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WASTE WATER PURIFICATION BASED ON NATURAL ICE CRYSTALLISATION

Examiner(s): Professor Aki Mikkola
D. Sc. (Tech.) Marko Matikainen

ABSTRACT

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In this thesis, a test system for the breaking and harvesting of ice grown from water is developed using a systematic methodology. The purpose of this system is to form a part of a larger system to purify waste water by natural freezing. Once frozen the remaining waste water would be removed and the ice formed broken and harvested.

The systematic process resulted in three viable breaking methods and three viable harvesting methods. Of the three breaking methods, the one utilising bending was chosen to be tested. This test consisted of two levers applying a force to the sides of a cylindrical container to break the ice within. Ice harvesting was not tested.

Ice breaking testing was performed in the early winter months of 2016 and was deemed to be reasonably successful. Ice was broken, albeit not consistently or in appropriate sizes. Further experimentation and study of this method was deemed necessary.

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Eric Lehtonen
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1 INTRODUCTION

Natural ice was once somewhat of a commodity; its harvesting and worldwide distribution was a major industry with companies exporting their product far and wide. Alas, with the advent of affordable artificial refrigeration during the turn of the 20th century, the world ice trade died. (Maw & Dredge 1871; Weightman 2003.)

However, despite the collapse of natural ice as an industry of cooling, natural freezing saw some interest as a purifying mechanism. In 1901, Clark (1901, pp. 127–133) presented a paper to the Massachusetts Boards of Health and noted that freezing of water in rivers, canals and ponds led to a not insignificant reduction of the number of some of the bacteria species present. Later in the same meeting a Mr Winslow reported similar findings by a Dr Hill (Clark 1901, pp. 133–138). Hilliard & Davis (1918) review the work of others on the subject and conclude that while a reduction of bacteria is noticed, the resultant ice was by no means pure.

In more recent years the prospect of using freezing as a method to purify waste water or desalinate sea water is showing renewed interest. Although, most of this research focusses on artificial freezing and less so on natural freezing. (Conlon 1992; Gao, Smith & Sego 2004; Gao, Habib & Smith 2009; Williams et al. 2015; Melak et al. 2016.)

A very recent purification concept with natural freezing at its core of operation is the WINICE concept. The basis of which are the winter conditions in northern countries and the large waste pools often present during mining operations. The idea being to wait for the waste water to freeze and then by some contrivance, harvest the ice to be processed later as substantially purified water.

1.1 Objective of this work

As an alternative to the use of large, unmanageable waste ponds, a smaller containerised system has been proposed. Consisting of a standard intermodal shipping container in which are located one or more containers of waste water. These internal containers would be allowed to partially freeze, and once a desired level of freeze is met, the remaining waste water would be removed and the ice within the container would be broken and moved elsewhere for further treatment or release into nature. This would be a more controllable and manageable system than that of the original WINICE concept.

This work aims to answer the question: What methods are there to break and harvest ice from a container? This question forms part of the much larger question: How is it possible to utilise natural freeze water purification, in a small containerised system? The focus of this work is on the design and testing of a method of breaking ice, once it has frozen to the inner walls of a waste water container. Additional study is also performed regarding potential methods to remove (harvest) broken ice from waste water containers after the ice has been broken.

2 RESEARCH OF ICE PROPERTIES, BREAKING AND HARVESTING METHODS

In the early stages of the project, literature was sought out which would support the creation of design concepts and enable a better understanding of ice as a working material. It must be noted that the purpose and conditions of works referenced here are different to those of the WINICE concept. Some testing will be needed and there is a lot of scope for study regarding how ice behaves under the specific circumstances of the WINICE system. Studies of ice as a material seem to be relatively sparse and any studies performed into the mechanics and conditions of ice seem to focus on breaking sea/lake ice, scraping road ice, mitigating damage to aircraft by ice or harvesting the cooling energy of ice.

2.1 Ice properties

The mechanical properties of ice vary greatly depending on certain factors, the main ones being: porosity, composition, temperature, growth rate and age. Timco & Weeks (2010) performed a comprehensive review of sea ice properties and contribute a large portion of information to this section. Sea ice receives most of the scientific attention followed by glacier and model ice. Lake ice and ice formed from other compositions are relatively or completely without study. Ice is a potentially complex material with numerous classes and property groups, including thirteen distinct crystal structures and two amorphous states, ice type Ih (hexagonal) is the form of ice most relevant here (Shazly, Prakash & Lerch 2009, p. 1499).

2.1.1 Ice growth rate

To know the optimal time between harvesting actions in an automated ice harvesting system, the rate of ice growth is important. The growth rate of ice depends, as with many properties, on certain factors e.g. composition as well as temperature, the presence of super cooling, movement of the water, and wind speed (Timco & Weeks 2010, p. 107; Hasan & Louhi-Kultanen 2015). The ice crystal structure also depends on these variables; however, it is beyond the scope of this text (Timco & Weeks 2010, p. 107).

Smith et al. (2012), suggest a growth rate for Antarctic sea ice (in the region of McMurdo Sound) of the magnitude 10^{-7} m/s, for the sea in the super cooled region near ice shelves. For Arctic ice in Van Mijenfjorden on the archipelago of Svalbard, Norway, growth was of the magnitude of 10^{-8} per year (Høyland 2009, p. 347).

In a more appropriately scoped work experiments were performed on a water/sodium sulphate solution. These experiments used a specially designed freezing chamber which could simulate various wind speed and temperature conditions, they simulated conditions where temperatures were 1–4 °C under the freezing point of solution with concentrations 1–4% sodium sulphate by weight. They concluded that the growth rate of ice depended on the temperature difference between solution freezing point and chamber temperature as well as freezing time. The composition did not affect the growth rate significantly. However, the composition did seem to affect the quality of the ice produced, the ice from higher concentrations being cloudier, less smooth and less pure. Ice growth rates of between 5×10^{-8} and 3×10^{-7} m/s were measured, with rates less than 10^{-7} m/s showing the purest ice. (Hasan & Louhi-Kultanen 2015.) In a later work by the same authors they performed artificial air cooling on a water/nickel sulphate solution. This resulted in growth rates between 3.5×10^{-8} and 4.5×10^{-7} m/s and showed the same influencing factors and caveats as the previous study (Hasan & Louhi-Kultanen 2016). Further work performed in the lab at Lappeenranta University of Technology has shown natural freezing rates between 1.2×10^{-7} and 4.4×10^{-7} m/s depending on temperature and air flow rate (John 2016).

2.1.2 Tensile strength

Tensile strength for new sea ice is in the range of 0.2 and 0.8 MPa for loads perpendicular to growth. When performed parallel to the direction of growth, the strength value could reach as high as 2 MPa. Tensile strength of new sea ice depends heavily on temperature and porosity of the ice. For such an important property, very little work has been done on this property of ice due to the difficulty of performing the tests. (Timco & Weeks 2010, pp. 113-114.) In a more recent literature review by Pernas-Sánchez et al. (2012, pp. 1919-1920), a 0.7 to 3.1 MPa tensile strength range is given.

In an early experiment by Haynes (1973), tensile strengths for model ice were measured as between 0.5 and 2.2 MPa. The ice for these experiments was created by adding water to packed snow, rather than freezing directly, it had a density of 904 kg/m^3 and a random grain structure. The test apparatus is illustrated in figure 1, it is notable that it uses fluid pressure to surround the ice and force the specimen apart, thus applying a compressive load to the ice as well as a tensile load, an increase in this compressive load served to decrease the tensile strength measured. It is also noted that an increase in strain rate could lead to a decrease in the measured tensile strength, when the ratio between compression and tension was close to unity. (Haynes 1973)

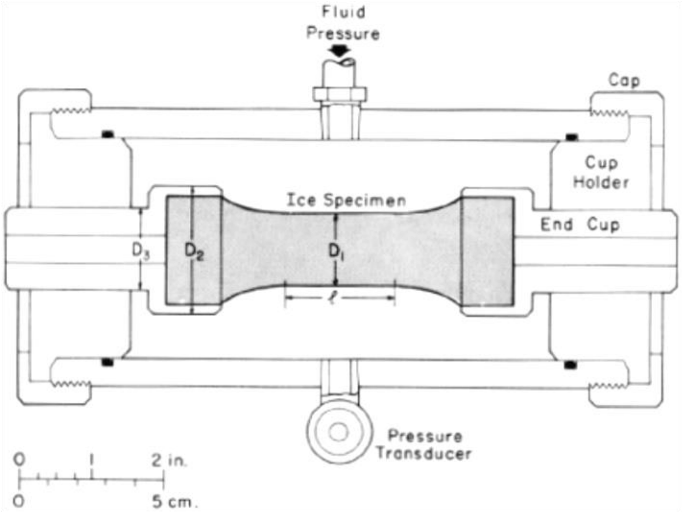

Figure 1. Schematic of the test chamber used for tests by Haynes (1973).

In a recent study on model ice by von Boch und Polach (2016), using experimental and numerical methods, tensile strengths are given as 3% of the elastic modulus of low density ice (von Boch und Polach 2016, p. 88). The ice showed varying elastic properties depending on thickness, with an average tensile strength of 3.2 MPa (von Boch und Polach 2016, p. 43). Ice models with uniform properties throughout their thickness and which were loaded in a uniaxial fashion had a tensile strength of 4.4 MPa (von Boch und Polach 2016, p. 55).

2.1.3 Compressive strength

The compressive strength of ice is a reasonably well studied and understood property. It has been shown (figure 2) with both sea and fresh water ice, that compressive strength shares a positive correlation with the strain rate (Timco & Weeks 2010; Shazly et al. 2009; Kim &

Keune 2007; Glen 1975). In addition to the strain rate; temperature, porosity and loading direction, as with tensile strength, influence the compressive strength of sea ice (Timco & Weeks 2010, p. 117). Ductile to brittle transition takes place at about 10^{-3}/s (Timco & Weeks 2010, p. 117; Shazly et al. 2009, p. 1500).

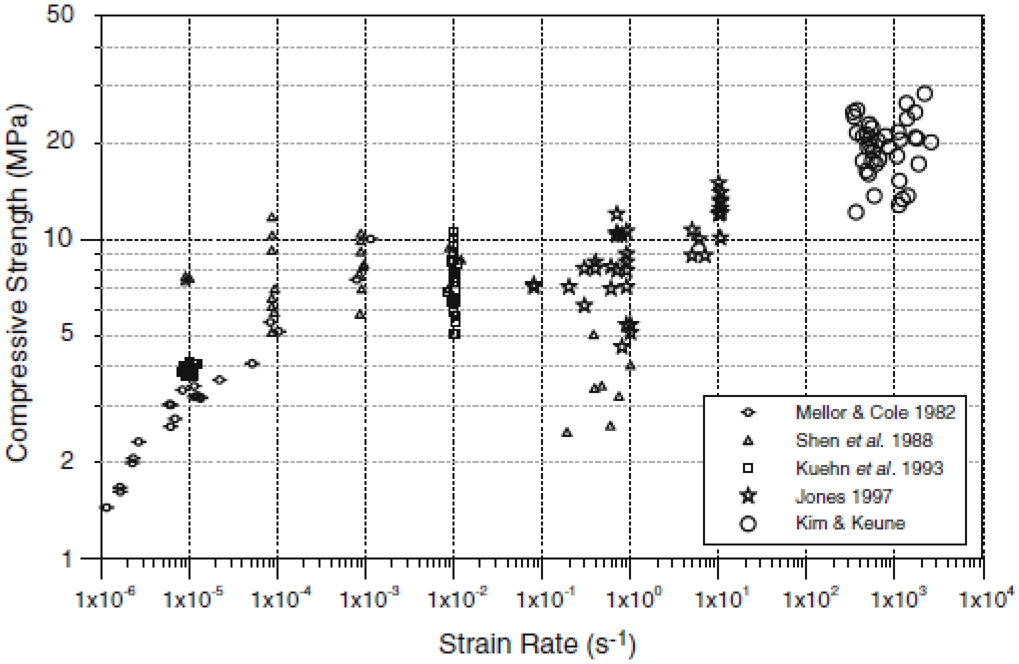

Figure 2. Experimental results showing the relation between compressive strength and strain rate (Kim & Keune 2007, p. 2806).

Timco & Weeks (2010, p. 118) report at a strain rate of 10^{-4}/s, compressive strength of new sea ice is between 0.5 and 5 MPa and at higher strain rates of 10/s compressive strength is between 8 and 12 MPa. Combescure et al. (2011) confirm compressive strengths of 10 MPa for strain rates of the same magnitude (50/s).

Higher strain rate tests of ice tend to focus on the effects of ice impacts with vehicles, specifically in the aerospace industry. In freshwater ice tests using a split Hopkinson pressure bar, Shazly et al. (2009, p. 1504-1507) measured compressive strengths in the ranges 25 – 35 MPa and 25 – 30 MPa in mono- and polycrystalline ice respectively. Strain rates were in the range of 10^2 – 10^3/s, these experiments were performed at -10 °C (Shazly et al. 2009, p. 1507). A maximum stress of 58 MPa was measured for polycrystalline ice in the previously given strain rate at a temperature of -30 °C (Shazly et al. 2009, p. 1509). In earlier experiments by Kim & Keune (2007, p. 2802) on freshwater ice in the strain rate range of 10^3/s, average strength figures of 20 MPa were measured.

2.1.4 Shear strength

Measuring the shear strength of ice is difficult and consequently very little work has been done on this property. What work that has been done has been subject to reliability concerns. Tests performed on young sea ice give values in the range of 0.4 – 2.3 MPa, the property is dependent on temperature, porosity and composition. (Timco & Weeks 2010, p. 116.)

A study of the adhesive forces of ice using snow/distilled water ice adhered to a surface was given as 0.6 MPa for a lapped stainless steel surface and 0.4 MPa for a polystyrene surface. These forces did not depend on the area of contact. Additionally, the adhesive strength of the ice/steel bond did not increase once the temperature had reached -14 °C but the ice/polystyrene bond strength increased linearly with temperature. While the type of test performed is within the scope of this work, the snow and distilled water ice blend is not indicative of the type of ice expected to be formed. (Jellinek 1959.)

2.1.5 Flexural/Bending strength

The bending strength of ice is not very well understood, mainly due to the difficulties in performing a test which gives a pure indication of the actual bending strength (Timco & Weeks 2010, p. 116). The property seems to relate negatively to the brine volume in new sea ice and is in the range of 0.1 – 1.5 MPa (Timco & Weeks 2010, p. 115).

2.1.6 Young’s Modulus

The elastic properties of ice (specifically sea ice) are somewhat confusing in that ice has numerous strain terms and basic measurement of stress vs. strain does not paint the full picture (Timco & Weeks 2010, p. 123). However, for the purposes of this project only a general idea of the macroscopic elastic properties are needed and simple tests can be taken as valid.

Per Timco & Weeks (2010) the Young’s modulus of sea ice increases with a decrease in temperature and brine content, and can be as high as 9.1 MPa. 10 GPa has been measured in ice with very low brine content. The static Young's modulus, while difficult to quantify, is within the range of 1 – 5 GPa. (Timco & Weeks 2010, p. 123.)

In impact testing of plates with high velocity freshwater ice cylinders, the Young's modulus was measured up to 12 GPa in the direction of the c axis (the hexagonal symmetry axis of the ice crystal) (Combescure et al. 2011). In low density model ice tests, the Young's modulus was measured as 108 MPa at about -1 °C (von Boch und Polach 2016, p. 43).

2.1.7 Poisson's ratio

The Poisson's ratio is not a widely understood or studied property of ice. Although not likely of major importance to this work, it bears mentioning due to its general importance as a material property. The Poisson's ratio is sensitive to grain orientation and temperature and falls in the range of 0.25 – 0.42 (Timco & Weeks 2010, p. 124; Godio & Rege 2015, p. 98).

2.2 Ice breaking theories

Efficient breaking and harvesting of ice will probably require frequent removal due to ice growth rate slowing as the ice grows thicker (Matsumoto, Akimito & Teraoka 2010, p. 422). It may be better to harvest frequently (daily, 12 hourly, et cetera) than to wait a lengthy period for a large thickness of ice to form. The period of breaking and harvesting can probably be optimised as an operating parameter, based on environmental conditions, rather than a design issue. Methods of ice harvesting from a surface which are elaborated on are: shaving, scraping, impacting, bending and heating.

2.2.1 Shaving (Milling)

Shaving the ice off layer by layer, or milling it, would produce fine ice pieces which would allow for finer packing of the ice for transport or later treatment. It would also be suitable for layers of ice thicker than with some other methods of harvesting. This method, however, is likely to be high in terms of required energy use and time consumption.

Lieu & Mote (1984) suggest that the cutting force for a negative rake cutting tool (in their case emulating a ski in a turn) increases with a decrease in rake angle (increase in edge angle) and can reach over 10 kN/m. However, with a closer to neutral (perpendicular to ice surface) rake, the force doesn't reach 1 kN/m (Lieu & Mote 1984). Negative rake angle is not useful for the purposes of this project as machining heat and surface finish are not issues of concern. Positive rake angles would result in a much-reduced cutting force. There is also shown a dependence between depth of cut and cutting force and a lack of dependence between cutting speed and cutting force (Lieu & Mote 1984). Their normal (left) and tangential (right) cutting force results are shown in figure 3.

