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Frazil or Anchor Ice Blockage of Submerged Water Intakes?

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Historically, ice blockages of water intakes have been called "frazil ice blockages" or simply "ice blockages." In this paper, we posit that ice blockages of submerged intakes share many characteristics with anchor-ice accumulations, and indeed essentially comprise anchor ice. Anchor ice is initiated by frazil formation and is a derivative of frazil growth. The extent to which frazil accumulation or anchor ice growth predominates depends largely on the net effect of several factors associated with ice blockage events, including prevailing atmospheric thermal and moisture conditions and, importantly, water flow conditions. Our analyses suggest that, in certain water conditions (notably, relatively shallow water) frazil predominates whereas in others (deep water) anchor ice predominates; and, in mid-range water depths both frazil accumulation and anchor ice growth vie for predominance. The shared characteristics of frazil accumulation and anchor ice growth enable ice formation processes to occur more-or-less together. Field reports of anchor ice on river and lake beds indicate the presence of accumulated frazil as well as the obvious in situ growth of ice crystals, especially in deeper water. We discuss the processes and flow-depth situations producing frazil and anchor ice, and relate them to intake types. Our discussion uses published studies of intake blockage, frazil formation, and anchor ice growth, and makes extensive use of our own observations from the Laramie River in Wyoming. We conclude there is much more to learn more about how both processes combine and block intakes. Moreover, we point out that, during freeze-up conditions, partially submerged intakes often block with drifting ice slush, which we also posit is largely derived from anchor ice.

1. **Introduction**

There is a long published record of ice blockage of water intakes (e.g. Altberg 1936). Historically, ice blockages of water intakes have been called “frazil ice blockages” or simply “ice blockages.” Titles of research papers describing the results of frazil blockages of intakes include “Frazil – the invisible strangler” (Foulds and Wigle 1977), “Frazil ice blockage of intake trash racks” (Daly 1991), “Laboratory investigation of trash rack freezeup by frazil ice” (Andersson and Daly 1992), “Frazil ice blockage of water intakes in the Great Lakes” (Daly and Ettema 2006), “Frazil ice concerns for channels, penstocks, siphons, and tunnels in mountainous regions” (Ettema et al. 2009), and “Multiple frazil ice blockages of a water intake on the St Lawrence River” (Richard and Morse 2008). These titles suggest that frazil is the prime culprit in intake ice blockages. While acknowledging frazil is a necessary precursor for an ice blockage, we posit that ice blockages share many characteristics with anchor ice accumulations.

We discuss this suggestion, and also make the point that river-intake blockages involving drifting slush ice (one might say “debris” blockages, as with blockage by vegetation) often largely comprise detached anchor ice accumulations. Ice blockages of water intakes are an extension of the commonly-occurring phenomena of anchor ice formation in turbulent water bodies. This point is not just a matter of semantics, but opens an important clarifying insight into how intakes block.

Our discussion focuses on fully submerged water intakes, though we identifying the two main types of water intake (Figure 1A&B): fully submerged and partially submerged. This distinction is important, because the former intake type accretes ice from within the water column, whereas the latter (sometimes called an intake crib) additionally attracts drifting ice. Fully submerged intakes occur in large water bodies, notably lakes, while partially submerged intakes are used for rivers as well as large water bodies. We argue that ice blockages at both intake types are primarily anchor ice blockages.

2. The Difference between Frazil and Anchor Ice

We take an old-school approach when defining anchor ice and frazil, using the definition proposed by Barnes (1906, p.109): “The term anchor-ice we shall use to designate all ice found attached to the bottom, irrespective of nature of its formation. Thus, frazil becomes anchor-ice when it attaches to the bottom. The birth of frazil is in the water itself by surface-cooling, through wind or rapid agitation, and by radiation.” This statement contains important inferences and concepts. Anchor ice is defined by its attachment to the bottom, not by its method of initial formation. Barnes, along with later authors, take a broad view of what constitutes “bottom”, including sticks and other debris that extend up into the water column. Thus, a mass of ice crystals on a submerged stick is “anchor ice”. An analogous argument could be advanced for ice blockages; i.e., the ice is attached to the “bottom” (an intake structure); so it is properly designated as anchor ice. Frazil, by contrast, is born in the water column. It remains “frazil” only as long as it is suspended in the water column. Barnes is insistent that a distinction be made between frazil and anchor ice, stating: “. . . and it cannot be too strongly emphasized, the importance of adhering to this distinction, for clearness of expression.” Although we agree that it is important to make this distinction, it is also important to remember that most, if not all, anchor ice is a derivative form of frazil.

