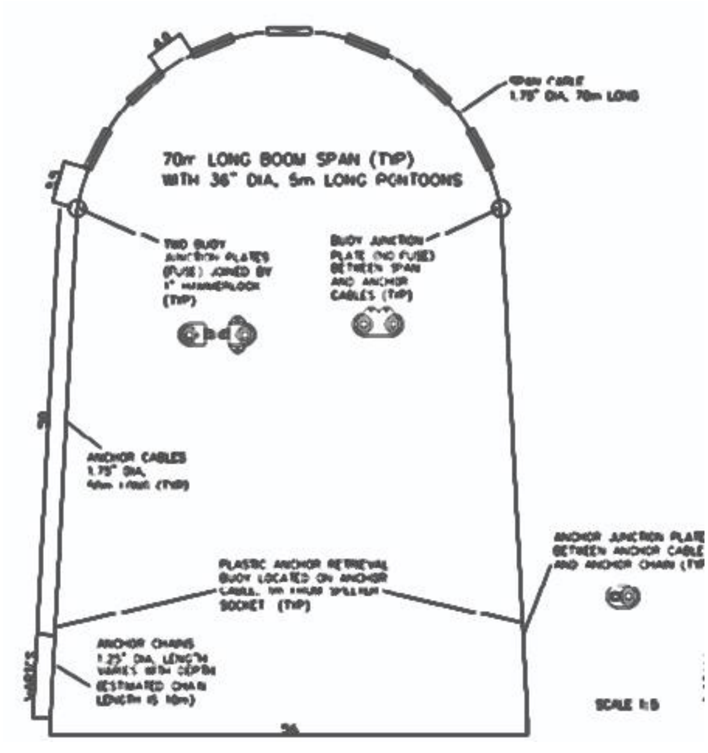

Figure 11: One Complete Span 56 m wide

A modified 1" hammerlock (Custom made) was used as a fuse. It was installed on one side of all spans of both boom A and B (Left span junction plates only). A Grade 100, 1" hammerlock was machined and tested to fail at 770KN or about 20% less than the grade 80, 1.25" chain, which failed during testing at 870kN (Ecole Polytechnique, Willem and Bouaanani, 2015).

A similarly modified 1" hammerlock was used as a fuse on the anchor junction plate as well. It was installed on one side (opposite side of other fuse) of all spans of both boom A and B (Right anchor junction plates only).

3.5 Safety Factors of the Components Resistance

The resistance capacity of each component used for the ice boom anchors is shown in Table 3. The factor of safety of each component relative to the ice loads is noted in the force calculation of all booms for the freeze up and breakup conditions.

The breaking strengths are used here, as the safety factors are easier to understand when applied to the entire system, and not just the individual components. For example Table 4 shows a calculation of loads on Ice Boom A. The safety factors are shown for both the anchor cables and anchor chains, which are the critical components of the Ice Booms.

Table 3: The components of the Ice Boom anchor Systems and their breaking strengths.

Components Average force on each span	Breaking Strength	
	kN	Tonnes
Anchor (5.5 m in competent rock)	5000	*510*
Dywidag Bar (65mm)	1747	*178*
Coupler weld (1.25" link)(To be inspected)	1300	*133*
Chain 1.25" Grade 80 (Polytechnique tests)	870	*89*
Hammer lock 1.25" (grade 80)	1271	*130*
Hammerlock 1" (Grade 100) (Custom Fuse)	770	*78*
Steel Anchor Cable 1 3/4"	1408	*144*
Spelter Socket 1 3/4" (larger than)	1408	*144*
Anchor Junction Plates (calculate)	3560	*363*

4. Comparison between the calculated load for the design and the actual ice break up

The 2017 ice breakup occurred between May 18 and 26, 2017. The flow was greater than 7,000m^3/s. The water level was approximately 156 m. The ice was still solid and firmly bonded to the booms (Figure 12).

Figure 12: Pictures of Boom A (left) and B taken May 18, 2017.

The calculated ice loads for the design assumptions and the actual conditions are shown in Table 5. The safety factor calculated for the fuse was 1.82 for the highest ice cover roughness. The flow increase almost doubled the loads on the spans and reduced the safety factor of the boom resistance to less than 1 (for the rough ice conditions).

Table 4: Calculated load on the boom for the design and during the ice breakup of May 2017

Options	Ice Roughness	Span Width	Max River Discharge	Apex Angle	Effective Area	Wind Speed	Current upstream	Force on the Boom	Line load on Boom	Number of Spans	Load on the Span	Number of Anchors	Load on the Anchors	Safety factor Anchor chain	Safety factor Fuse
		(m)	m^3/s	(Deg.)	(m^2)	(km/hr)	(m/s)	(kN)	(kN/m)	(-)	(KN)	(-)	(KN)	(1.25")	(1.00" mod)
Boom B	Smooth	530	5600	20	391747	74	0.73	4826	9.1	13	371	26	186	6.85	4.15
Design	Average	530	5600	20	391747	74	0.73	7916	14.9	13	609	26	304	4.18	2.53
70/30 split	Rough	530	5600	20	391747	74	0.73	11005	20.8	13	847	26	423	3.00	1.82
Boom B	Smooth	530	7830	20	391747	33	1.01	8194	15.5	13	630	26	315	4.03	2.44
Breakup 2017	Average	530	7830	20	391747	33	1.01	14235	26.9	13	1095	26	547	2.32	1.41
70/30 split	Rough	530	7830	20	391747	33	1.01	20275	38.3	13	1560	26	780	1.63	0.99

Figure 13: Pictures of Boom A (left) and Boom B taken May 22, 2017.