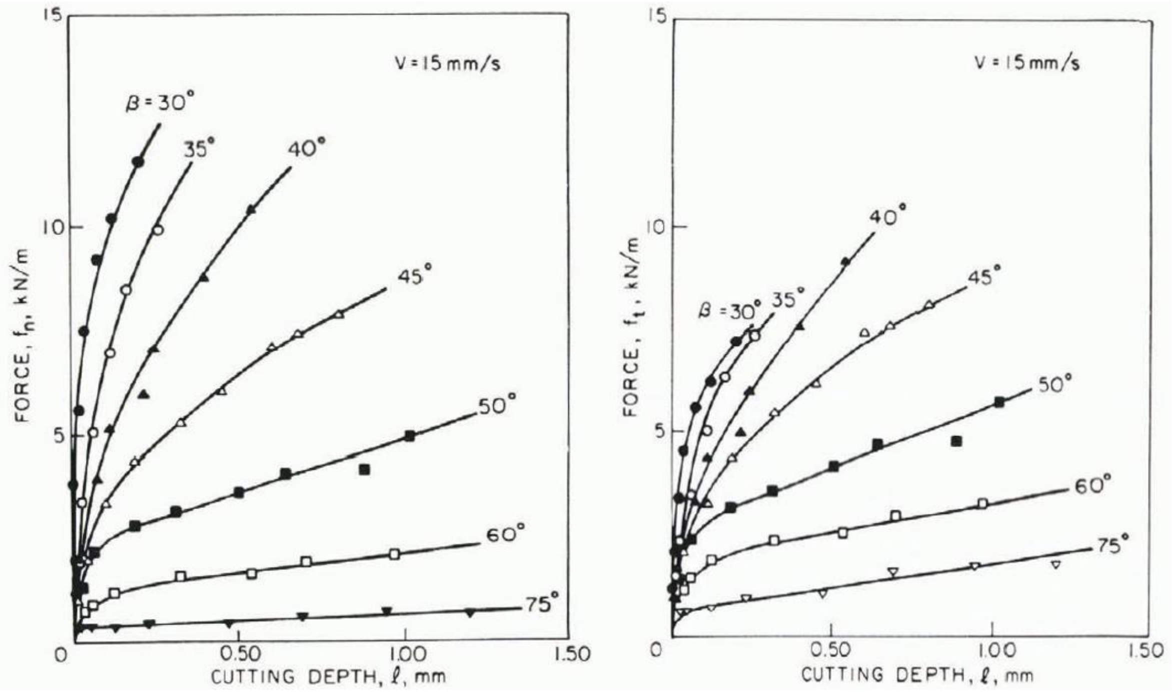

Figure 3. Comparison of cutting forces vs. depth of cut and edge angle. Left: Force normal to the cutting force, right: tangential cutting force. (Lieu & Mote 1984, p. 80)

Nixon & DeJong (1997) performed tests using positive rake on model road ice and gained results of around 3 kN/m with much deeper cuts and faster cutting rates. As with the Lieu & Mote study, they were cutting ice from ice which has been shown to make a difference to the required force (Matsumoto et al. 2010, p. 426).

This method appears like it would be too slow and power hungry. In addition, the removal would have to be uniform and clean. Shaving methods would probably require more supervision than others, which implies the addition of a monitoring system or a person present for each cut. The cuts would perhaps have to be performed on a drained tank so that, due to the slow speed, the ice doesn’t continue freezing as the cutter is cutting elsewhere.

2.2.2 Scraping

Scraping is similar to shaving. However, rather than taking a shallow cut of ice from the underlying ice and repeating until the ice is totally removed, this method uses one pass and removes all ice in as few feeds as possible. This would require having a cutter in contact with the cylinder wall before the ice is formed, so that when it is time to cut, the scraper only needs to be moved around the cylinder and not directly fed through the ice. This method has the advantage that it removes all ice in one pass and should break the ice up as the cutter is fed. It must be noted that that majority of the works cited here relate to harnessing the cooling energy of ice.

Scraping the ice from the freeze surface could be one valid option. Experiments designed to estimate forces for ice slurry manufacture resulted in shearing stresses of less than 1 MPa. The ice for these tests was less than 5 mm thick and was scraped from various differing surfaces. (Matsumoto & Kobayashi 2007; Matsumoto et al. 2010.)

Experiments were performed on an ethylene-glycol solution with a 7.5% concentration and with varying temperature differences between the carbon steel freeze surface and solution. It was found that the scraping force did not vary too much when the freeze time was constant and the ice thickness varied. However, there was scraping force variation when the freeze time varied and the thickness remained constant. (Matsumoto et al. 2010.)

Experimentation with a fixed freeze surface temperature and different liquid temperatures resulted in the ice with the higher temperature difference requiring the least force to remove. An increase in freezing surface temperature caused an increase in scraping force and increase in temperature difference caused a decrease in scraping force. (Matsumoto et al. 2010.)

A steady increase in scraping force was noted when multiple scrapings were performed, this is due to the increase in force when ice is scraped from ice rather than steel. It is also noted that an increase in the concentration of ethylene-glycol decreases force as does a decrease in the surface roughness of the freeze surface. (Matsumoto et al. 2010, pp. 425–426.)

Per Matsumoto et al. (2010) ice scrapings can take one of two forms, these forms are known as Type A and Type B. Figure 4 shows the general requirements for the formation of each type of ice.

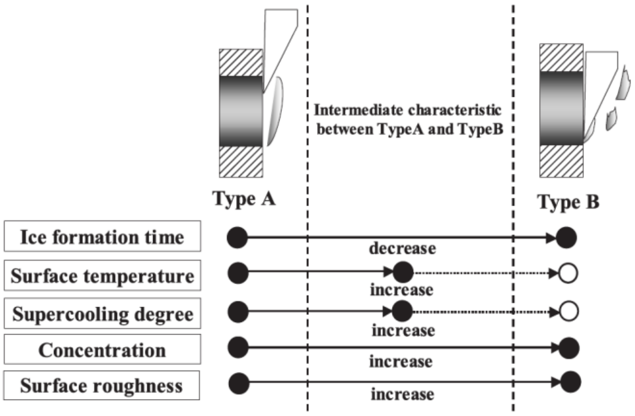

Figure 4. Ice scraping types. White circles indicate data deficiencies (Matsumoto et al. 2010, p. 425).

These observations seem to indicate that cooling the liquid is more critical than cooling the surface and that the time of freezing is a more significant factor in determining the required force than the thickness of the ice. It should be borne in mind that this method could very well depend upon the concentration and composition of the liquid being treated, and further understanding of solution and ice behaviour would be required for the relevant compositions.

Scraping forces of up to 6000 N/m have been given in two older studies (Lieu & Mote 1984; Nixon & DeJong 1997). These are potentially ten times higher than given by Matsumoto's studies and thus warrant discussion. The primary differences between Matsumoto and these studies lies with the depth of cut and the rake angle. Matsumoto attempted to remove all the ice in one feed, these older studies had fractional depths of cut resulting in ice being scraped from ice, this was shown to increase cutting force (Matsumoto et al. 2010, pp. 425–426). Additionally, the rake angles used by both of these older studies are not compatible with Matsumoto's work nor were the cutting surfaces. Further differences between the Nixon & DeJong study and Matsumoto's studies were with the frozen surface. The older study was aimed at calculating forces for road ice clearing, so the surface used was asphalt and concrete. Finally, the freezing time of the older studies (Nixon's study taking 24 hours to freeze their samples) is significantly longer than for Matsumoto, and as Matsumoto showed, freezing time is a major factor in cutting force. (Lieu & Mote 1984; Nixon & DeJong 1997; Matsumoto & Kobayashi 2007; Matsumoto et al. 2010.)

2.2.3 Impact/compression

The bending strength of ice is less than its compressive strength (Timco & Weeks 2010). However, there is a possibility of using nearly static, low strain rate, compression as a means of breaking ice from the freeze surface. However, due to time considerations, this seems to be less suitable than using impact.

Impacting the ice with a pneumatic or mechanical actuator is one possible method of removal. One uncertainty with impact based removal is that there are some contradictory studies regarding the compressive strength, fracture toughness, hardness and impact strength of ice (Timco & Weeks 2010). This makes it hard to decide on the best means of approach and perhaps it would be necessary to perform additional impact and fracture tests on ice to know if this route is worth pursuing. Impact strength of ice was hard to find however compressive strength is studied in some detail.

Impact testing of ice is mostly performed to judge the effect of ice impacts on vehicles or structures. The most common experiments performed are those where ice is propelled at a material and the effects on the target material are judged, with only the material properties of the ice being measured. In addition, strain-rate experiments have been frequently performed leading to a common observance that the compressive strength of ice correlates positively with strain rate. (Shazly et al. 2009; Carney et al. 2006, Combescure et al. 2011; Kim & Keune 2007.)

2.2.4 Bending

As previously written by Timco & Weeks (2010), the bending strength of ice is less than its compressive strength, consequently bending would be a valid option of removal. This could be achieved by applying a force on the outside of the container to generate a bump inside, under the ice layer. This bump will serve to bend the ice and break it free of the container.

A device to perform this process could be relatively simple requiring only a mechanism to apply the bending load to the container. The mechanism would probably have to operate in the temperature conditions expected of the container, if atmospheric freezing was to be employed. Under artificial freezing the mechanism would not need to be so rugged.

This method has the potential to be a low energy solution. Energy requirements would depend on the material the container is constructed out of, the strain required to bend the ice enough to cause it to break away from the container surface and break up into manageable pieces as well as the temperature, microstructure and thickness of the ice, to name a few factors.

$$\frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \tag{1}$$

$$F = \frac{\pi}{4} E^* L d \tag{2}$$

Required force should be calculable using conventional means but numerical analysis is likely the best way to understand this approach. Equations 1 and 2 show a general method to calculate contact force (Popov 2010, p. 19).

Where F is the force of contact, E* is the equivalent Young's modulus for the materials being interacted with, v_n and E_n are the Poisson's ratio and Young's modulus [MPa] for the materials in question individually, L is the length of contact [m] and d the depth of penetration [m]. (Popov 2010, p. 19.)

The foreseeable main concerns with this method are wear and fatigue on the cylinder itself and the concern that not all ice is broken off when the bend is performed. This would mean that not every bend would be enough to break all the ice from the surface, which could lead to thicker and thinner built up areas on the surface. This in turn could lead to unreliable ice harvesting over time and may require additional supervision.

2.2.5 Heating

One method of ice removal would comprise heating the walls of the cylinder marginally to create a thin film of liquid water to act as a lubricant. The idea being to cause the whole ice pack to release itself from the cylinder and slide up to the surface of the liquid in the tank. Another method would involve melting the ice after draining the unfrozen waste.

$$Q = C_p m \Delta T \tag{3}$$

$$Q = L_f m \tag{4}$$

The minimum amount of heat energy required would be that required to melt the volume of ice. This energy consists of the energy to heat the ice to melting point (equation 3), the energy to melt the ice (equation 4) and any energy required to heat the resultant water to above melting temperature (equation 3). This will be in addition to the energy required to get the heat through the cylinder itself and any losses in the heating system (not accounted for).

Where Q is the heat required [J], C_p is the specific heat of the substance [J/kg K], m the mass [kg], ΔT the change in temperature [K] and L_f the latent heat of fusion/melting for the substance [J/kg].

2.2.6 Aviation concepts

Vibration and pressure methods, both used in aeronautics for ice removal, could have potential in this project (Palacios et al. 2011; FAA 2012). Problems arise due to the differing conditions of aviation de-icing versus the WINICE arrangement. This raises doubts as to the ability of pressure to work if ice is forming inside the pores through which pressure will be introduced, or vibration to work in a vessel heavily damped by water.

Electronic methods also exist for aircraft de-icing. These methods are expensive, electronically noisy and somewhat an unknown quantity. Electro-impulse de-icing, which induces small electromagnetic deflections in the aircraft skin to upset the ice. Electro-expulsive systems operate in a similar fashion however they consist of two layers of conductors built into an elastic coating which repel each other when a current pulse is passed through them, breaking the ice and requiring less than 1 kW to deice 12 m of wing. This method negates the structural risk associated with the electro-impulsive method. Piezoelectric methods are also available. (Zdobyslaw 2004.) The application of voltage to the freezing surface of ice formed out of a water/oil mixture has shown to reduce the force required to remove ice from said surface (Matsumoto & Otaki 2008, p. 386).

2.2.7 Ice slurry concepts

The use of an ice slurry, that is ice particles contained in a carrier fluid, would also be possible. The concept of WINICE depends on the waste liquid's composition having a lower freezing point than water, so pure water ice should be able to be carried in the liquid. This is similar to methods used by some air conditioning systems (Hirata, Ishikawa & Yamada 2001, pp. 190–191). However, in these air conditioning systems the carrier liquid is usually an ethylene-glycol solution (Hirata et al. 2001, p. 190). Work would need to be done to understand the relationship between water ice particles and the carrier liquid in the WINICE case. This method may also only work effectively with artificial cooling, as the temperature of both freezing surface and liquid may need close control. The unique issues in this concept would need to be understood properly.

2.2.8 Conclusions regarding ice removal methods

Ice removal should be performed frequently due to growth slowing and purity reducing as the layer of ice gets thicker. There are numerous methods of removing material from material and the seemingly most suitable have been covered in the previous sections.

Shaving/Milling removes powdered ice layerwise and is hence more time consuming than some methods, it does however give powdered ice which could be easier for transport/further processing. Scraping could potentially result in larger chunks of ice being removed in a single pass, but this seems to depend on the time frame of freezing/scraping and the material properties of the container, scraper and ice. Additionally, scraping tool geometry will play a role in the effectiveness of this method. Scraping energy is likely less than shaving but could still be high.

Impact/compression offers a potentially lower energy approach to the previous methods but the lack of study into how ice sheets are broken up by impacting/compressing tools is a concern. Bending could lead to a low energy, quick and simple method of ice removal without needing any machinery inside the container. A polymer container would seem to be ideal for this method.

Heating is a method that requires no machinery, which is one major advantage over other methods. The energy use requirements of heating methods will need to be considered further if this method is initially chosen as viable. The potential for a clean solid lump of ice being removed is appealing for handling and post processing, although transport (if necessary) may be an issue. Melting the nearly pure ice from the drained container also deserves consideration.

Further methods of less mainstream interest are creating an ice slurry and separating the ice that way or continuous ice generation and removal using a belt or cylinder dipped into the liquid to be purified. The energy requirement for this sort of system may be high and they may not be adaptable to natural freezing. Aviation methods (specifically vibration) also show promise.

2.3 Ice harvesting theories

The harvesting of ice and collecting it into a useful form is an old occupation. There is recorded history of ice harvesting going back as far as records exist. Traditionally ice was harvested mainly for the purposes of air conditioning and comfort, the preservation of food and medicine, the cooling of beverages, and to cool machinery. (Weightman 2003; Maw et al. 1871)

The WINICE project requires that ice be grown and harvested, however the purpose of the ice and the energy required to harvest it is not the same as in the ice industry of the past. In this case, ice will be harvested to be melted and possibly further treated as part of a water purification scheme and it is desired that the process uses as little energy as possible. In the Victorian era ice fields of Norway, it took a hundred men to harvest the ice (Maw et al. 1871). This is not a feasible or economical approach for the needs of the WINICE project.

The method(s) chosen to harvest broken ice from the barrel must be repeatable, reliable and require as little human interaction as possible as well as be as low in energy use as possible. Four possible broad schemes for harvesting are: lifting the ice from the barrel, pouring the ice from the barrel, sucking the ice from the barrel and blowing or pushing the ice from the barrel. An additional option, melting the ice, is also a fair possibility.

Selection criteria for the harvesting method will be ostensibly the same as with ice breaking. The harvesting process is part of the overall purification process so similar requirements apply. One additional requirement is that the chosen harvesting system should be compatible with the chosen breaking system.

2.3.1 Lifting

Lifting items out of containers is a common approach to retrieving said items. Numerous patents exist for contrivances to extract something from something else. For example, to get olives out of the jar, to aid philatelists in their endeavours, to help golfers retrieve their balls from the rough and assist pool attendants in keeping their pools free from scum (Pat. US 2184216 1939; Pat. US 3282620 1964; Pat. US 4844526 1987; Pat. US 5137623 1990). These methods, however, require the system to retrieve items piecemeal. The task of ice harvesting for this project would require something much closer to instantaneous.

Lifting (or in some cases placing) whole masses of material in one motion can be achieved in numerous ways. Simple baskets would require either the basket inside the drum before freezing or for it to be lowered into the drum once breaking had been completed. Collapsible vegetable steamers are used daily to do this (Pat. US 2667117 1950; Pat. US 4138939 1977). The Archimedes’ screw, or screw conveyer has been used for centuries to lift water or other substances from a lower place to a higher (Pat. US 2709956 1955; Pat. US 3280963 1966; Pat. US 5573660 1996). A simple adaption of the traditional use could be made to lift surface items out of a liquid filled barrel. The screw could be lowered and rotated into the barrel and then lifted out without rotation.