3. Comparing Anchor Ice and Ice Blockages

In this section we compare and contrast morphology of ice making up anchor ice and ice blockages of intakes. The comparison includes conditions leading to formation of both forms of ice, the morphology of these ice forms, locations where they accumulate, and reflections on the concurrence of ice blockages and anchor ice formation. For the moment we do not address "debris" blockages resulting from drifting slush ice.

Conditions leading to frazil blockages and anchor ice formation. The conditions described in the literature for so-called frazil ice blockage of intakes (Daly 1991; Daly and Ettema 2006; Foulds and Wigle 1977; Richard and Morse 2008) are identical to the conditions necessary for anchor ice formation (e.g., Altberg 1936; Arden and Wigle 1972; Barnes 1906; Stickler and Alfredsen 2009; Tesaker 1994; Wigle 1970). This is not surprising, as both frazil blockages and anchor ice are derivative forms of frazil; frazil is the first, necessary condition for the formation of these derivative ice types. Therefore it is understandable that ice blockages are commonly termed frazil blockages.

Frazil forms when the water column is supercooled by a few hundredths of a degree (Daly 1984). Supercooling of the water column requires large heat loss rate from the water to the atmosphere, which in turn requires frigid air temperatures, turbulent flows, open water, and, usually, cold, clear nights. Daly (1991) points out that the association of frazil production and open water is so strong that intakes blockages will only occur if there is no surface ice cover. Frazil, small, disk-shaped ice crystals, are carried with the supercooled water to the bottom. Frazil suspended in supercooled water is "sticky", and will stick tenaciously to any object it comes in contact with, including other ice (forming frazil flocs and pans), intakes (causing ice blockages), and the bottom (forming anchor ice masses).

Anchor ice forms by initial frazil adhesion to the bed, then continues to grow by a combination of continued frazil accretion and in-situ ice growth; i.e. continued growth of ice crystals already attached to the bed. It is the in-situ growth that accounts for variations in anchor ice crystal morphology, the strength of an anchor ice mass (by the inter-growth of ice crystals), and the strength of the bond between the anchor ice mass and the substrate. Thus, it is in-situ growth that allows anchor ice to grow to a size sufficient to form rafts of slush ice when released. The portioning of accretionary ice and in-situ ice growth in any particular anchor ice sample is contained in its ice crystal morphology. This story, though, has yet to be fully unraveled and properly told; it involves the tricky task of thin-sectioning anchor ice. Dubé et al. (2014) have made exciting strides in unraveling this story through their application of CAT-scan technology.

When the water column is no longer supercooled (usually during daylight hours), anchor ice releases from the bed and floats to the water surface to form drifting slush ice. In a similar fashion, frazil blockages only occur when the water is supercooled; frazil in water at the freezing point is "passive," i.e. not sticky. Because of this, ice blockages (and anchor ice masses) formed at night often release in the morning when water warms to the freezing point. The addition of heat to the water column can be very useful for suppressing both frazil blockages (Daly 1991) and anchor ice accumulation (Daly 1994).

Morphology and porosity of frazil blockages and anchor ice. Ice morphology can be considered from two different, but related, perspectives: the overall (or gross) morphology of the ice mass, or the morphology of individual ice crystals. The gross morphology of frazil ice blockages is very poorly understood, because (surprisingly!) pure frazil blockages are rarely observed. From a series of laboratory experiments using trash racks, Andersson and Daly (1992) report that ice blockages begin with initial bridging at the water surface, and the ice blockage grows both downward and upstream through time, eventually bridging between rack bars and occluding the trash rack surface. Daly (1991) reports that frazil accumulates almost exclusively on the upstream side of trash racks, although pressure differential across the trash may extrude the frazil accumulation through the trash rack bars. Kempema and Ettema (2013) collected time-series images of ice growth on a small portion of wedge wire screen placed in the Laramie River. They found that the morphology of ice crystals varied with changing flow and weather conditions (Figure 2A&B). Like Daly, they found that ice blockage accumulations collected predominately on the outside of the metal screen elements. At times, these ice accumulations reached 20 cm in thickness (Figure 2B).