Figure 14: Boom A, May 26, 2017. (Boom B was almost completely released that day).

5. Conclusions

The results of four years of operation shows that an ice boom can be effective in forming an ice cover in northern rivers. The last two years of the four years of operation, an ice cover formed and was effective in reducing the frazil volume to a point where an acceptable water level rise due to the hanging ice dam downstream of Gull Rapids was achieved.

The effect of thermal expansion of the ice and the associated pressure was not considered in this paper (Comfort et al, 1996). However, due to the observed large temperature changes that occurred in a very short period of time, thermal expansion could generate very high pressure. If the anchoring system is stretched to its limits during the ice formation where the currents are high, and remains so during the winter, that would generate high thermal loads that would fail the fuses and/or other boom components. In this case, the ice and the boom will remain in place but will release only during the breakup.

The results also showed, that for a south to north flowing river, the breakup can be challenging for an ice boom to resist the ice push, as the competent ice could remain bonded to the boom and its components during the highest breakup loads. Additional anchor points and larger diameter chains would be possible to use but was not possible considering the longer construction period and the time constrains. Fuses placed at strategic locations along the boom cables/chains, well below the ice surface, could help to prevent them from being damaged. This will require ongoing maintenance and repair after each severe ice breakup.

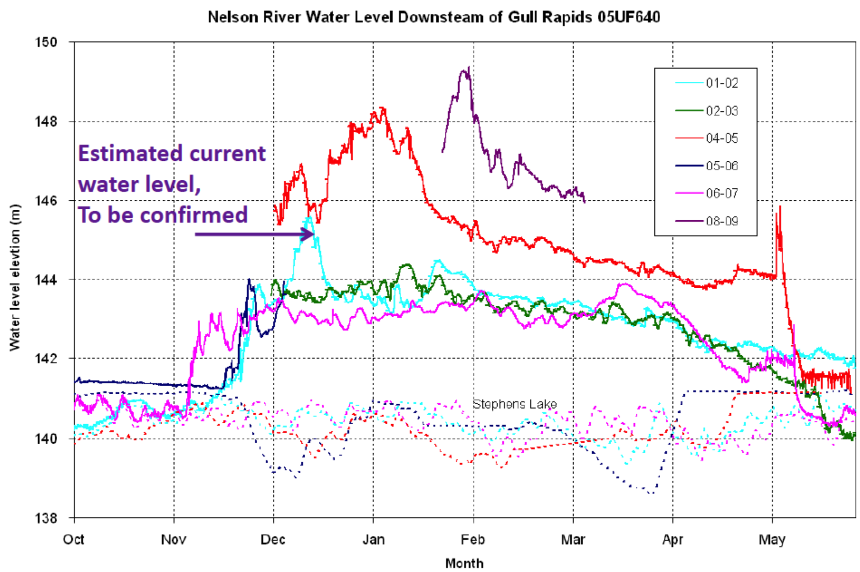

Figure 15: The water level upstream of Gull Rapids due to the Hanging Ice Dam (prior to 2010).

6. Acknowledgement

The authors would like to acknowledge the assistance of Mike Morris, and other Manitoba Hydro team at the Winnipeg office and at the Keeyask construction site for their support during the execution of the project. We also acknowledge Peter Kenny and his team of M. Sullivan and Son Ltd. who installed the boom.

7. References

Abdelnour, R., Abdelnour, E., Robert, E., and Malenchak, J., (2016) Ice Boom Performance: Rare Release Events During Early Freeze-up. 23nd IAHR International Symposium on Ice, Ann Arbor, Michigan USA, May 31 to June 3, 2016

Abdelnour, E., Comfort, G., Abdelnour, R., Malenchak, J., (2012) Design, Fabrication, and Deployment of an Ice Boom at Jenpeg Generating Station. Canadian Dam Association 2012 Annual Conference, Saskatoon, SK, Canada, September 22-27.

Comfort, G., Abdelnour, R., Gong, Y., and Dinovitzer, A., (1996), Field Observations of Static Ice Loads on Hydroelectric Structures and the Mechanism Producing them, IAHR Ice Symposium, 1996, Beijing, China, August.

D.V. Bonin and J.L. Groeneveld “Keeyask Generating Station␟Stage IV Studies, Axis GR-4␟Ice Boom Design” ␟Memorandum GN-4.3.7, Rev 6␟Manitoba Hydro File 00195-13800-0007_07, May 18, 2011

X. Willem and N. Bouaanani. Tension tests on chains, Shackles and Hammerlocks. Ecole Polytechnique, June 2015.