One’s hand is often used to grab a reasonable number of items from a container, and mechanical contrivances which emulate this action are in existence. One kind of which is known as an orange peel grappler and several patents exist for them (Pat. US 5330242 1994; Pat. US 6155619 2000; Pat. US 2012/0299321 A1 2012). A belt conveyor system, akin to systems employed in emptying bulk carrier cargo ships, would also be able to lift out floating items from the container.

2.3.2 Pouring

Possibly the simplest way to gain access to the contents of a container is to pour said contents away. Pouring the water and ice pieces out of the bucket could, however, seem somewhat akin to throwing the baby out with the bathwater. However, this method does at least ensure that the liquid in use for the next cycle of freezing will be of adequate concentration. The most simplistic method would be to mount the container on trunnions and rotate it about them once the time has come.

The ladles in metal foundries enjoy a more convoluted solution consisting of a container mounted to a lifting device using trunnions. This is moved to an appropriate location and emptied via a mechanism which tries to ensure the steadiest flow over the whole pouring process. (Pat. US 2094736 1937.) A reasonably compact and simple method of container emptying could be achieved with a silo and hopper arrangement, similar to those used to store grain and animal feed (Pat. US 3455475 1969; Pat. US 8672194 B2 2014).

2.3.3 Sucking

Sucking the ice pieces from the barrel is the third general method. The simplest version would be to use a suction head to pick up the ice piecewise and carry it to another location. Machine vision technology could be trained to recognise ice shapes and pick then out quite quickly, however this system falls at the same hurdles as the piecemeal lifting method.

Alternatively, the whole content of the barrel could be sucked out and the ice pieces filtered out of the water. The pumping of pieces will prescribe the use of pumps which can handle large particles and inevitably the ice pieces will be crushed by the pumping action. This could be a possible way to developing a slurry harvesting method. It could also be possible to suck the water out and then harvest the remaining ice in another fashion.

The use of air flow and suction could be a possibility, rather than sucking ice pieces or water directly. This could be achieved by placing suction hoses around the outer rim of the barrel, filling the barrel to its brim, and using the force of suction to pull the ice pieces out of the barrel.

2.3.4 Blowing

Ice could be blown out of the barrel using pressurised fluid. One method of operation could be to blow high pressure fluid from inside the barrel at individual ice pieces thus propelling them out of the barrel. This method suffers the same problems as other methods designed to pick individual pieces of ice.

Another method could be a reversal of the suction and air flow proposal. Blow air over the top of the brimmed barrel and propel the pieces out of the barrel. This could also be combined with the suction method such that one side blows and one side sucks.

2.3.5 Heating

As an alternative method, rather than breaking the ice using mechanical means then pouring the water and ice out. It may be possible to heat the container so that the remaining ice melts and then pump the now almost clean water away for further processing. This method suffers from the same problems as heating methods for breaking the ice in that it goes against the spirit of the project.

3 WASTE WATER TREATMENT SYSTEM REQUIREMENTS

The requirement list for a waste water treatment system is built up of two separate lists. The first being the demands, whose contents are absolute in their requirement. The second list is for the wishes, which only serve to improve the quality of the design concepts but are not necessary to consider the concept appropriate.

3.1 Demands

The following eight demands are given as requirements of a waste water treatment system. These requirements must be met for a concept to be deemed appropriate and moved on to the more detailed selection stage.

- *Workable.* The system is physically able to be built and operated as designed and capable (at least in theory) of performing the task it is designed to do.
- *Economically viable.* It should be economically reasonable to build and operate the system.
- *Low environmental impact.* The production, running and end of life impact on the environment of the system is within acceptable limits. Ideally the system will consume as little energy as possible and if possible be entirely reliant on renewable means of power. Its production and end of life disposal results in minimal environmental damage.
- *Can safely contain or eliminate substances that are not able to be purified.* Once the substance to be treated has been, there are likely to be leftover chemicals, particles and other harmful materials which were contained in the water. These materials should not cause any damage to the environment or people near the system or operating the system. If these substances cannot be disposed of at the time they should be stored safely for later disposal.
- *Consistent quality.* The quality of treated water outflow should be stable for all operating cycles of the process. Some statistical change in quality can be expected but it should remain within a defined allowable range of quality for its operating life.
- *Stable high yield process.* The system should be able to treat a large enough volume of water to be considered viable. The yield of the device should also remain stable during its life as with quality.

- *Reliable.* It should ideally operate maintenance and supervision free for extended periods of time and only require periodic and simple maintenance.
- *Safe.* The system offers no risk of mechanically or chemically induced harm to passers-by or workers nearby.

3.2 Wishes

The following ten wishes do not have to be met by any design concepts, however if they can be met by a design concept, it will be favourable for that design concept. These requirements are mostly cost related as the most important aspects besides cost (safety, environment and capability) are addressed by the demands.

- *Cost comparable to established technologies.* It can be made, operated, maintained and disposed of at a cost comparable with other systems that perform the same or similar types of purification.
- *Low levels of maintenance.* Maintenance should be limited to quick and simple tasks that could be performed by someone with minimal training or who can follow a service manual.
- *Low maintenance costs.* Maintenance should not be time, resource or financially expensive. The cheaper maintenance can be, the better lifetime costs are likely to be.
- *Can operate in all seasons.* During summer the system can freeze waste water with as little energy use as possible and during winter the system can operate at very low temperatures.
- *Can operate with minimal supervision.* While it is likely to be essential to have some trained person(s) able to maintain the system, it would be good for the system to operate independently of human interaction for large portions of its life. In addition to this, it would be good that if supervision is required, that minimal special or time consuming training is required for the supervisor. Operating manuals should be provided with check lists and basic usage guides for normal operation. Further to this, it would be good if the system’s health and operation can be checked by a simple indication panel, readout or remote access page at a glance and by taking up minimal time. Self-checking and reporting would be useful.
- *Self-contained.* The system should be able to perform its task with only what is contained in its housing. It should ideally be plug and play so that in one end goes dirty water and power and out of the other comes treated water.

- *Self-powered.* If possible the system should not require any external power sources. So, it could be powered by solar or some other renewable and portable means.
- *Able to be manufactured with minimum bespoke components.* Ideally the system should not require special fabrication, it should use standardised or off the shelf components in its construction where possible and any custom parts should be able to be produced by any fabricator using basic equipment.
- *Fit into a standard intermodal container.* For portability and extendibility, the ability to be fitted into a standard twenty-foot unit (or forty-foot unit) to enable the system to be carried by almost any form of transport anywhere it needs to be transported to.
- *Does not create additional harmful compounds.* The process of purification should not produce any new compounds or substances that would require more steps of cleansing and could lead to environmental or personal harm.

The requirements of a water treatment system can be given by the following sentence. The primary requirements of the system are that it can safely, reliably and repeatedly treat an adequate volume of waste water at as low an operating cost and environmental impact as is possible.

Many of the given requirements play an important role in the choice of design concepts for each individual sub-process of the water treatment system. They are referred to in later sections of this work.

4 ICE BREAKING CONCEPT SELECTION

The primary focus of this work is to establish feasible ideas for ice breaking in a small container. The design constraint capacity of the container was given as between 50 and 200 litres. Expected ice yield, rate of ice removal, container shape and process energy use are open as of now. (Matikainen 2016.)

4.1 Cylindrical barrel concepts

The first choice of container is a 200-litre barrel. This allows easy access to its contents and easy access for machinery installation, without any cumbersome assembly requirements. There are likely better shape options, but cylindrical containers are easily acquired for testing purposes.

A meeting, held on the 22nd of June 2016, was arranged between several members of Aki Mikkola’s team at LUT. During this meeting, possible concept ideas were discussed.

4.2 Selection methodology

The initial selection methodology for a device to remove ice from the wall of a cylinder is very broad. Any imagined concept of ice removal is entertained and these are then removed in two stages. The first stage is a broad stroke which removes any concepts that are simply not compatible with the project. The second stage is matching with the basic requirements given in the requirements list and a concept(s) that are most suitable chosen (§3). Table 1 lists concepts and their description, table 2 gives the results of the selection stages and figure 5 illustrates the concepts.

Table 1. Early concepts for ice removal.

Concept	**Description**
Scraping 1	Horizontal blade single pass
Scraping 2	Vertical blade single pass
Scraping 3	Incremental full thickness sideways cutting with vertical cutter
Scraping 4	Incremental full thickness downward cutting with horizontal cutter
Scraping 5	Incremental fractional thickness (milling)

Table 1 continued. Early concepts for ice removal.

Concept	**Description**
Bending 1	Vertical tool pushed between ice and container
Bending 2	Point loads from outside of the container
Bending 3	Full length external rollers
Bending 4	Partial length external rollers
Bending 5	Smaller individual (wheel) rollers
Bending 6	Tightening around the barrel
Chemical 1	Use of salts
Chemical 2	Use of alcohols
Chemical 3	Use of other substances
Chemical 4	Hydrophobic cylinder coating
Heat 1	Joule heating
Heat 2	Gas heating
Heat 3	Process fluid (water, steam)
Heat 4	Thermoelectric heating
Heat 5	Atomic decay heat
Heat 6	Reheat frozen fluid
Heat 7	Heat pump
Crushing 1	Internally with low strain rate
Crushing 2	Internal impact, high strain rate (rock drilling)
Crushing 3	Vertical compressive crushing
Aviation 1	Vibration induced breaking
Aviation 2	Impulse (aviation technology)
Aviation 3	Expulse (aviation technology)
Fluid 1	Pressurised fluid used to force ice from cylinder walls
Explosion 1	Controlled explosion to break the ice from the container

Table 2. Concept evaluation.

Concept	**S1**	**S2**	**Notes**
Scraping 1	✓	X	Failed selection two
Scraping 2	✓	X	Failed selection two

Table 2 continued. Concept evaluation.

Concept	**S1**	**S2**	**Notes**
Scraping 3	✓	X	Failed selection two
Scraping 4	✓	X	Failed selection two
Scraping 5	X		Complexity and ice mechanics[1]
Bending 1	✓	X	Failed selection two
Bending 2	✓	X	Failed selection two
Bending 3	✓	X	Failed selection two
Bending 4	✓	X	Failed selection two
Bending 5	✓	X	Failed selection two
Bending 6	✓	✓	
Chemical 1	X		Goes against the spirit of the project
Chemical 2	X		Goes against the spirit of the project
Chemical 3	X		Goes against the spirit of the project
Chemical 4	X		Manufacturing expense, longevity, reliability
Heat 1	✓	✓	
Heat 2	✓	X	Failed selection two
Heat 3	✓	X	Failed selection two
Heat 4	✓	X	Failed selection two
Heat 5	X		Radioactivity / Inaccessibility
Heat 6	X		Goes against the concept of the project
Heat 7	✓	X	Failed selection two
Crushing 1	X		High compressive strength[2]
Crushing 2	X		High compressive strength[2]
Crushing 3	X		High compressive strength[2]
Aviation 1	✓	✓	
Aviation 2	✓	X	Failed selection two
Aviation 3	✓	X	Failed selection two

Table 2 continued. Concept evaluation.

Concept	**S1**	**S2**	**Notes**
Fluid 1	X		Not suitable for this purpose
Explosion 1	X		Safety, cost, personnel requirement, legality

1. Literature review reveals that ice is harder to cut/shear from other ice than from a smooth surface.

2. Literature review shows that compressive strength is higher than tensile/bending strength.

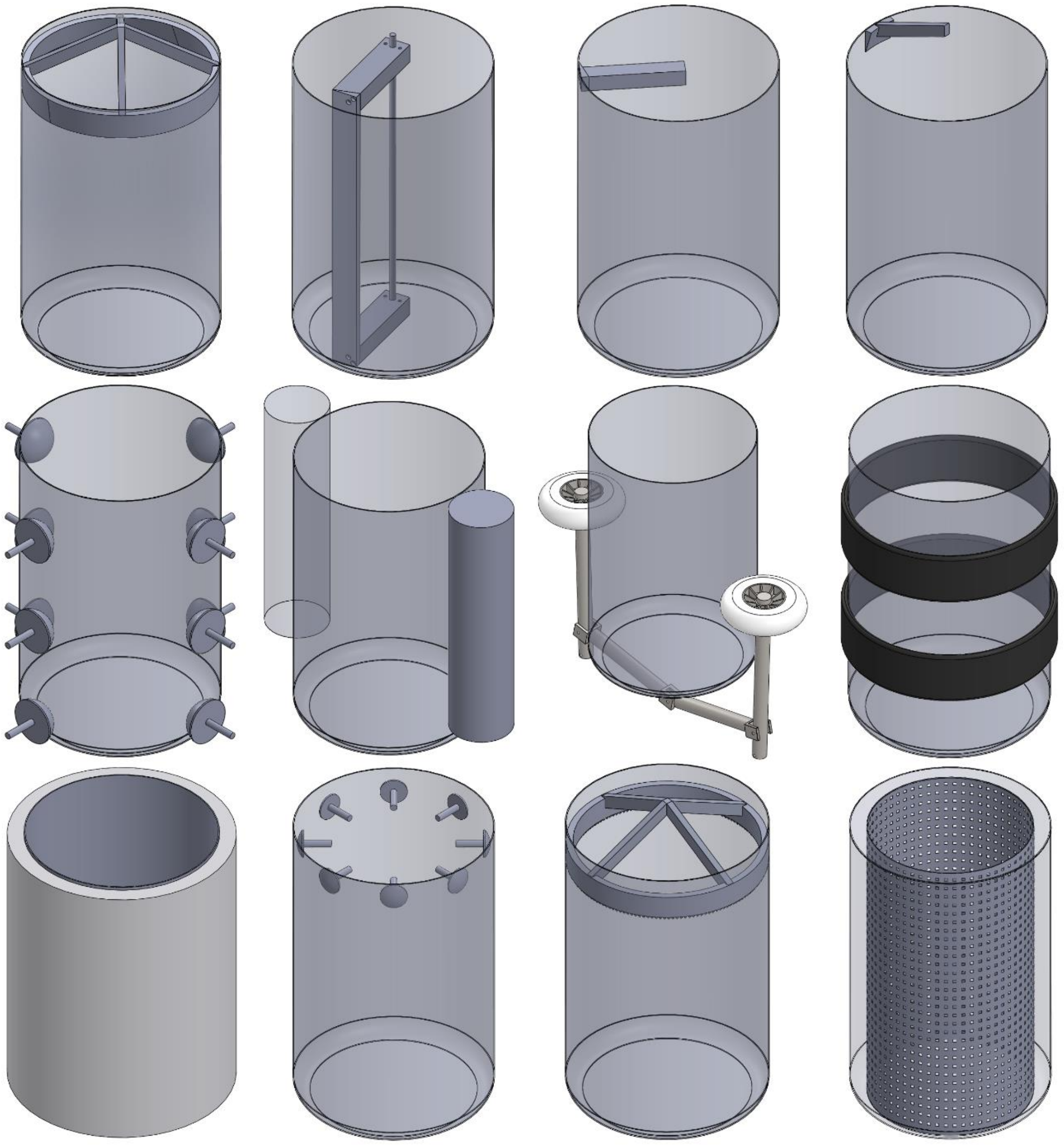

Figure 5. Some design concepts for the ice breaking system. From top left to bottom right: scraping 1, scraping 2, scraping 3, scraping 4, bending 2, bending 3, bending 5, bending 6, heating solutions (except 5 & 6), crushing 1 & 2, crushing 3 and fluid pressure methods.

4.2.1 Selection criteria

To make an appropriate selection of initial design ideas an objective set of selection criteria must be established. The criteria can be divided into three broad categories, costs, environmental impact and effectiveness of the process. The selection criteria are based on the requirements list (§3), however some of these criteria will not be usable at such an early stage of design. Weights of the criteria are given; these were agreed to match the needs of the project. Tables 3 through 5 detail the criteria for use in this stage of the design process.

Table 3. Cost based criteria

Code	**Weight**	**Criterion**	**Details**
C1	1	Capital cost	The cost of making the system, materials, production, licenses, etc.
C2	1.5	Operating cost	The daily cost of operating the system.
C3	1.5	Maintenance cost	Costs and intervals of routine maintenance.

Table 4. Environment based criteria

Code	**Weight**	**Criterion**	**Details**
E1	1.5	Energy	Energy required to operate the system.
E2	0.5	Noise	Level of noise generated by the system.
E3	1	Environmental suitability of process	System ability to operate in different environments.
E4	0.25	Size of solution	Size of the system once produced.

Table 5. Process effectiveness based criteria

Code	**Weight**	**Criterion**	**Details**
P1	2	Failure potential (Reliability)	How the systems could fail.
P2	1	Scalability	The ease at which the system can be scaled for smaller/larger volumes of wastewater.

4.3 Selection stage 1

Selection stage one serves as a filter to remove any concepts or ideas that are otherwise unworkable or incompatible. Scraping (5) is not a viable solution due to ice being harder to shear from itself than from a smooth surface. All chemical means are eliminated because they either directly oppose the aims of the project (chemical 1 – 3) or the technology to implement them is not very mature. Consequently, chemical 4 lacks established reliability and affordable manufacturing processes. All heating concepts are somewhat against the aims of the project, but some are kept due to their early promise in the concept design meeting. Heat 5 option can be immediately removed due to the radioactive and environmental risk this method poses. Heat 6 can be removed because it does not fit the aims of the project. Crushing options are removed due to the higher strength of ice when under compression and impact. Explosion methods are removed due to the potential safety risks, costs of legal regulations and the necessity for personnel trained in explosives to prepare the system for each removal cycle. Fluid pressure expulsion types of methods are removed due to the likelihood of the wastewater seeping into the nozzles and pores where the pressurised fluid would be injected and causing the method to become unreliable or fail.