The ice blockages described by Andersson and Daly (1992), Daly (1991) and Chen et al. (2004) consisted mainly of accreted, fine-grained frazil crystals (Figure 3). Frazil crystal morphology is well characterized in the literature. Kempema and Ettema (2013) found that the original ice accumulation in their study consisted of frazil crystals adhering to wedge wire screen elements. However, these crystals grew rapidly once they were attached to the screen (through in situ growth), with most crystals losing their characteristic disk shape. At the extreme end of are the crystals making up ice blockages of Great Lakes intakes (Daly and Ettema 2006; Daly and Kempema 2010; Foulds and Wigle 1977). In this environment, the ice blockage crystals are very large (Figure 4), suggesting that ice mass grew predominately through the process of in situ growth. Chen et al. (2004), in contrast, show in lab ice-tank experiment how at small-scale a blockage can occur from frazil accumulation, though crystals in the accumulation exhibited slight growth (Figure 5A&B).

The gross morphology of anchor ice has been studied in lab experiments (Doering 2002; Kerr et al. 2002; Qu and Doering 2007). These experiments document the initial formation and morphology of anchor ice masses. Kerr et al. (2002) report that initial anchor ice formed by frazil attachment to the bed, but as anchor ice masses grew, they developed into tails, scales, or balls by accumulation of more frazil. Observations in rivers (Dubé et al. 2014; Kempema et al. 2008; Kempema and Ettema 2009; Stickler and Alfredsen 2009; Stickler et al. 2010) show that these initial morphologies can grow into mats, dams, flumes, and other forms that can have profound effects on stage, discharge, and sediment reworking.

As with frazil blockages, there is some controversy associated with the major growth mechanism of anchor ice masses, which in turn affects the crystal morphology in the mass. Several researchers have concluded that, in rivers, increases in anchor ice mass occur predominately through accretion of frazil ice crystals from the flow (Doering et al. 2001; Hirayama et al. 2002; Kerr et al. 1997; Kerr et al. 2002; Qu and Doering 2007). In a discussion, Tesaker (1999) questions whether any anchor ice mass can consist of only frazil accumulation. He points out that frazil can only accumulate, increasing anchor ice mass, in supercooled water. He concludes the necessity of supercooled water for frazil accumulation is an indication of in-situ (or thermal) growth. Fluvial anchor ice cannot grow only through frazil accumulation. Some in situ growth is required to stick the accumulating frazil crystals together, and crystals bathed in supercooled water will continue to grow. Evidence of in-situ fluvial anchor ice growth is not always hard to discern. Kempema et al. (2008), Wigle (1970), Osterkamp and Gosink (1983), and Altberg (1936) all observed large, irregularly shaped ice crystals indicative of in situ growth in riverine anchor ice samples. The few lacustrine anchor ice observations suggest that individual ice crystals grow even larger in lake settings (Figure 4). Foulds and Wigle (1977) report diver's observations of anchor ice on the bed of Lake Erie around a water intake at 7.6 m water depth. These ice crystals measured up to 3.8 cm by 2.5 cm by 0.3 cm. Kempema et al. (2001) found anchor ice masses with individual crystals up to 10 cm in diameter along the west shore of Lake Michigan. Based on the delicate structure of these masses, they concluded that these large anchor ice crystals only grew under relatively calm conditions generating turbulence that advected supercooled water, but very few ice nuclei, to the lake bed. In this regard it is worth noting that blobs of water supercooled to, say, -0.01^{o}C, is essentially neutrally buoyant compared to buoyant frazil crystals, and thus more readily dispersed within the water column than frazil crystals.

Anchor ice porosities vary over roughly the same range as the porosities of so-called frazil blockages, though there are very few reported porosities of ice blockages. Dube et al. (2014) report porosities of 24% to 48% for anchor ice samples collected in the Montmorency River in Quebec. Stickler and Alfredsen (2009) found porosities ranging from 2% to 61% for two different types of fluvial anchor ice. In their laboratory studies, Qu and Doering (2007) produced anchor ice with porosities ranging from 58% to 88%. Andersson and Daly (1992) collected 20 porosity measurements in their lab experiments on intake blockage. They report porosities ranging from 39% to 92%, with a mean value of 67%. Kempema and Ettema (2013) collected 12 porosity samples during their wedge wire screen experiments. Their sample had porosities ranging from 42% to 68%, with a mean value of 53%. The porosities of accumulated frazil in the experiments by Chen et al. (2004) increased from about 0% to about 70% to 60% when frazil fully enveloped the model intake screen; then dropped to about 10 to 15% when the screen collapsed into the intake, consolidating accumulated ice (Figure 5A&B). These values are averages, as porosity decreased at locations of higher flow velocity into the model intake.