4.4 Selection stage 2

Selection stage two goes into more detail in selecting the appropriate solution. The aim at the end is to have at least three options available (ideally, each from different groups) for final selection and eventual embodiment design. The selection is carried out using criteria given in §3. Table 2 gives the results of the selection.

4.4.1 Cost based criteria

For the evaluation of capital cost a rough calculation of required material and equipment was performed. Table 6 shows a rough estimate of the costs of each concept.

Table 6. Estimated capital cost breakdown for each breaking concept.

Concept	**Cost items**	**Amount**	**Total**
Scraping 1	Motor/gearbox/drive Raw materials (SS316)	€4000 800kg	€6448[1]

Table 6 continued. Estimated capital cost breakdown for each breaking concept.

Concept	**Cost items**	**Amount**	**Total**
Scraping 2	Linear hydraulic system Raw materials (SS316)	€2000 800kg	€4448[1]
Scraping 3	Motor/gearbox/drive Linear feed actuation Raw materials (SS316)	€2000 €2000 700kg	€6142[1]
Scraping 4	Linear hydraulic system Rotational motion Raw materials (SS316)	€2000 €1000 700kg	€5142[1]
Bending 1	Linear hydraulic system Raw materials (SS316)	€2000 800kg	€4448[1]
Bending 2	Barrel Linear actuators (x12)	€100 €500	€600
Bending 3	Barrel Rollers (x2)	€100 €1000	€1100
Bending 4			
Bending 5	Barrel Wheels (x2) Raw materials (SS316)	€100 €80 200kg	€792[1]
Bending 6	Barrel Inflatable bladder Pressure equipment	€100 €1000 €700	€1800[2]
Heat 1	Barrel Heating jacket	€100 €1500	€1600[3]
Heat 2			
Heat 3			

Table 6 continued. Estimated capital cost breakdown for each breaking concept.

Concept	**Cost items**	**Amount**	**Total**
Heat 4	Barrel Peltier devices (x900)	€100 €14000	€14100[4]
Heat 7	Heating jacket Heat pump	€1500 €1200	€2700
Aviation 1	Barrel Ultrasonic actuators (x2)	€100 €2000	€2100
Aviation 2	Barrel System (manufacturer quote)	€100 Did not reply	NA
Aviation 3	Barrel System	€100 Unable to quantify	NA

General note: Cost is raw material and equipment cost only, no manufacturing costs can be estimated at this stage nor can any frame or structure be calculated for at this time. All prices are taken from trade/B2B supplier or directories online (Alibaba, Direct Industry).

1. Steel price of €3.06/kg (Argus 2016).
2. Inflatable ship launching bladders were chosen as a price benchmark. Actual bladder about 29 litre capacity.
3. The nature of the heating jacket will vary for each concept but prices don't seem to vary heavily.
4. Price taken for a collection of smaller Peltier devices at retail price (Marlow 2016). Does not include heatsink or control hardware.

The cost of scraping and bending solutions (except 6) will consist primarily of the cost of the actuation device, drive system and required reduction gearing. Additional costs will go to the acquisition and production of the framework and cutting/bending tools for the solution as well as the barrel. Bending (6) would require very sturdy flexible tube/bladder in the shape of a ring along with high pressure hydraulic pump to fill the bladder and the barrel and any framework required to keep the assembly together. Heating (except 4) solutions include the price of a barrel and heating system for said barrel. The heating system likely comes in the form of a jacket of heating elements or heat exchangers depending on the specific solution. Heating (4) would require a multitude of small thermoelectric devices as well as heat sinks/cooling and control hardware, in addition to a barrel.

Estimating manufacturing costs cannot be done quantitatively without a more embodied design so they are omitted from the capital cost analysis. At this stage, all that can be done is estimate the concepts' manufacturing complexity relative to each other. The estimated order of manufacturing cost, per group, from lowest to highest is heating < aviation < bending < scraping. The rationale for this is that bending will require some shaft and framework fabrication and scraping will require mostly custom parts, not least a sturdier barrel than for the other solutions. Heating solutions will, at least in early prototyping stages, be comprised of third party components and aviation solutions will need to be sourced from specialist companies. In general, the more material removed, assembly work and fabrication steps, the higher is the likely expense.

Operating costs include only the cost to run the system, so at this stage essentially only energy costs (E1 according to table 4), considering an average of €0.07/kWh (Eurostat 2016). Duty time of 1 minute every 30 minutes for each day of the year. Specific cost of treatment should be competitive with established treatment solutions of a similar scope. Table 7 details the cost breakdown.

Table 7. Estimated operating cost breakdown for each breaking concept.

Concept	**Cost breakdown**	**Amount (pa)**
Scraping 1	1.838 m perimeter, 0.89 m feed, performed in 60 seconds = 170 W 1 cut every 30 minutes, 24 hour running = 8.2 kWh/day	€152[1]
Scraping 2	0.890 m cut length, 1.838 m feed, performed in 60 seconds = 183 W 1 cut every 30 minutes, 24 hour running = 8.8 kWh/day	€224[1]
Scraping 3	0.1 m cut length, 0.1 m feed, 9 feeds per minute, performed in 60 seconds = 4458 W 1 cut every 30 minutes, 24 hour running = 214 kWh/day	€5463[1]
Scraping 4	0.1 m cut width, 0.1 m feed, 9 feeds per minute, performed in 60 seconds = 2536 W 1 cut every 30 minutes, 24 hour running = 122 kWh/day	€3110[1,2]

Table 7 continued. Estimated operating cost breakdown for each breaking concept.

Concept	**Cost breakdown**	**Amount (pa)**
Bending 1	9 tools each performing a 0.1 m cut width, 0.89 m feed, performed in 60 seconds = 80 W 1 cut every 30 minutes, 24 hour running = 4 kWh/day	€100[2,3]
Bending 2	12 mushrooms, 800 N load each, performed in 60 seconds = 1.6 W 1 bend every 30 minutes, 24 hour running = 0.08 kWh/day	€2[3]
Bending 3	1.838 m barrel/roller rotation, required torque of 2 kNm, 0.1 rad/s, performed in 60 seconds = 210 W 1 bend every 30 minutes, 24 hour running = 10.1 kWh/day	€258
Bending 4		
Bending 5		
Bending 6	Flow of at least 2 m^3/h (bladder filled in 60 seconds), pressure of at least 20 MPa, 7.5 kW pump (Hammelmann 2016). 125 W 1 expansion every 30 minutes, 24 hour running = 6 kWh/day	€153
Heat 1	Heat required to melt 2 mm of ice on the boundary between container and ice when the ice is 10 mm thick at -10 C and the water is 10 C. Boundary area is 1.64 m^2. To heat the drum to 10 C requires 36kJ, to heat the ice to its melting point requires 2kJ, to melt the ice requires 135 kJ and to heat the resultant water requires 20kJ. 200kJ in total heated up in a one minute period requires 3.3 kW. 1 melt every 30 minutes, 24 hour running = 160 kWh/day	€4088[4]
Heat 2		
Heat 3		
Heat 7		

Table 7 continued. Estimated operating cost breakdown for each breaking concept.

Heat 4	Heat required to melt 2 mm of ice on the boundary between container and ice when the ice is 10 mm thick at -10 C and the water is 10 C. Thermoelectric methods depend on differences in temperature. Ambient temperature is given at worst case 30 C. Giving a ΔT of 40 C. With a Q_{max} of 9.2 W, I_{max} of 1.9 A, V_{max} of 8 V. Running power is 15.2 watts per module, 900 modules gives 13.7 kW per heat cycle. 1 melt every 30 minutes, 24 hour running = 657 kWh/day	€16777[5]
Aviation 1	Per Palacios (2011) ultrasonic ice removal requires 0.07 W/cm^2. With a barrel area of 16357 cm^2, each ice removal would require 1145 W. 1 removal every 30 minutes, 24 hour running = 55 kWh/day	€1404
Aviation 2	These were unable to be calculated.	
Aviation 3		

1. These figures only account for scraping force.
2. These calculations do not account for the required force to shear ice from ice on each feed.
3. These calculations resulted in results that were outside the bounds of sanity.
4. Price given for joule heating. Gas, process fluid and heat pump costs not calculated.
5. Calculation is based on a static temperature. Voltage is temperature dependent so would influence the power requirements.

Maintenance costs cannot be quantified at this stage without a more embodied design. As with manufacturing costs each concept will be ranked qualitatively, relative to the others, on its potential maintenance cost. Table 8 gives details of this ranking.

Table 8. Estimated maintenance cost breakdown for each concept.

Concept	**Possible maintenance items**	**Ranking**
Scraping 1	Replacement of worn cutting tool, replacement of worn barrel, repair/replacement of power transmission equipment, replacement of control electronics.	10
Scraping 2		10
Scraping 3		9
Scraping 4		9

Table 8 continued. Estimated maintenance cost breakdown for each concept.

Bending 1	Replacement of worn cutting tool, replacement of worn barrel, repair/replacement of power transmission equipment, replacement of control electronics.	10
Bending 2	Replacement of worn bending mushroom/roller, replacement of worn barrel, repair/replacement of power transmission equipment, replacement of control electronics.	7
Bending 3		6
Bending 4		6
Bending 5		4
Bending 6	Cleaning/replacement of pump filters, replacement of worn bladder, replacement of worn barrel, repair/replacement of valves and controls, repair/replacement of pump, replacement of pressure transmission lines.	5
Heat 1	Repair/replacement of heating jacket, replacement of worn barrel, replacement of control systems, replacement of fluid transmission lines.	2
Heat 2		3
Heat 3		3
Heat 4	Replacement of elements, replacement of heatsinks, replacement of barrel, replacement of control electronics.	11
Heat 7	Filter/fan/general maintenance of heat pump system, replacement of worn barrel, repair/replacement of heat pump system, replacement of control systems, replacement of fluid transmission lines.	8
Aviation 1	Replacement of worn actuators, replacement of worn barrel, replacement of control electronics.	1
Aviation 2	Cannot specify	NA
Aviation 3		NA

Scraping solutions (1 and 2) have a high expected maintenance cost due to the cutting and wearing nature of their operation and due to the size and bulk of the expected design.

Scraping (3 and 4) have smaller cutting tools however they require additional feeding mechanisms so still rank highly in terms of maintenance costs.

Bending (1) is a more complex form of scraping (4) so ranks highly. Bending (2) requires many specialist bending mushrooms along with actuation for each one, so maintenance potential and cost can be expected to be higher than for bending (3 – 6). Bending (3 and 4) are similar concepts so they have similar potential for maintenance and cost. Bending (5) is a simpler concept than the other roller type concepts so access and availability of the parts should be better than with the long rollers. Bending (6) has the problem of requiring a specialist bladder which will need replacing periodically, along with a pump to pressurise the bladder which will require maintenance, possibly more so than a simple mechanical drive.

Joule heating (1) should offer the easiest approach to maintenance being that most components of this concept will be off the shelf, readily available and easily swapped out. Heating (2 and 3) offer a slightly higher cost because heat exchangers and safe gas burners are not as readily available or as light in weight as electric heating shrouds. Heating (4) is likely to be expensive, there could be nearly 1000 devices, plus their heatsinks and controllers. Peltier devices are fragile and prone to failure in moist and harsh environments and would be hard to replace without harming the rest of the installation. Heating (7) is similar to heating (1 – 3) but the heat source is a heat pump and would require more specialist maintenance procedures than a simple shroud.

Aviation (1) is the only aviation method that could be estimated for. There are only 2 transducers and they should bolt in and out quickly. There is a concern with barrel fatigue, but this can be designed for.

Life expectancy of the systems could be one possible decision factor; however, an accurate estimation would be impossible at this stage. Per Güereca et al. (2009) Mexican wastewater treatment works are designed for a 20-year life expectancy and per O’Sullivan et al (2015) and Machado et al. (2007) storm and wastewater treatment systems are expected to last 30 years, albeit these are simpler more passive systems. Any chosen system should, ideally, be capable of meeting this with only scheduled maintenance.

4.4.2 Environment based criteria

Energy use estimations have already been included in the operating cost section. However, over the whole product lifecycle, energy use must be analysed. Lifecycle includes manufacturing, assembly, operation, dismantling and disposal of the system. As with manufacturing costs an estimation of lifecycle energy use goes from lowest to highest: heating < aviation < bending < scraping. The rationale is the same for both. This aspect cannot be elaborated on in this stage of the design process.

Noise levels perceptible outside of the system should firstly be within allowable national standards and directives. Systems should be designed as such that noise is reduced as much as possible within the costs allowed. Information is scarce on the noise level of small, isolated areas of thin ice breaking, however it is unlikely this would be greater than the noise of any mechanics in the system. The sound of metal on metal contact and hydraulic actuation is of a higher pitch than most sounds, so will be perceived as being louder than systems of lower frequency (Goelzer, Hansen & Sehrndt 2001, p. 43). However, in situations of combined high and low frequency sounds, low frequency tends to lessen the impact of high frequencies (Goelzer et al. 2001, p. 43). Unfortunately, it is difficult to quantify noise levels for these processes so a qualitative ranking is the best that can be done at this stage.

In IEC 60034-9 (2003) maximum noise levels for suitable electric motors (at full load) are given as up to 84 dB and this would be a good base point for the operating noise level for the system’s operation itself. Noise requirements will differ for industrial, remote and residential areas and for all night operation, in accordance with national directives.

Table 9 shows an overview of noise levels of the concepts. The table lists factors contributing to the noise of each concept with a qualitative ranking of each concept based on these factors.

Table 9. Estimated continuous noise impact for each breaking concept.

Concept	**Noise sources**	**Level**	**Ranking**
Scraping 1	Hydraulic system	74 dB(A)[1]	10
	Ice breaking Tool/barrel interaction	NA	
Scraping 2	Motor rotation	85 dB(A)[2]	11
	Ice breaking Tool/barrel interaction	NA	
Scraping 3	Motor rotation	85 dB(A)	9
	Ice breaking Tool/barrel interaction	NA	
Scraping 4	Hydraulic system	74 dB(A)	9
	Ice breaking Tool/barrel interaction	NA	
Bending 1	Hydraulic system	74 dB(A)	10
	Ice breaking Tool/barrel interaction	NA	
Bending 2	Mushroom actuation	74 dB(A)	6
	Ice breaking Barrel bending	NA	
Bending 3	Motor rotation	85 dB(A)	7
	Ice breaking Barrel bending	NA	

Table 9 continued. Estimated continuous noise impact for each breaking concept.

Concept	**Noise sources**	**Level**	**Ranking**
Bending 4	Motor rotation	85 dB(A)	7
	Ice breaking Barrel bending	NA	
Bending 5	Motor rotation	85 dB(A)	7
	Ice breaking Barrel bending	NA	
Bending 6	Compressor or pump	100 dB(A)[3,4]	8
	Ice breaking Barrel bending	NA	
Heat 1	Ice cracking Electrical noise	NA	1
Heat 2	Ice cracking Burner noise	NA	2
Heat 3	Ice cracking Fluid flow noise	NA	2
Heat 4	Ice cracking Cooling system noise Electrical noise	NA	4
Heat 7	Ice cracking Heat pump noise	NA	3
Aviation 1	Actuation noise Ice breaking Barrel vibration	NA	5

Table 9 continued. Estimated continuous noise impact for each breaking concept.

Concept	**Noise sources**	**Level**	**Ranking**
Aviation 2	Actuation noise Ice breaking	NA	NA
Aviation 3	Actuation noise Ice breaking	NA	NA

1. Eaton Vickers 2002
2. IEC 60034-9 2003
3. Goelzer et al. 2001
4. EPD 1999

The environmental suitability of the process depends on the environment the system will be installed into. For example, natural freezing depends on an environment that reaches and sustains freezing temperatures for extended periods of time. Table 10 evaluates the possible environmental issues that could be faced with each solution. The number of possible issues is the rank of the solution.

Table 10. Environmental compatibility for each breaking concept.

Concept	**Potential environmental compatibility issues**	**Ranking**
Scraping 1	Corrosion of submerged parts, low temperature effects on moving parts, geometrical tolerance issues due to temperature changes	3
Scraping 2		
Scraping 3	Corrosion of submerged parts, low temperature effects on moving parts (rotation and feed), geometrical tolerance issues due to temperature changes	4
Scraping 4		
Bending 1	Corrosion of submerged parts, low temperature effects on moving parts, geometrical tolerance issues due to temperature changes	3
Bending 2	Low temperature effects on moving parts, low temperature degradation of roller material	2
Bending 3		
Bending 4		
Bending 5		
Bending 6	Low temperature effects on pressure liquid, low temperature degradation of bladder material, low temperature problems relating to the pump	3

Table 10 continued. Environmental compatibility for each breaking concept.

Concept	**Potential environmental compatibility issues**	**Ranking**
Heat 1	None	0
Heat 2	Low temperature effects on gas nozzles	1
Heat 3	Low temperature effects on heat exchanger channels	1
Heat 4	Effects of temperature on thermoelectric modules, low-temperature effects on electronics, low temperature effects on cooling system	3
Heat 7	Effectiveness of heat pumps as temperatures drop	1
Aviation 1	Low temperature effects on actuators	1
Aviation 2	NA	NA
Aviation 3	NA	NA

The size estimates given are that of a rectangular box into which all components of the system will fit. This should be small enough to meet the requirements laid out in §3 when included with ice harvesting and further processing equipment needed for the entire system. The size of the barrel will always be the same and is 0.305 m^3 and the size of motors and hydraulics are all kept roughly the same for each concept. The idea is not to accurately predict the design geometry but to give a rough figure of the design volume requirements. Table 11 gives the estimated justification for the size of each solution.

Table 11. Bounding box size for each braking concept.

Concept	**Rationale (All dimensions in m^3)**	**Size [m3]**	**Ranking**
Scraping 1	Barrel volume: 0.305, another barrel volume for hydraulic actuator and stability structure: 0.305, hydraulic system: 0.5[1]	1.11	10
Scraping 2	Barrel volume: 0.305, motor and drive hardware: 0.128[2]	0.43	2

Table 11 continued. Bounding box size for each braking concept.

Concept	**Rationale (All dimensions in m^3)**	**Size [m3]**	**Ranking**
Scraping 3	Barrel volume: 0.305, cutting rotation motor and drive hardware: 0.128, feed motor and drive hardware: 0.128	0.56	5
Scraping 4	Barrel volume: 0.305, another barrel volume for hydraulic actuator and stability structure: 0.305, hydraulic system: 0.5[1], feed motor and drive hardware: 0.128	1.24	11
Bending 1	Barrel volume: 0.305, another barrel volume for hydraulic actuator and stability structure: 0.305, hydraulic system: 0.5[1]	1.11	10
Bending 2	Barrel volume: 0.305, actuators: 0.0053[3], hydraulic system: 0.5[1]	0.81	8
Bending 3	Barrel volume: 0.305, rollers: 0.0016[4], motor and drive hardware: 0.128[2]	0.59	6
Bending 4	Barrel volume: 0.305, rollers: 0.09[5], motor and drive hardware: 0.128[2]	0.52	4
Bending 5	Barrel volume: 0.305, rollers: 0.009[6], motor and drive hardware: 0.128[2]	0.45	3
Bending 6	Barrel volume: 0.305, bladder (inflated): 0.12, pump and control hardware: 0.67[7]	1.1	9
Heat 1	Barrel volume: 0.305, heating jacket: 0.355[8]	0.66	7
Heat 2			
Heat 3			
Heat 4	Barrel volume: 0.305, modules: 0.033[9], control electronics: 0.087[10]	0.43	2
Heat 7	Barrel volume: 0.305, heating jacket: 0.355[8]	0.66	7
Aviation 1	Barrel volume: 0.305, actuator and controllers: 0.01[11]	0.32	1
Aviation 2	NA	NA	NA

Table 11 continued. Bounding box size for each braking concept.

Concept	**Rationale (All dimensions in m^3)**	**Size [m3]**	**Ranking**
Aviation 3			

1. Bosch 2014
2. IMO 2016
3. MOOG 2016
4. Assuming rollers of 0.3 m diameter, barrel rotating
5. Assuming rollers of 0.3 m diameter, 0.5 m long, barrel rotating
6. 0.3 m diameter wheels, with shafts, barrel rotating
7. Hammelmann 2013
8. Heating jacket assumed to be 5 cm thick.
9. Not including any heat transfer material necessary.
10. Individual controllers per 2 devices (Meerstetter 2016)
11. Etrema 2009

4.4.3 Effectiveness based criteria

The potential for failure for each solution would require a more embodied design to have been created, however, some estimations of the potential failure modes can be made from what is known about the solutions. Each solution suffers from some basic possibilities; the possibility of human error and act of god are ever present. The possibility of barrel corrosion is present under some circumstances depending on barrel materials and fatigue is an issue requiring investigation wherever cyclic loading occurs.

The scraping solutions have the highest potential for failure, the scraping tools will be partially in contact with the container, they use mechanical actuation and in some cases, more than one direction of motion during the process. This is a potential risk, the more mechanical and contact elements present in the system the more potential for failure. This applies similarly for most bending solutions which mechanically deform the container, as well as contact between container and rollers. In addition to this, the bending solutions have actuation and mechanical movements which need considering in failure predictions. Heating solutions themselves do not wear in a mechanical fashion, however heating elements have a limited life and the thermal cycling could lead to the integrity of the drum being reduced.

All solutions have the requirement of third-party components which are all subject to failure. Failure prediction information would have to be sourced from the supplier to integrate the information into failure prediction calculations. Table 12 shows some possible failure aspects of each system and their totals.

Table 12. Failure potential and risks for each breaking concept.

Concept	**Potential failure**	**Count**
Scraping 1	Abrasive wear of tool-ice/tool-barrel interfaces, corrosion of tool/barrel, fatigue failure of tool/mechanism, structural failure of tool/mechanism/barrel, actuator failure[1], gear failure[1], act of god, human error	13
Scraping 2		
Scraping 3	Abrasive wear of tool-ice/tool-barrel interfaces, corrosion of tool/barrel, fatigue failure of tool/mechanism (cut and feed), structural failure of tool/mechanism (cut and feed)/barrel, actuator (cutting and feed) failure, gear failure, act of god, human error	16
Scraping 4		
Bending 1	Abrasive wear of tool-ice/tool-barrel interfaces, corrosion of tool/barrel, fatigue failure of tool/mechanism, structural failure of tool/mechanism/barrel, actuator failure, gear failure, act of god, human error	13
Bending 2	Corrosion of barrel, fatigue failure of tool/mechanism/barrel, structural failure of tool/mechanism/barrel, actuator failure, gear failure, act of god, human error	11
Bending 3	Abrasion between roller-barrel, corrosion of barrel, fatigue failure of roller/mechanism/barrel, structural failure of roller/mechanism/barrel, actuator failure, gear failure, act of god, human error	12
Bending 4		
Bending 5		
Bending 6	Contact wear between bladder and barrel, corrosion of barrel, fatigue failure of barrel, structural failure of barrel, bladder failure[1], pump failure[1], act of god, human error	8
Heat 1	Thermal fatigue of barrel, corrosion of barrel, thermal fatigue of heating jacket[1], heat supply failure[1], act of god, human error	6
Heat 2		
Heat 3		

Table 12 continued. Failure potential and risks for each breaking concept.

Concept	**Potential failure**	**Count**
Heat 4	Moisture damage to elements, moisture damage to control electronics, mechanical degradation between barrel-element/element-heat transfer media, element failure[1], corrosion of barrel, power conversion system failure[1], sensor failure[1], act of god, human error	10
Heat 7	Thermal fatigue of barrel, corrosion of barrel, thermal fatigue of heating jacket, heat supply failure, act of god, human error	6
Aviation 1	Corrosion of barrel, fatigue failure of barrel, mechanical failure of barrel-actuator interface, actuator failure[1], control system failure[1], support structure failure, act of god, human error	8
Aviation 2	NA	NA
Aviation 3	NA	NA

1. These components are likely to be sourced externally and will have their own failure modes.

The scalability of the system is limited by the requirement that the system be between 50 and 200 litres in capacity. There is little reason that any of these systems can't be scaled down from the 200 L volume chosen for the initial stages of selection. Once a design is finalised, the exact scalability and specifications of the system elements can be calculated. Table 13 lists the design variables for scalability as well as a qualitative scalability ranking for each solution.

Table 13. Scalability potential for each concept.

Concept	**Scalability aspects**	**Ranking**
Scraping 1	Required motor torque, required mechanism geometry, required tool geometry, required barrel geometry	6
Scraping 2		
Scraping 3		5
Scraping 4		
Bending 1		4
Bending 2	Required number of mushrooms, required power	4

Table 13 continued. Scalability potential for each concept.

Concept	**Scalability aspects**	**Ranking**
Bending 3	Required motor torque, required roller geometry	3
Bending 4		
Bending 5	Required motor torque, required number of rollers	3
Bending 6	Required pump power, required number of bladders	3
Heat 1	Required energy, required jacket size	1
Heat 2		
Heat 3	Required heat energy to be removed from process fluid, required jacket size	1
Heat 4	Element quantity, control electronics quantity, power requirement	3
Heat 7	Heat pump capacity, heat pump power, required jacket size	2
Aviation 1	Required frequency, required power	1
Aviation 2	NA	NA
Aviation 3	NA	NA

4.5 Selection

Table 14 shows a simple grid summing up the weighted results of all criteria. The selections are made by the smallest total value from three differing groups.

Table 14. Weighted breaking concept evaluation (Smaller is better).

Concept	**Criteria**									**Total**
	Cost			**Environment**				**Effectiveness**		
	C1	**C2**	**C3**	**E1**	**E2**	**E3**	**E4**	**P1**	**P2**	
Scraping 1	10	4	15	See note 1	5	3	2,5	26	6	73,5
Scraping 2	7	5	15		5,5	3	0,5	26	6	70,5
Scraping 3	9	10	13,5		4,5	4	1,25	32	5	84,25
Scraping 4	8	8	13,5		4,5	4	2,75	32	5	81,75
Bending 1	7	3	15		5	3	2,5	26	4	67
Bending 2	1	1	10,5		3	2	2	22	4	46
Bending 3	3	6	9		3,5	2	1,5	24	3	55
Bending 4	3	6	9		3,5	2	1	24	3	54,5
Bending 5	2	6	6		3,5	2	0,75	24	3	50,25
Bending 6	5	2	7,5		4	3	2,25	16	3	**43,75**
Heat 1	4	9	3		0,5	0	1,75	12	1	**35,75**
Heat 2	4	9	4,5		1	1	1,75	12	1	38,75
Heat 3	4	9	4,5		1	1	1,75	12	1	38,75
Heat 4	11	11	16,5		2	3	0,5	20	3	72,5
Heat 7	6	9	12		1,5	1	1,75	12	2	49,75
Aviation 1	5	7	1,5		2,5	1	0,25	16	1	**37,75**
Aviation 2	NA	NA	NA		NA	NA	NA	NA	NA	NA
Aviation 3	NA	NA	NA		NA	NA	NA	NA	NA	NA

1. In this case energy use is only estimable for operating costs, a full life cycle energy cost can't be performed until a more embodied design is available.

While not all the demands and wishes given in §3 could be elaborated on in the conceptual design stage many could and this evaluation gives the three most suitable solutions as bending 6, heat 1 and aviation 1. These are "fluid expandable tube", "joule heating" and "vibration induced breaking" respectively.

Viewing the weighted total, a pattern is quite clearly visible in that scraping solutions are not viable for this type of ice removal. Heating performs very well but this must be taken with the knowledge that losses are not accounted for in the calculation of required energy.

Bending in general fits very well between scraping and heat, and could, once a more embodied design is worked on, turn out to be superior to heat when all losses and factors are accounted for. It is a shame that information about other aviation methods was not easily located as it would have been good to compare these methods as well. In general, aviation 1 looks like a very good solution, if the mechanics of the system can be worked out and formed into an adequate solution.

5 ICE HARVESTING CONCEPT SELECTION

The initial selection methodology for ice harvesting will follow the same process as used in §4. Table 15 lists concepts and their description, table 16 gives the results of the selection stages and figure 6 shows some of the concepts.

Table 15. Early concepts for ice removal.

Concept	**Description**
Lifting 1	Piecemeal with grabber
Lifting 2	Non-collapsible basket
Lifting 3	Vegetable steamer (collapsible) basket
Lifting 4	Helix basket
Lifting 5	Orange peel grabber
Lifting 6	Conveyor belt and cups
Pouring 1	Simple trunnion mount, and pour
Pouring 2	Trunnion and crane
Pouring 3	Open bottom
Sucking 1	Piecemeal with vacuum
Sucking 2	Pumping the water and ice from the barrel
Sucking 3	Pumping the water from the barrel and otherwise getting to the ice
Sucking 4	Suck the ice floating on top of the barrel, from the side
Blowing 1	Blowing each piece individually from below
Blowing 2	Pumping water into the barrel rapidly to cause ice to fall over the brim
Blowing 3	Blowing ice floating on top of the barrel (similar to an air curtain)
Slurry 1	Pumping slurry onto a fine mesh

Table 16. Concept evaluation.

Concept	**S1**	**S2**	**Notes**
Lifting 1	X		Complicated and slow
Lifting 2	X		Would require the basket to be inside the barrel during freeze. Not compatible with chosen breaking methods.
Lifting 3	✓	X	Failed selection two
Lifting 4	✓	X	Failed selection two
Lifting 5	✓	X	Failed selection two
Lifting 6	X		Overly complex
Pouring 1	✓	✓	
Pouring 2	X		Pouring 1 is acceptable. This concept is similar but more complicated
Pouring 3	✓	✓	
Sucking 1	X		Complicated and slow
Sucking 2	✓	✓	
Sucking 3	X		Similar to pouring 3. Requires another method of ice removal in addition.
Sucking 4	X		Very powerful pump required.
Blowing 1	X		Bloody stupid
Blowing 2	X		Unpredictable, messy, unsafe
Blowing 3	✓	X	Failed selection two
Slurry 1	X		An idea for further exploration, but not for the currently selected breaking methods

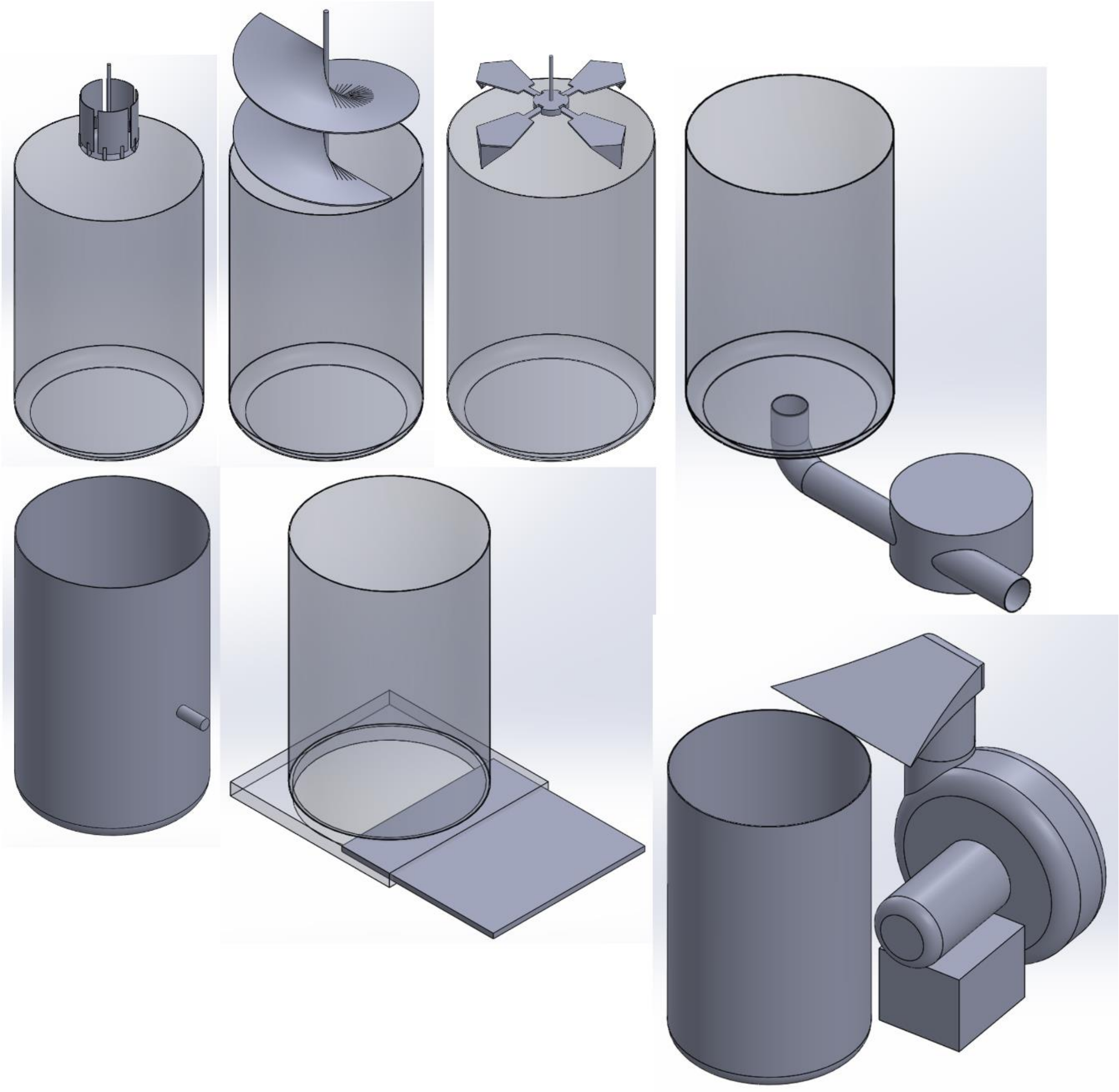

Figure 6. Some design concepts for the ice harvesting system. From top left to bottom right: lifting 3, lifting 4, lifting 5, sucking 2, pouring 1, pouring 3 and blowing 3.