Our evaluation of ice crystal morphology and porosity of anchor ice samples versus so-called frazil blockages shows that there is a wide range of variation for both of these ice forms. Their ice crystals may be fine- to coarse-grained, ranging from less than 1 mm to more than 10 cm in diameter. In fact, the variation between anchor-ice samples collected at different times, of from different locations, is at least as great as the variations found between anchor ice samples and frazil ice blockage samples. This wide range is attributable to the extent of ice crystal growth once a frazil crystal attaches to an anchor ice or intake accumulation. More work is needed to characterize ice crystal size and composition of anchor ice and ice blockages.

Concurrence of anchor ice and frazil blockages. As discussed above, the same conditions lead to so-called frazil blockage of intakes and anchor ice formation, and it is difficult, if not impossible, to distinguish between ice crystals formed on an intake, and ice crystals formed in an anchor ice mass. It therefore seems likely that frazil blockages and anchor-ice accumulations on the bed occur together, and indeed comprise the same essential phenomenon. But it is hard to find much information on this point. In part, this is because plant operators concerned with ice blockages do not care about what is happening on the bed, and researchers studying anchor ice usually are not near a water intake. However, we found four reports of concurrence of frazil blockages and anchor ice formation on the adjacent bed. Two reports are from rivers and two are from the Great Lakes.

Richard and Morse (2008) studied intake blockages of the municipal water intake for the city of Quebec. They inferred anchor-ice blockages based on signal attenuation of their Ice Profiling System, an instrument package designed to measure water depth and ice floe thickness. When anchor ice grew to more than 30 cm thickness, the IPS signal was completely attenuated. Richard and Morse report 14 partial or complete anchor ice events based on signal attenuation during the winter of 2005/2006 along with 35 ice blockage events of the municipal water intake. Unfortunately, their system gave no indication of the nature of either the anchor ice on the bed or the ice comprising the associated ice blockages. Kempema and Ettema (2013) found that anchor ice and ice blockage of their wedgewire screen occurred together regularly (Figure 6). When ice samples from the bed and from the wedgewire screen were placed side by side, they could not distinguish between them (Figure 3). They noted that ice blockages occasionally formed on the wedgewire screen, but not on the bed, but they saw no occurrence when anchor ice was found on the bed but the screen was ice free. Foulds and Wigle (1977) relate a diver's report that the lake bed around an intake crib in 7.6 m-deep water, along with the location buoy chain, were covered with anchor ice crystals when the diver make an inspection dive on the ice-blocked crib. The ice crystals on the bottom had a similar morphology to the crystals clogging the intake. Further evidence of the concurrence of anchor ice and ice blockages also comes from a video collected in January 2008. This video was made by a public utility to collect information on a frazil blockage of a wedge wire screen intake on the west shore of Lake Michigan (https://www.youtube.com/watch?v=COMV3UEE47A). In addition to the spectacular images of the intake blockage (Figure 4), the video shows small, widely scattered patches of anchor ice resting on the lake bed. The patches are small, but the ice crystals in the patches appear to be about the same size as ice crystals making up the frazil blockage. These four observations offer evidence of the coincident occurrence of so-called frazil blockages and anchor ice accumulation.

4. Discussion

Existing observations show that anchor ice accumulations and the ice forming ice blockages at water intakes are identical twin sons of the same mother, namely frazil ice. As such, they most likely often form simultaneously near water intakes. The ice comprising both anchor ice accumulations and ice blockage show a wide range of crystal morphologies dependent upon the conditions under which the ice formed. Based on scant observational evidence, it appears that ice in ice blockages and ice on the surrounding bed (either river- or lake-) have similar morphologies, because the same conditions lead to their formation.

Kempema et al. (2008) suggested 15 parameters, reduced to 10 major dimensionless variables could comprise a descriptive model of anchor ice formation. They looked for simple predictive relationships between the largest crystal size observed in an anchor ice sample and Reynolds Number, Froude number, and cooling rate. No significant correlations were found, because of the lack of information regarding several parameters, such as atmospheric moisture conditions during ice formation. Likely, final ice crystal morphology in both anchor ice masses and ice making up frazil blockages, results from a complex interaction of these parameters. This suggestion is reinforced by anchor ice samples that show variation in crystal size from top to bottom through the sample. Tsang (1982) and Ashton (1986) give examples of this ice stratigraphy, with smaller crystals overlying larger crystals. They attribute this grading to the fact that the larger crystals were deposited first, and so were exposed to a supercooled flow longer and could grow to a larger size. Kempema and Ettema (2009) found both increasing and decreasing crystal size with height above the bed in the Laramie River. The change in crystal size was attributed to changing flow and atmospheric conditions throughout the night. For example, a change in cooling rate associated with a passing warm or cold front could change the ice crystal size either reducing or increasing crystal size, respectively as the anchor ice mass grows. Additionally, early season freezing of initially warmer water bodies forces more moisture into the air above the water body, potentially creating a higher volumetric density of seed crystals available to enter the water body. Similarly, a late-night snowfall results in accumulation of fine-grained ice crystals on top of already developed, larger anchor ice crystals.

5. Concluding Comments

The major point of our paper is to emphasize that ice blockages have more in common with anchor ice accumulation than with frazil crystals suspended in the water column. Only one mention of "anchor ice blockages" of intakes was found during our literature review for this paper. Malenchak and Clark (2013), in a reference to Daly's work (1991) note that "… anchor ice has been known to block intakes up to a depth of 20m." However, we do not advocate a push to change the term "frazil ice blockage" to "anchor ice blockage" because at this point we believe this would create undo confusion. By recognizing that frazil ice blockages are a special form of anchor ice, we hope to encourage enlightened communication between researchers interested in these two fascinating processes.

We offer a further, maybe ironic, observation about the similarity of anchor ice and ice blockages. Both Altberg (1936) and Foulds and Wigle (1977) constructed and presented photographs of anchor-ice samplers. In both cases, the anchor-ice sampler consisted of wire mesh trays that were placed on the river- or lake-bed and retrieved at a later time. They essentially made crude intake screens to gather the growing ice masses. This suggests that intake covers are very likely the best anchor ice accumulators, regardless of whether the intake is withdrawing water.

6. Acknowledgment

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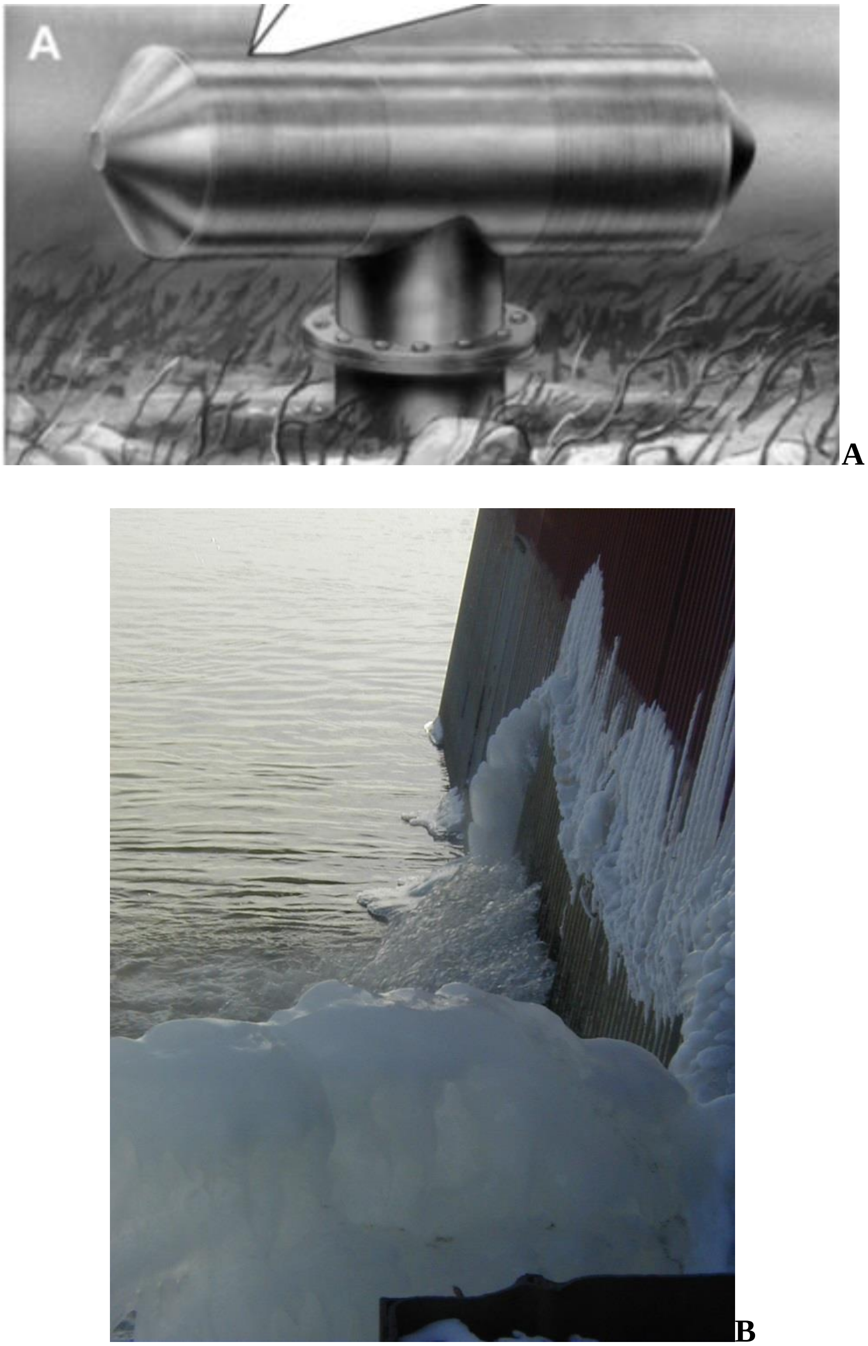