5.1.1 Selection criteria

The selection criteria for ice harvesting methods are essentially the same as for ice breaking methods. Tables 3 through 5 in §4.3.1 detail the criteria for use in this stage of the design process.

5.2 Selection stage 1

Selection stage one serves as a filter to remove any concepts or ideas that are otherwise unworkable. Lifting 1, 2 and 6 are removed as they are respectively: too slow and complex, not compatible with the ice breaking solution chosen and too complicated. Pouring 2 adds additional complexity to pouring 1. Sucking 1 suffers from the same problems as with lifting 1, it is too complicated to implement and too slow and sucking 3 adds more energy to do the same job as pouring 3. Sucking 4 would require a very high flow rate pump in order to produce the flow required to suck the ice from the surface. Blowing 1 is not a good solution, complicated, messy and likely high energy use. Blowing 2 is not very predictable in where the ice will fall or where the expelled water will drain to, in additional it is messy and potentially unsafe to those working on the device. Slurry 1 can be eliminated as it isn't compatible with the breaking methods chosen. However, the idea could be worth exploring in future.

5.3 Selection stage 2

Selection stage two goes into more detail in selecting the appropriate solution. The aim at the end is to have at least three options available (each from different groups) for final selection and eventual embodiment design. The selection is carried out using criteria given in §5.1.1 (selection criteria). Table 16 gives the results of the selection.

5.3.1 Cost based criteria

For the evaluation of capital cost a rough calculation of required material and equipment was performed. Table 17 shows a rough estimate of the costs of each concept.

Table 17. Estimated capital cost breakdown for each harvesting concept.

Concept	**Cost items**	**Amount**	**Total**
Lifting 3	Linear vertical actuation	€2000[1]	€2125[2]
	Horizontal motion actuator	-	
	Actuator for opening/closing	€50	
	Material (SS316)	25 kg	
Lifting 4	Linear vertical actuation	€2000[1]	€2105[2]
	Horizontal motion actuator	-	
	Angular actuator for rotation of screw	€30	
	Material (SS316)	25 kg	

Table 17 continued. Estimated capital cost breakdown for each harvesting concept.

Concept	**Cost items**	**Amount**	**Total**
Lifting 5	Linear vertical actuation Horizontal motion actuator Actuator for opening/closing Material (SS316)	€2000[1] - €50 25 kg	€2125[2]
Pouring 1	Angular actuation Material	€1000 €50	€1050[3]
Pouring 3	Gate valve Valve actuator	€500 €1000	€1500
Sucking 2	Pump	€2000	€2000
Blowing 3	Blower Material	€900 €100	€1000

General note: Cost is raw material and equipment cost only, no manufacturing costs can be estimated at this stage nor can any frame or structure be calculated for now. Material costs are a liberal estimate; no detail calculations have been made as of this stage. All prices are taken from trade/B2B supplier or directories online.

1. Vertical lifting and horizontal positioning achieved by a small crane. Low end price for small automated jib crane.
2. Steel price of €3.06/kg (Argus 2016).
3. Material is hard to estimate, polypropylene bonded to the drum and attached to bearing material. Perhaps some reinforcement around the band.

The lifting solutions will require the most fabrication, in that they use significant bespoke mechanisms and geometries. They will all require the use of a linear motion as well as some form of actuation. In the case of versions 3 and 5 the actuation likely will be linear and for version 4 it will be angular. Lifting methods leave higher concentration water in the barrel, this could need draining and replacing with fresh wastewater. In this eventuality, additional cost will go to pumping or pouring arrangements.

Pouring removes the water and ice in one motion. The standout solution involves pouring through a mesh so that the wastewater remaining is diverted to another location and the ice is collected on the mesh and then diverted to storage or further treatment. Pouring 1 is a simple solution which would require only the use of a trunnion, mount and angular actuation.

Pouring 3 would require a custom barrel and sealing mechanism, actuated either linearly or angularly.

The sucking and blowing solutions will require pumps of some kind. Sucking 2 would be best suited to a peristaltic type pump as these do not react badly to solid matter mixed with the fluid being pumped (Pumpkin Pumps 2014). A 300 l/min pump would empty the barrel in in less than a minute, which is a good time to prevent refreezing and allow for a quick turnaround. Once pumped the ice would likely be smaller than as broken so a finer mesh filter would be needed than with other methods. Blowing 2 uses a pump to add water rapidly to the barrel causing the ice pieces to flow over the top of the barrel into some sort of collector which allows water to pass through and ice to be sorted for storage or treatment. The same pump as for sucking 2 is specified. Once all the ice is removed the remaining wastewater may need removing and replacing with wastewater of the correct concentration.

Sucking 4 and blowing 3 share similarities. They both use the flow of air over the top of the barrel to move the ice pieces over the brim of the barrel. These would require air pumps which can deliver significant air flow and nozzles designed to maximise that potential flow. Combining blowing and sucking could enhance the capabilities of this solution. These solutions are hard to calculate for.

Estimating manufacturing costs cannot be done quantitatively without a more embodied design, so they are omitted from the capital cost analysis. At this stage, all that can be done is estimate the concepts’ manufacturing complexity relative to each other. Thus, the estimated order of manufacturing cost, per group, from lowest to highest is pouring < blowing < sucking < lifting. The rationale for this is that lifting will require some mechanism fabrication along with the production of wire mesh based surfaces. Sucking and blowing will require the production of nozzles and ducting to transfer air flow and possible ice piece flow, or alternatively a catching arrangement for ice. Pouring will require at the very least some modification of the plastic barrel. All methods will need some ice transportation/water removal method.

It should be noted that for testing purposes lifting and handling of any harvesting devices will be performed manually or with the aid of warehouse equipment. But for a production device a permanent optimised set up must be arranged.

Operating costs include only the cost to run the system, so at this stage essentially only energy costs (E1 per table 4 in §4.3.1), taking an average of €0.07/kWh (Eurostat 2016). Duty time of 1 minute every 30 minutes for each day of the year. Specific cost of treatment should be competitive with established treatment solutions of a similar scope. Table 18 details the cost breakdown.

Table 18. Estimated operating cost breakdown for each harvesting concept

Concept	**Cost items**	**Total (pa)**
Lifting 3	Lift 0.5 m, move across 1 m to barrel, lower 0.5 m into barrel, open basket, lift 0.5 m, move 1 m away from barrel, lower 0.5 m, open basket to dropping position, close basket. Each step taking about 10 s each: 15 W. Total 110 W. Once every 30 minutes, 24 hour running = 5.3 kWh/day	€135[1]
Lifting 4		
Lifting 5		
Pouring 1	Rotate barrel 90°, whole process with estimated maximum moment: 185 Nm, rotation performed in 10 seconds: 30 W Once every 30 minutes, 24 hour running = 1.44 kWh/day	€37
Pouring 3	Steel/steel gate valve, loaded with water, negligible Δp. Open (move 0.635 m) in 10 seconds: 83 W Once every 30 minutes, 24 hour running = 1.99 kWh/day	€51[2]
Sucking 2	Flow of at least 12 m^3/h (barrel emptied in 60 seconds), minimal head and Δp, 2.2 kW pump (Pumpkin Pumps, 2014): 37 W Once every 30 minutes, 24 hour running = 1.78 kWh/day	€45
Blowing 3	High air flow (600 m^3/h peak) through 1 x 570 mm air blade nozzle. 60 second duration, 8.6 kW blower: 143 W Once every 30 minutes, 24 hour running = 6.88 kWh/day	€176

1. Assumed same power requirements for linear motion as well as basket actuation and rotational motion.
2. Steel/steel $\mu=0.8$. Valve disk 100 mm greater in diameter than barrel bottom.

Maintenance costs cannot be quantified at this stage without a more embodied design. As with manufacturing costs each concept will be ranked relative to the other on its potential maintenance cost. Table 19 gives details of this ranking.

Table 19. Estimated maintenance cost breakdown for each harvesting concept

Concept	**Possible maintenance items**	**Ranking**
Lifting 3	Replacement of worn/corroded hinges, replacement of worn/corroded plates, replacement of opening actuator, repair/replacement of worn/corroded opening mechanism, repair/replacement of lifting/moving device, replacement of drive motor, replacement of electronics	5
Lifting 4	Replacement of worn/corroded basket, repair/replacement of rotation actuator, repair/replacement of lifting/moving device, replacement of drive motor, replacement of electronics	3
Lifting 5	Replacement of worn/corroded tines, replacement of worn/corroded tine hub, replacement of opening actuator, repair/replacement of worn/corroded opening mechanism, repair/replacement of lifting/moving device, replacement of drive motor, replacement of electronics	5
Pouring 1	Replacement of bearing surface, replacement of barrel[1], repair/replacement of gearbox, repair/replacement of tilting motor, replacement of electronics	1
Pouring 3	Replacement of valve sealing elements, repair/replacement of valve body, replacement of valve gate, repair/replacement of actuator, replacement of electronics	2
Sucking 2	Cleaning/replacement of pump filters, repair/replacement of valves and controls, repair/replacement of pump, replacement of fluid transmission lines, replacement of electronics	4
Blowing 3	Cleaning/replacement of filter, cleaning/replacement of air blade nozzle, repair/replacement of air ducting, repair/replacement of blower, replacement of electronics	3

1. Barrel and trunnions may have to be an integrated or inseparable part, requiring replacement when either sub-part fails

Lifting solutions have a high expected maintenance cost due to the complexity of the mechanics of these solutions. The mechanics of lifting solutions 3 and 5 are regularly submerged in the waste water leading to potential for corrosion and fouling.

Pouring solution 1 may be the cheapest solution to maintain. All the mechanics for this solution are outside of the barrel and the equipment is not expected to be particularly specialised. Pouring 3 on the other hand uses some special equipment (the gate valve) which may need to be bespoke which will add to the cost of replacement. Pouring 3 also requires part of the mechanics of the valve to be in contact with the waste water with all the risks that entails.

Sucking solution 2 will require a peristaltic pump (or other capable of handling solids), these have a certain expense to them when they need replacement. Pumps will also require their own maintenance procedures and expenditure. Additional maintenance required will be on the pipework from barrel to pump, joints and seals between barrel and harvesting solution.

The blowing solution (3) is the most sensitive to alignment and conditions of all solutions. The ductwork from blower to barrel top must be aligned properly and checked for impediment and misalignment. The “air curtain” nozzle must be custom made to reasonably high tolerances and will not be an inexpensive item. The blower itself will have maintenance costs and procedures itself which would have to be considered.

Life expectancy of the systems could be one possible factor; however, an accurate estimation would be impossible at this stage. The notes in §4.5.1 apply to the harvesting sub process also.

5.3.2 Environment based criteria

Environment based criteria for ice harvesting concepts are the same as for ice breaking concepts given in §4.6. This applies to energy use, noise, suitability and size.

Energy use estimations have already been included in §5.3.1. However, the same caveats regarding the product lifecycle given in §4.5.2 apply for harvesting concepts too. As with manufacturing costs an estimation of lifecycle energy use goes from lowest to highest:

pouring < blowing < sucking < lifting. The rationale is the same for both. This aspect must be elaborated on in a later stage of the design process.

As previously stated, in IEC 60034-9 (2003) maximum noise levels for suitable small electric motors (at full load) are given as up to 75 dB and this would be a good base point for the operating noise level for the system's operation itself. Noise requirements will differ depending on time and location of operation, in accordance with national directives.

Table 20 shows an overview of noise levels of the concepts. The table lists factors contributing to the noise of each concept with a qualitative ranking of each concept based on these factors.

Table 20. Estimated continuous noise impact for each harvesting concept.

Concept	**Noise sources**	**Level**	**Ranking**
Lifting 3	Crane motion Basket actuation Barrel pump	75 dB(A)[1] 92 dB(A)[2]	4
Lifting 4	Crane motion Basket rotation Barrel pump	75 dB(A) 92 dB(A)	3
Lifting 5	Crane motion Grabber actuation Barrel pump	75 dB(A) 92 dB(A)	4
Pouring 1	Rotation motor Water pouring	75 dB(A)[1]	2
Pouring 3	Valve actuation Water pouring		1

Table 20 continued. Estimated continuous noise impact for each harvesting concept.

Concept	Noise sources	Level	Ranking
Sucking 2	Pump Ice crushing noise in pump	92 dB(A)[1]	4
Blowing 3	Air flow Blower Ice falling Water spray Barrel pump	105 dB(A)[2] 105 dB(A)[2] 92 dB(A)	5

1. IEC 60034-9 2003
2. EPD 1999
3. Goelzer et al. 2001

Table 21 evaluates the possible environmental issues that could be faced with each solution. The number of possible issues is the rank of the solution. The caveats are the same as expressed in §4.5.2.

Table 21. Environmental compatibility for each harvesting concept.

Concept	Potential environmental compatibility issues	Ranking
Lifting 3	Corrosion of submerged parts, low temperature effects on mechanism, low temperature effects on motors/actuators, lubricants contaminating ice	5
Lifting 4	Corrosion of submerged parts, low temperature effects on mechanism, low temperature effects on motors, lubricants contaminating ice	4
Lifting 5	Corrosion of submerged parts, low temperature effects on mechanism, low temperature effects on motors/actuators, lubricants contaminating ice	5
Pouring 1	Low temperature effects on structural integrity of trunnion-barrel interface[1], low temperature effects on mechanism, low temperature effects on motor	3

Table 21 continued. Environmental compatibility for each harvesting concept

Concept	**Potential environmental compatibility issues**	**Ranking**
Pouring 3	Low temperature effects on sealed surfaces, corrosion of parts exposed to water, low temperature effects on mechanism, low temperature effects on actuator, low temperature effects on barrel-valve interface	5
Sucking 2	Low temperature effects on pump/pump lines/pump motor, low temperature effects on barrel-pipework interface	4
Blowing 3	Low temperature effects on blower/blower motor, low temperature effects on nozzle	3

1. Barrel and trunnions may have to be an integrated or inseparable part, requiring replacement when either sub-part fails

The size estimates given are that of a cuboid into which all components of the system will fit. This should be small enough to meet the requirements laid out in §3 when included with ice breaking and further processing equipment needed for the entire system. The size of equipment such as motors and actuators are all kept roughly the same for each concept. The idea is not to accurately predict the design geometry but to give a rough figure of the design volume requirements. Table 22 gives the estimated justification for the size of each solution. By default, these sizes include the barrel volume but omit the breaking method volume.

Table 22. Bounding box size for each harvesting concept.

Concept	**Rationale (all dimensions in m^3)**	**Size [m^3]**	**Ranking**
Lifting 3	Barrel: 0.305, crane and 90° envelope: 2.17, basket: 0.0061, pump and control hardware: 0.67[1]	3.15	5
Lifting 4			
Lifting 5			
Pouring 1	Barrel with 10 cm length trunnions, combined upright and poured: 0.622, motor and drive hardware: 0.032[2]	0.654	2
Pouring 3	Barrel volume: 0.305, gate valve: 0.018, actuator: 0.0053[3]	0.3283	1
Sucking 2	Barrel volume: 0.305, Pump and control hardware: 0.67[1]	0.975	4

Table 22 continued. Bounding box size for each harvesting concept.

Concept	**Rationale (all dimensions in m^3)**	**Size [m^3]**	**Ranking**
Blowing 3	Barrel volume: 0.305, blower: 0.344[4], ducting: 0.022	0.671	3

1. Hammelmann 2013
2. ABB 2016
3. MOOG 2016
4. Cincinnati fan 2010

5.3.3 Effectiveness based criteria

Effectiveness based criteria has been covered in more detail in §4.5.3 and the criteria are similar for ice harvesting. The only additional criterion is that the harvesting method should be compatible with the ice breaking methods chosen. This is filtered out in an earlier selection stage.

The potential for failure for each solution would require a more embodied design to have been created, however, some estimations of the potential failure modes can be made from what is known about the solutions. Each solution suffers from some basic possibilities; the possibility of human error and act of god are ever present.

All solutions have the requirement of third-party components which are all subject to failure. Failure prediction information would have to be sourced from the supplier to integrate the information into failure prediction calculations. Table 23 shows some possible failure aspects of each system and their totals.

Table 23. Failure potential and risks for each harvesting concept.

Concept	**Potential failure**	**Count**
Lifting 3	Wear phenomena on hinge areas of basket/mechanism/crane, corrosion of basket/mechanism, damage to basket/mechanism by ice, structural failure of basket/mechanism, structural failure of crane[1], motor/actuator/pump failure[1], water damage to electric components, act of god, human error	16

Table 23 continued. Failure potential and risks for each harvesting concept.