Figure 1. (A) Diagram of a fully-submerged wedge wire screen intake on the bottom. The wedge wire screen is comprised of triangular, small-diameter wire helically wrapped around the outer portions of the horizontal cylinder. Water flows through the screen to the vertical collection pipe. From Amaral (2003). (B) A partially submerged intake for a power plant on the Cedar River, Iowa.

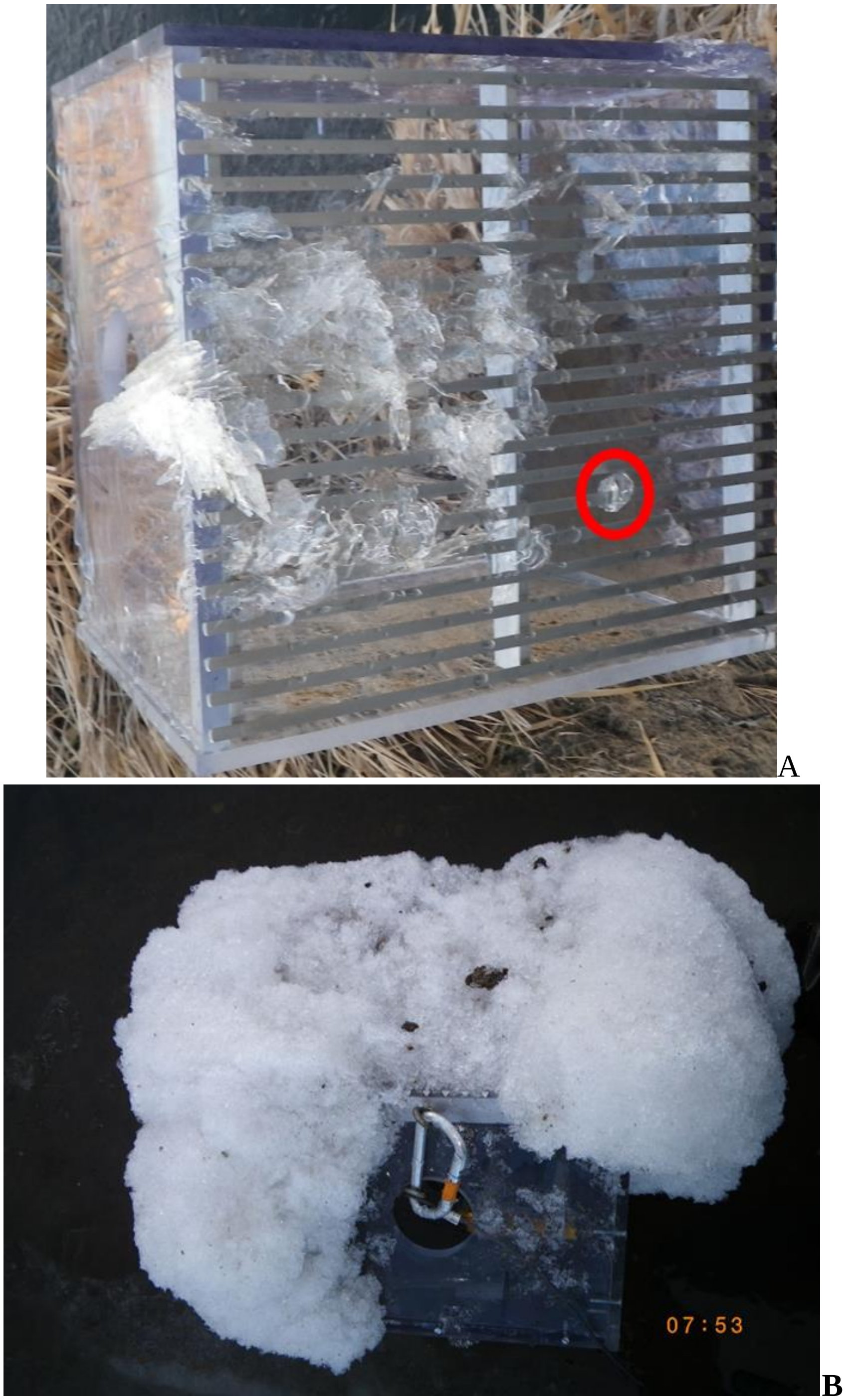

Figure 2. Different ice blockage forms observed durnig wedge-wire box experiment in the Laramie River, WY in 2013. (A) On this night, a relatively few, large, irregularly shaped crystals grew on the wedge-wire screen elements. The ice represents predominately in situ growth. The red circle outlines a crystal that grew completely around the 6 mm wedge wire screen. (B) Accumulation on night when ice grew through a combination of accumulation of frazil from flow and in situ growth. The wedge-wire elements are towards the top in this image, flow was from left to right.

Figure 3. Frazil freshly accumulated onto a screen (background) during an intake blockage tank experiment (from Chen et al 2004). 15 minutes into experiment

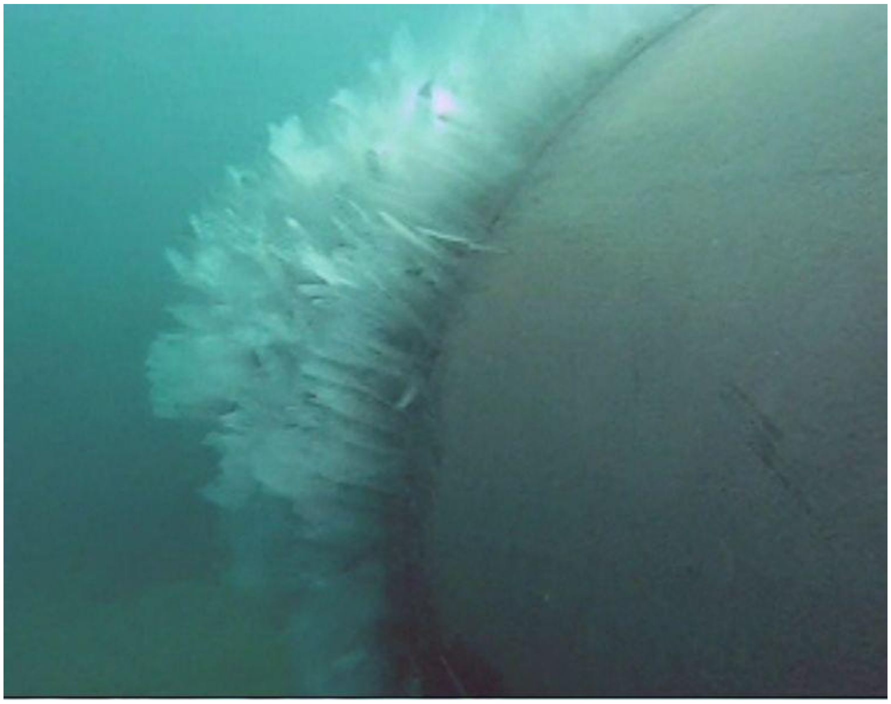

Figure 4. Frazil ice blockage of a wedge wire screen intake at 8 m water depth in Lake Michigan (Figure 1). The wedge wire screen is 1.6m in diameter, individual frazil crystals are > 10 cm long. Image curtesy of Manitowoc Public Utilities.