Concept	**Potential failure**	**Count**
Lifting 4	Wear phenomena on hinge areas of mechanism/crane, Corrosion of basket/mechanism, damage to basket/mechanism by ice, structural failure of basket/mechanism, structural failure of crane[1], motor/actuator/pump failure[1], water damage to electric components, act of god, human error	15
Lifting 5	Wear phenomena on hinge areas of basket/mechanism/crane, corrosion of basket/mechanism, damage to basket/mechanism by ice, structural failure of basket/mechanism, structural failure of crane[1], motor/actuator/pump failure[1], water damage to electric components, act of god, human error	16
Pouring 1	Wear phenomena on trunnion bearing surfaces, corrosion of trunnion/bearing surfaces/mounts, abrasive wear of barrel by ice and water flow, motor failure[1], water damage to electric components, act of god, human error	10
Pouring 3	Wear phenomena on gate valve seal/gate, corrosion of gate valve, abrasive wear of valve by ice and water flow, actuator failure[1], water damage to electric components, act of god, human error	7
Sucking 2	Pump failure[1], duct work failure, abrasive wear of ducting/pump, ice damage to pump/barrel exit, act of god, human error	7
Blowing 3	Blower failure[1], pump failure[1], ducting failure, air blade failure, damage to barrel by moving ice, damage to components by moving ice, water damage to electric components, act of god, human error	9

1. These components are likely to be sourced externally and will have their own failure modes.

The scalability of the system is limited by the requirement that the system be between 50 and 200 litres in capacity. Once a design is finalised the exact scalability and specifications of the system elements can be calculated. Table 24 lists the design variables for scalability as well as a qualitative scalability ranking for each solution.

Table 24. Scalability potential for each harvesting concept

Concept	**Scalability aspects**	**Ranking**
Lifting 3	Lift/yaw motor power, actuator force, geometry of basket parts, number of basket tines, geometry of actuation mechanism, crane geometry/travel	5
Lifting 4	Lift/yaw/rotate motor power, geometry of basket parts, crane geometry/travel	4
Lifting 5	Lift/yaw motor power, actuator force, geometry of basket parts, number of basket tines, geometry of actuation mechanism, crane geometry/travel	5
Pouring 1	Trunnion geometry/barrel location, motor torque	1
Pouring 3	Gate valve geometry, valve fixing geometry, actuator force,	2
Sucking 2	Pump power, ducting geometry	1
Blowing 3	Blower power, ducting/air blade geometry	3

5.4 Selection

Table 25 shows a simple grid summing up the weighted results of all criteria. The selections made are the smallest total value from three differing groups.

Table 25. Weighted harvesting concept evaluation (Smaller is better).

Concept	**Criteria**									**Total**
	Cost			**Environment**				**Effectiveness**		
	C1	**C2**	**C3**	**E1**	**E2**	**E3**	**E4**	**P1**	**P2**	
Lifting 3	5	6	7,5	See note 1	2	5	1,25	32	5	63,75
Lifting 4	5	6	4,5		1,5	4	1,25	30	4	56,25
Lifting 5	5	6	7,5		2	5	1,25	32	5	63,75
Pouring 1	2	1,5	1,5		1	3	0,5	20	1	**30,5**
Pouring 3	3	4,5	3		0,5	5	0,25	14	2	**32,25**
Sucking 2	4	3	6		2	4	1	14	1	**35**
Blowing 3	1	7,5	4,5		2,5	3	0,75	18	3	40,25

1. In this case energy use is only estimable for operating costs, a full life cycle energy cost can’t be performed until a more embodied design is available.

While not all the demands and wishes given in §3 could be elaborated on in the conceptual design stage, many could and this evaluation gives the three most suitable solutions. These solutions are pouring 1, 3 and sucking 2 which are “trunnion mounted ladle”, “open bottomed hopper” and “pumping out” respectively.

Viewing the weighted total, a pattern is quite clearly visible in that the lifting solutions are not suitable, too much complexity combined with the necessity to submerge the lifting device counts them out. Blowing is the next worst and seems to fail mainly on running costs and noise. In addition to these problems, the problem of design comes up. Designing a system to do what the blowing concept aims to do is not a simple task, it has many variables and may not even work even with a good embodied design. Sucking and pouring are the best options available to the project with pouring 1 coming top overall, mainly due to its simplicity and the lack of complex mechanics or systems.

6 ICE BREAKING TEST SYSTEM

Testing of the concepts chosen should be performed to ascertain whether said concepts are worth pursuing further into the design process. The tests will be performed in the winter months to allow for natural freezing and reduction of costs.

6.1 Overview of concepts to be tested

Three concepts were chosen in the previous stage of design. These were a bending concept to deform the barrel and break the ice, a heating concept using joule heating to melt a thin layer of ice where the ice joins the barrel and an aviation originated solution using vibration to break the ice from the barrel.

Of these three concepts, it was decided to remove the heating concept due to the high likelihood of heat loss significantly reducing its efficiency and effectiveness. Heating methods are also somewhat against the spirit of the project, so are not favoured by the project's organisation. It was also necessary to remove the vibration testing due to time constraints. However, a plan of action for vibration testing is attached as appendix 3 to the work.

6.2 Test system general arrangement

The general arrangement of the bending concept (figure 7) allows for the bladder to be suspended from the rim of the barrel. The supporting material will be some form of strapping akin to that used in logistics for load securing. The strapping can be attached to the top of the barrel by bracket or bolt. The load securing strapping could also be used as an alternative to the inflatable tube for inducing the bending itself.

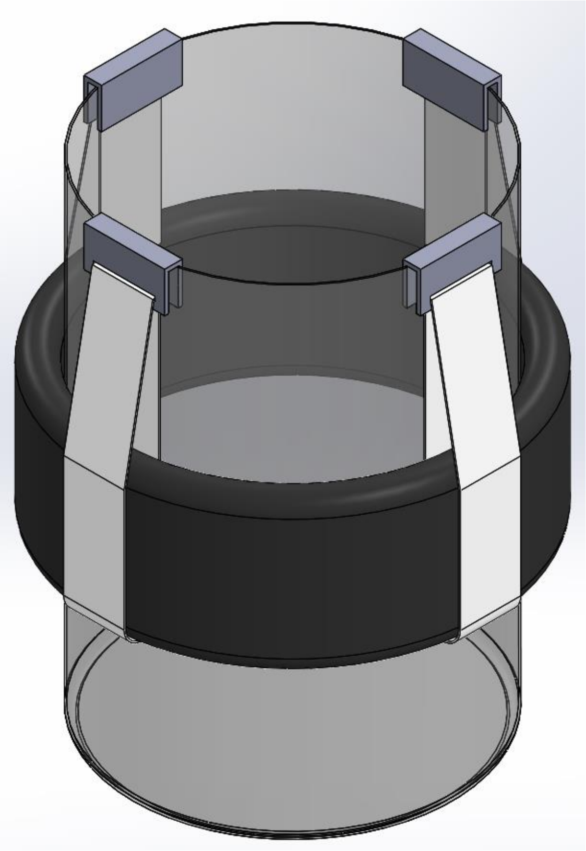

Figure 7. Bending test general arrangements.

6.2.1 Initial general equipment requirements

The equipment required for this test system is at least the barrel. The initial additional requirements for the concept are given in table 26.

Table 26. Details of the desired equipment for the bending concept.

Item	**Quantity**	**Details**
Inflatable bladder	1	Tube diameter of about 100-150 mm. Centre diameter inflated of about 450 mm Peak pressure tolerance of up to 50 MPa Valve for attachment to pressure source
Supporting strap	4	Polyester, nylon. Cargo or other form of webbing would be suitable. It may be necessary to fabricate a frame to house the bladder.

Table 26 continued. Details of the desired equipment for the bending concept.

Top bracket	4	Machined, welded or otherwise fabricated to hold onto the edge of the container and support the webbing.
Pressure source	1	Pump or another pressure source. Bladder inflation. Up to 50 MPa capable.
Pressure tubing and ancillaries	1	To connect pressure source to bladder. Pressure line and safety equipment.

Equipment not available in the LUT lab is sourced from external suppliers. Instructions were given that, ideally, little if any fabrication work will be performed in LUT, to reduce time requirements and costs.

6.3 Foreseeable problems

It is possible that sourcing a bladder material that can handle the required pressure will not be possible and it may not be financially viable. In this eventuality, it may be possible to use a less reinforced material. To ensure that pressure is applied evenly to the barrel surface, a frame or cage may need to be built around the bladder. For testing purposes, it may be suitable to use some other method of barrel compression.

In addition to sourcing materials, problems with the repeatability of the tests could be encountered. Due to the use of natural freezing and the very simple methods of breaking the ice, it is possible that many variables will be added to the system such as: temperature of freeze, temperature of test, positioning of the breaking appliance and rate of force application. This could lead to inaccuracies in the results, discrepancies and a lack of repeatability in the work.

6.4 Actual test system setup

The testing arrangement is palletised to enable easy transport between the lab and outdoors, and easy positioning for testing. Bungee cords to give some stability to the barrel on the pallet when it is not loaded.

The original arrangement and idea of the bending test consisted of a 200-litre container, bladder and pressure equipment. Figure 8 (left) shows this system’s arrangement in position and set up for use. This original arrangement was not able to be realised as the only available inflatable bladders were pneumatic bike or car inner tubes (figure 8, right). These tubes, when tested unrestrained, predictably did not apply pressure to the barrel sides and just expanded outwards and fell to the ground.

Figure 8. Palletised bending test arrangement concept (left) and realised.

An alternative arrangement using load securing strapping and a ratchet tightening mechanism were provided for testing (figure 9). This method proved too physically difficult to apply adequate force to the barrel to induce breaking.

Figure 9. Logistic strapping test arrangement.

A further modification to the idea was proposed; this was to use steel box stock joined together into a makeshift clamp, with threaded rod for applying compression and a load cell to measure the load. This acts as two class 2 levers (figures 10 and 11). This method, on initial proof testing, was more successful. Table 27 lists details of the equipment used in these tests.

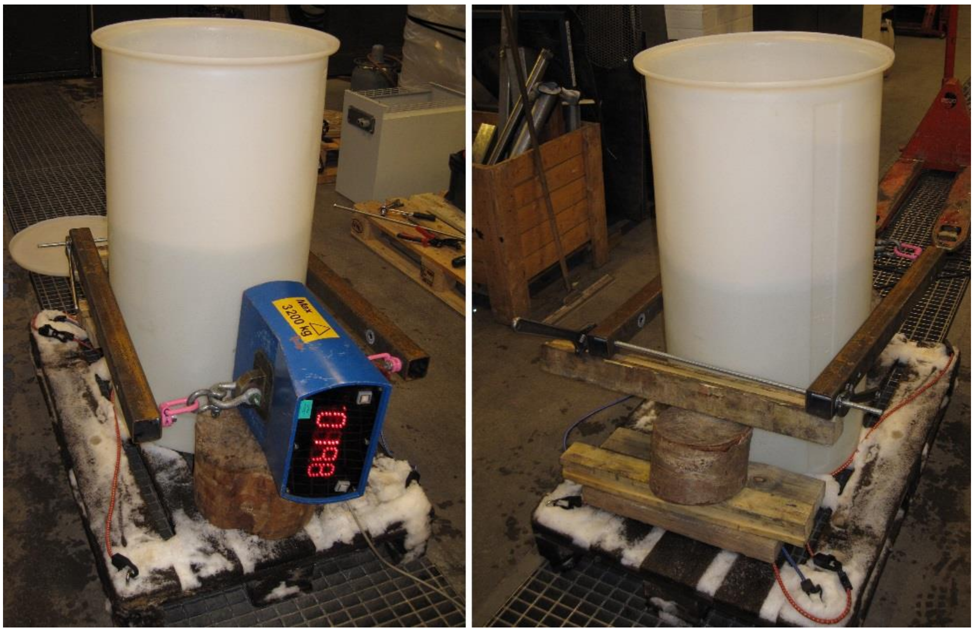

Figure 10. Front (left) and rear final test arrangement. This arrangement was used for all successful tests. The value shown on the scale is not related to any test.

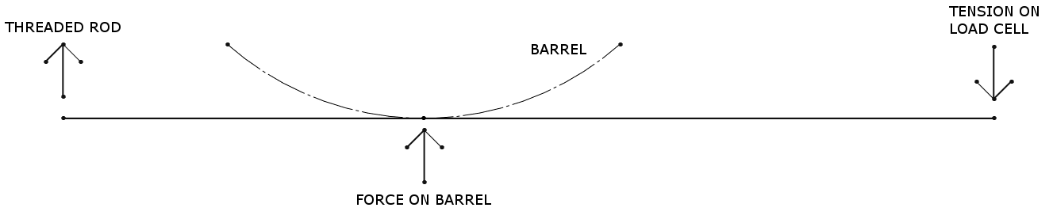

Figure 11. Diagrammatic view of the final testing arrangement. Showing one side's half of the symmetric arrangement.

Table 27. All equipment used for all bending testing methods. Items in italics were part of failed methods.

Manufacturer	**Model**	**Description**	**Quantity**
Generic	Europallet	Standard EU-pallet	1
Cipax	10200	200-litre polyethylene container, with lid	1
Generic	NA	Bungee cord with hooks (1000 mm)	4
Generic	NA	Loop to attach bungee cord to pallet	4
Biltema	*110/90-19*	*Motorcycle inner tube*	*1*
NA	*NA*	*Shop air supply*	*NA*
Unknown	*NA*	*Logistic load securing strapping material*	*1*
Unknown	*NA*	*Ratchetting load securing mechanism*	*1*
Tamtron	KK-3200	3200 kg load cell	1
Generic	NA	Square bar stock (800 mm)	2
Generic	NA	M12-8.8 Threaded rod (650 mm)	2
Generic	NA	M12 Nut	4

6.5 Test procedure

To ensure the viability and operational limits of the chosen concept designs, testing will need to be performed. This testing will be performed in a more controlled environment and at a smaller scale than the idealised eventual product.

Testing should proceed in the same fashion for both bending and vibration methods:

1. Fill container
    a. The designated container is 210 L, fill to 100 L.
2. Allow partial natural freezing of contents

    a. The freeze rate of ice is, on average, about 1 mm/h @ -1 – -3 °C and with wind speeds of 0.5 – 3 m/s (John 2016).
    b. Ice thickness should not be allowed to reach 100 mm.
3. Apply removal method
    a. Loosely install the bending equipment then slowly and steadily tighten the threaded rod until the ice begins to break. Stop when the ice has broken or the barrel begins to deform excessively.
4. Analyse results of removal
    a. Note the temperature during freezing
    b. Note the load required
    c. Note the ice thickness
    d. Note the ice cracking pattern
    e. Check the size of the ice pieces
    f. Check the completeness of breaking

The running of this simple procedure will result in one of several possible outcomes. The undesirable outcomes are:

- Ice does not form on the walls of the barrel
- Ice fails to break
- Ice pieces are too large or small
- Ice forms on the bottom of the barrel and is not removed
- Some ice remains on the barrel walls
- Barrel damage occurs
- Removal equipment is damaged/fails

In addition to the possible outcomes there is the desired outcome. This outcome is one which results in uniformly broken ice which can be separated from the remaining water in the barrel using one of the chosen methods. If testing proves successful with fresh water, it should be tried with contaminated water, to ensure that the process would work under all expected operating circumstances.

7 ICE BREAKING TEST RESULTS

In the final months of 2016 four test breaks were performed, table 28 shows the results and appendix 1 shows all the measurements. After these measurements, a single measurement was made on the empty barrel at rod displacements of 10, 20, 30 and 40 mm, the results of this test are shown in table 29.

Table 28. Test results

Test	**Date**	**Ave freeze temp [C] / Length of freeze [days]**	**Load @ fracture [kg]**	**Displacement @ fracture (ave) [mm]**
1	30/11/2016	-3.3 / 6	553	10.9
2	5/12/2016	-5.2 / 4	330	9.1
3	12/12/2016	-5.8 / 4	883	2.6
4	14/12/2016	-6.7 / 3	144	10.9

Table 29. Empty barrel static loads. Lever lengths were: 320 / 480 & 360 / 440.

Rod Displacement [mm]	**Static load [kg]**
10	7.1
20	9.4
30	16.6
40	23.6

Preloading the bars in order that they remain in position without holding requires about 5 kg on the load cell, the load cell is tared after this point is met. The bars were roughly 600 mm from the top of the barrel for each test, this was just below the upper surface of the ice. The load and displacement measurements are calculated from the results shown in appendix 1. Measurements are taken at the moment the cracking of the ice occurs. On the initial breaking of the ice, a very loud bang, in addition to the immediate reduction in measured load is noticed. If additional load is added once breaking has occurred, the measured load does not increase. The load decreases gradually if left for any length of time.

The first and third tests were very similar in conditions, they were performed while the ice was still adhered to the inner surface of the barrel after a steady freeze under reasonably steady conditions. They offered the greatest resistance to breaking and a large difference in resistance in comparison to test two where the ice had slightly melted to become free from the barrel wall. The fourth test was performed on thinner ice while still adhered to the barrel walls. Ice thickness and initial breaking patterns are shown in figures 12 and 13 respectively.