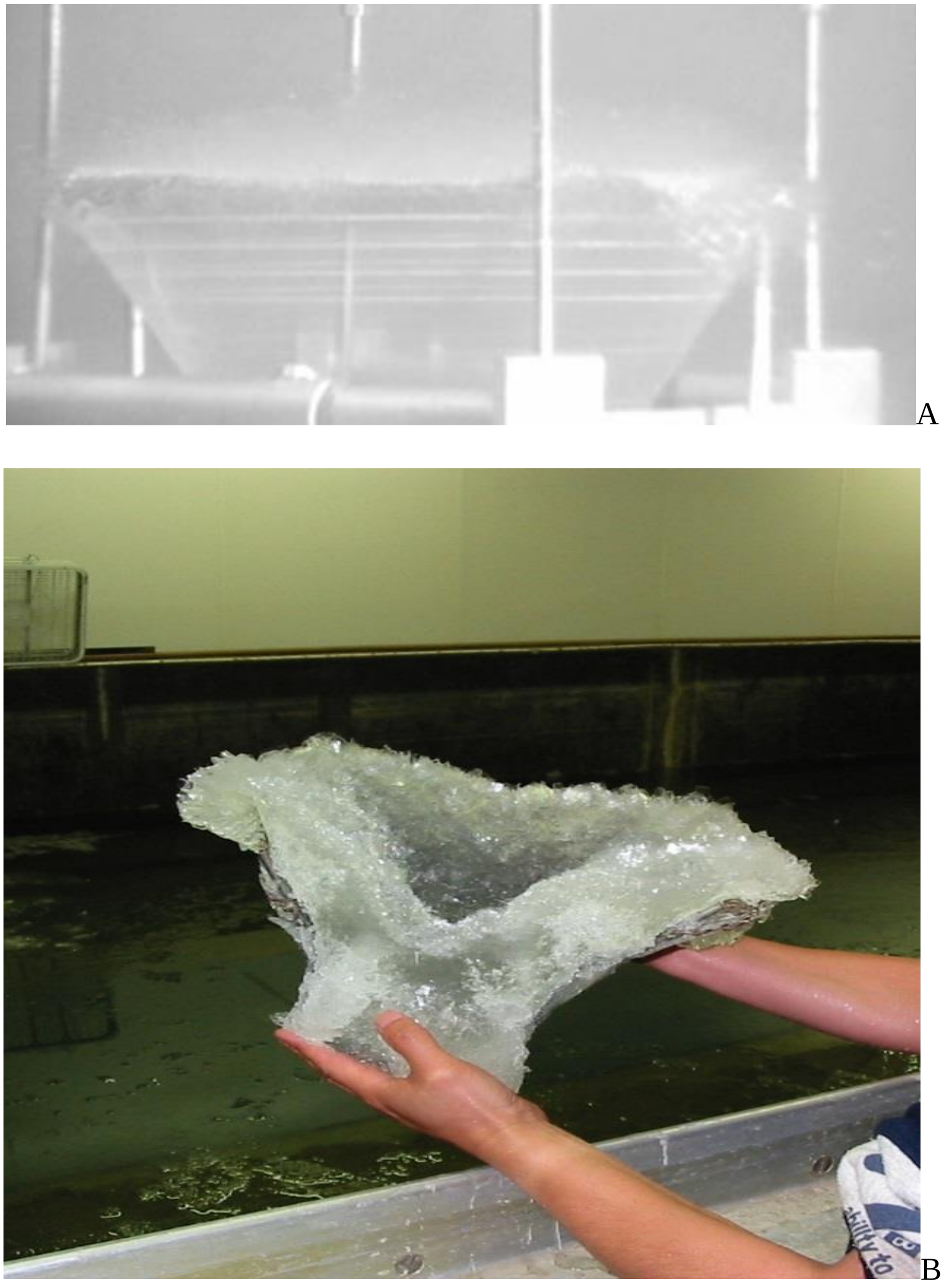

Figure 5. (A) Early stage of complete frazil ice blockage of cone-shaped intake from tank experiments of Chen et al. (2004). (B) Collapsed ice mass from same cone after about 60 minutes of model intake operation. Crystals on the rim of the ice mass show evidence of in situ growth. Porosity varied through this ice mass (from Chen et al. 2004)

Figure 6. Ice blockage of experimental wedge wire screen elements mounted in an acrylic box on the morning of 2/28/13. It was impossible to distinguish between ice formed on the wedge wire screen and anchor ice formed on the surrounding bottom.