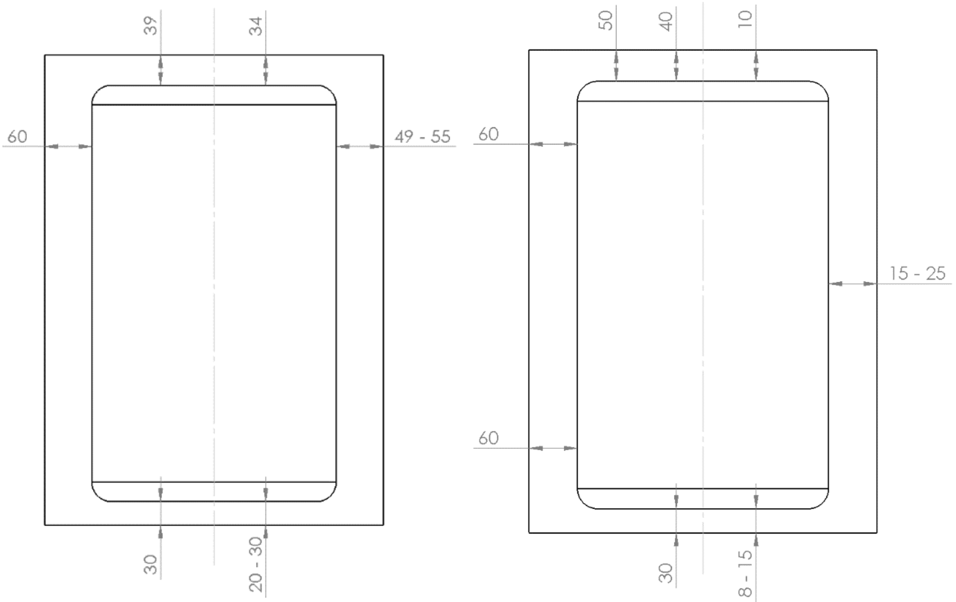

Figure 12. Left image: Ice thicknesses for the for the first (left half) and second tests. Right image: Ice thicknesses for the third (left half) and fourth tests.

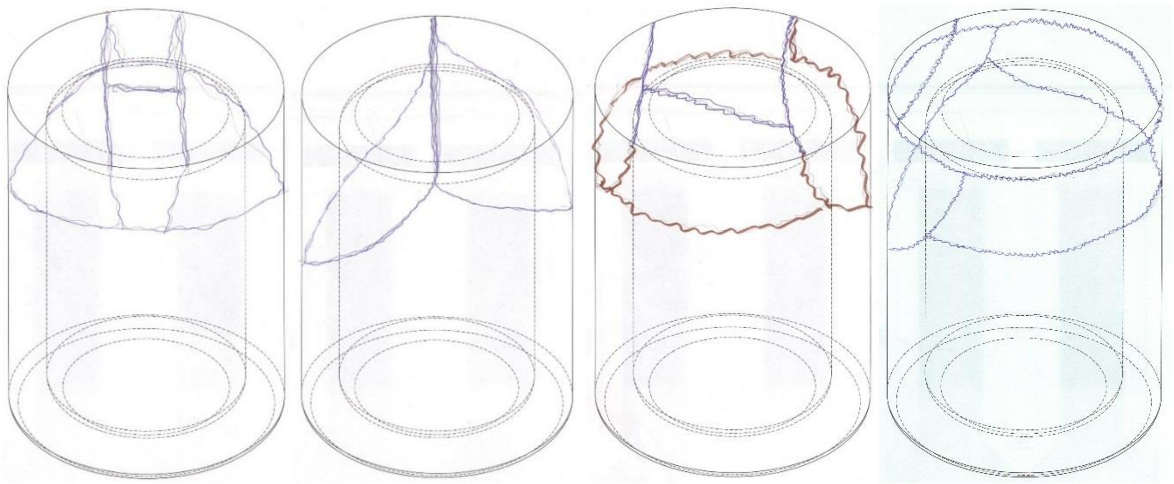

Figure 13. From left to right: First to fourth test ice breaking patterns. Red lines indicate potentially inaccurate cracks due to breakage during moving of the container.

8 CONCLUSION AND SUMMARY

The preceding work aimed to answer the question of how to break and harvest broken ice from a container. This would form part of a larger natural freezing water purification system housed in an intermodal shipping container. The overall aim of the work was met, however, time and resource constraints prevented the work being as complete as originally envisioned.

The process of system design was a problem orientated one, each function of the system is handled and embodied individually. The breaking, harvesting and post-treatment of the ice is designed for on its own and integrated into the final solution. A generative approach was used to find potential solutions for each function, that is, many possible differing approaches were initially conceptualised and from that the final solution for each function was evolved.

A literature search led to the creation of several possible solutions for breaking and harvesting and these were selected based on factors given in a list of requirements. These requirements and criteria were grouped into cost, environment and effectiveness related groups. In general, the selected methods were simple and had as little mechanism involved as possible. Once the ideal breaking and harvesting methods were chosen they were set up for testing. This is where time constraints had an impact and only one method of breaking could be tested, that of bending the ice externally with an inflatable bladder.

Several tests were performed on a container of partially frozen fresh water. This was done using methods which aimed to bend the ice, this takes advantage of ice’s relatively low strength in tension. Initial attempts to break the ice with methods which skirt the whole circumference of the cylindrical container failed. A successful method involving applying force to a pair of class 2 levers with the barrel as load, a load cell as the fulcrum and a threaded rod as the effecting mechanism. This method resulted in a consistent break in the ice. However, this did not result in the ice being broken up into manageable pieces.

Some observations were made after the tests. The first observation is the apparent effect of adhesion on the required breaking force. Tests where the ice was similar in thickness but differed in whether the ice was still adhered to the barrel walls, resulted in the adhered ice requiring nearly twice the force to break. The second observation is that of the significant difference ice thickness makes, with ice that is only roughly double the thickness requiring a force that is over six times greater to break. The final observation is that when the displacement at the barrel is increased after breaking, the force does not increase, leading to the assumption that once broken, ice can freely move relative to the barrel and other ice and no longer offers any resistance.

It is reasonable to suggest that bending could be a viable method of ice breaking for water purification purposes. However, further study of the best methods to perform the bend is needed. In addition to this, study of ice formed from waste water is also needed. Disregarding bending, it would be scientifically interesting to test the effects of vibration, both sonic and ultrasonic, on ice and check the feasibility of the vibration methods of breaking.

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APPENDIX I, 1

Table showing measurements from each test breaking.

Test	**1**	**2**	**3**	**4**
Date	30/11/2016	5/12/2016	12/12/2016	14/12/2016
Average freeze temp [C]	-3.3	-5.2	-5.8	-6.7
Length of freeze [days]	6	4	4	3
Load on cell @ fracture [kg]	210	130	411	65
Load on barrel @ fracture [kg] (calculated)	553	330	883	144
Load on cell immediately after fracture [kg]	55	40	90	40
Displacement of thread @ fracture [mm]	35	30	10	40
Displacement of barrel @ fracture [mm] (calculated)	10.9 10.9	9 9.2	2.7 2.7	11.3 10.6
Bar distances from load point: thread / load cell [mm]	305 / 495 303 / 497	320 / 480 310 / 490	370 / 430 375 / 425	350 / 450 375 / 425
Thread length: unloaded / loaded [mm]	505 / 470	515 / 485	490 / 480	475 /435

Table showing temperatures for each freeze period. First and last days are partial.

First test freeze

Temp \ Date	**25th November**	**26th November**	**27th November**	**28th November**	**29th November**	**30th November**
Daily average	-1.2	-0.2	-3.8	-6.4	-7.8	-0.6
Daily low	-2.9	-2.7	-6.1	-8	-11.3	-8.4
Daily high	1	1.3	1.3	-4.9	-5.8	0

Second test freeze

Temp \ Date	**2nd December**	**3rd December**	**4th December**	**5th December**
Daily average	-3.9	-6.3	-8.8	-1.9
Daily low	-4.9	-8.6	-11.5	-7.4
Daily high	-2.8	-2.7	-6.8	3.8

Third test freeze

Temp \ Date	**9th December**	**10th December**	**11th December**	**12th December**
Daily average	-1.5	-6.3	-7	-8.5
Daily low	-3.3	-7.6	-9	-11.9
Daily high	0.5	-3.3	-5.8	-5.5

Fourth test freeze

Temp \ Date	**12th December**	**13th December**	**14th December**
Daily average	-8.5	-6	-5.6
Daily low	-11.9	-7.5	-7.3
Daily high	-5.5	-4.7	-3.6

Prior work by the author regarding vibration testing of ice in a similar container. Finalised on 12/12/2016.

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TEST ARRANGEMENT FOR BREAKING ICE WITH VIBRATION

Lappeenranta: 12/12/2016

Author: Eric Lehtonen

TABLE OF CONTENTS

1 INTRODUCTION

Harvesting of ice for use by mankind used to be a very lucrative business which due to the advent of refrigeration technology, faded out at the turn of the last century (Maw & Dredge 1871; Weightman 2003). However, the freezing of water to aid in the purification or concentration of liquids is an established idea, showing recent growth in interest, with numerous studies and ideas being thrown into academic scrutiny (Clark 1901; Conlon 1992; Gao et al. 2009).

A very recent purification concept is that of the WINICE concept. The basis of which is the nature of the winter conditions in northern countries and the nature of large waste pools in mining applications. The idea being to wait for the waste water to freeze and then by some contrivance, harvest the ice to be processed later as significantly purified water. (Academy Finland 2014)

An alternative to the use of large, unmanageable waste pools is to use a smaller containerised system. Consisting of a standard intermodal shipping container in which are located one or more containers of waste water. These internal containers would be allowed to partially freeze, and once a desired level of freeze is met the remaining waste water would be removed and the ice within the container would be broken and moved on for further treatment.

One conceived method of breaking this formed ice is to use vibration. The purpose of this report is to answer the question: what kind of system would be required to test the viability of using vibration to break containerised ice?

2 METHODS

Ice frozen in a cylindrical container is to be attempted to be broken by sonic range vibrations. For this to be possible it is necessary to vibrate the container and possibly the unfrozen water within the container. At first it is necessary to estimate the expected resonance frequency of the container and the ice within. Following that, an arrangement of equipment can be planned which can achieve this frequency.

2.1 Frequency estimation

Using finite element analysis software (in this specific case, SOLIDWORKS by Dassault Systèmes) and a model of the container available for use in the LUT lab, the software calculated rough mode shapes and frequencies. These are given in figure 1 and table 1 respectively.

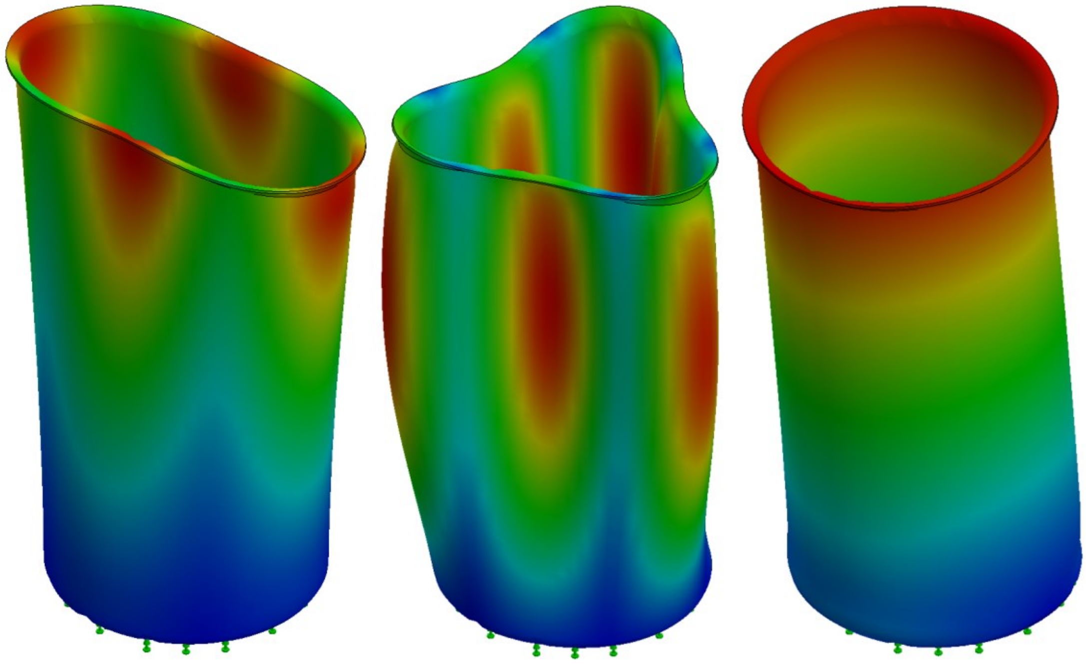

Figure 1. Mode shapes for modes 1 & 2 (left), 3 & 4 (middle) and 5.

These are clearly very rough and only serve to give a general idea of the expected mode shapes and frequencies. The boundary condition scheme chosen was fixed at the bottom of the container, this itself reduces the potential accuracy of the results. The models converged with an automesh of 14 mm nominal, tetrahedral elements.

Table 1. Table of modes, frequencies and relative amplitude values.

Mode	Frequency [Hz]	Amplitude
1	24.83	0.74
2	24.86	0.74
3	44.78	0.62
4	44.78	0.62
5	49.32	0.61

2.2 Problems with ice simulation

The nature of ice means that it is not easy to simulate with any accuracy. The only way to know how a volume of ice behaves, with any degree of certainty, is to perform tests. A lot of work has been done on understanding the behaviour of ice under various conditions and variables which influence the mechanical properties as well as some of the basic properties are known to a certain degree.

The vast majority of ice properties depend on the purity and composition of the ice. Ice freeze rate and age of the ice play a lesser but still significant part in the properties. The temperature of the ice when tests are performed also plays a major role in the properties of the ice at that specific moment. Table 2 gives a few of the most fundamental mechanical properties and their ranges of values. (Timco & Weeks 2010)

Table 2. Table of example ice properties.

Property	Value
Density [g/cm^3]	0.72 – 0.94
Tensile strength [MPa]	0.2 – 2
Shear strength [MPa]	0.5 – 2.3
Compressive strength [MPa]	0.5 – 12
Elastic modulus [GPa]	1.7 – 10
Poisson ratio [-]	0.18 – 0.48

3 RESULTS

3.1 Available equipment

To perform any testing, certain equipment is required. Table 3 lists equipment available in the LUT lab for these tests.

Table 3. Details of the LUT lab equipment available for use.

Manufacturer	**Model**	**Purpose**	**Quantity**
Brüel & Kjær	2712	Power amplifier	1
UNKNOWN	UNKNOWN	Vibration controller	1
Brüel & Kjær	4805 + 4814	Vibration exciter body + head	1
Brüel & Kjær	4809	Vibration exciter	1
Brüel & Kjær	8200	Force transducer	1
Brüel & Kjær	4393	Accelerometer	3
Brüel & Kjær	2825	Data acquisition system Incorporating modules: 3107, 3022, 7521	1 1 each
National Instruments	MegaPAC PXI-1025	PXI computer system	1
Brüel & Kjær	PULSE Labshop v4.1	Analysis software	1

In addition to this equipment, an oscilloscope may also be required for monitoring of the power supply outputs. For simply testing the ability of sonic vibrations to break ice, only a small amount of this equipment will be needed. However, other measurement equipment to measure the response of the barrel as the dynamics of the barrel/ice system change, would be needed to affect a usable system.

3.2 Test setup

The arrangement of the vibration test consists of a 200-litre container, 2 x vibration exciters, vibration exciter control and power supply hardware. If more detailed telemetry is required during the test, various accelerometers and data logging equipment are available for this purpose. Figure 2 shows the system in position and set up for use and figure 3 shows the general connection scheme for the test devices. Table 4 lists details of the equipment to be used in the test.

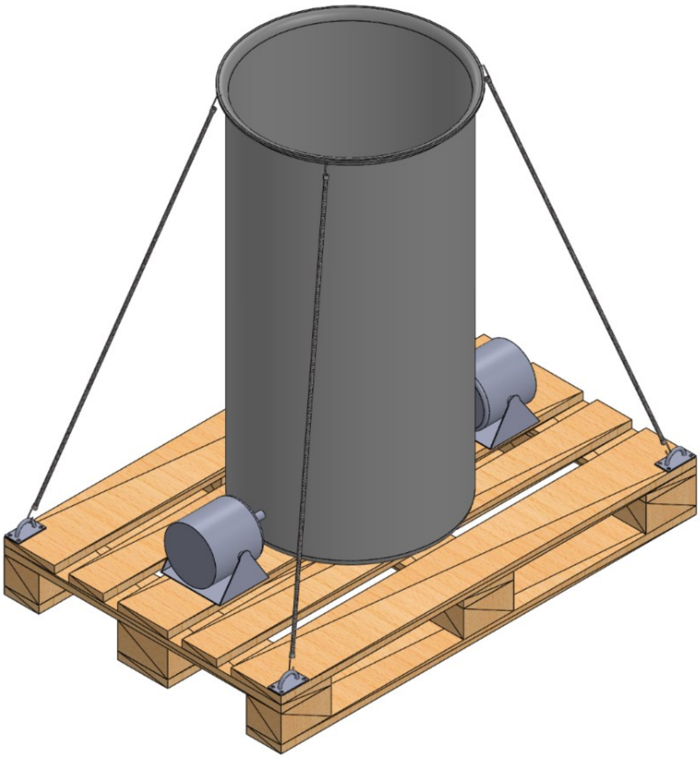

Figure 2. Palletised vibration test arrangement.

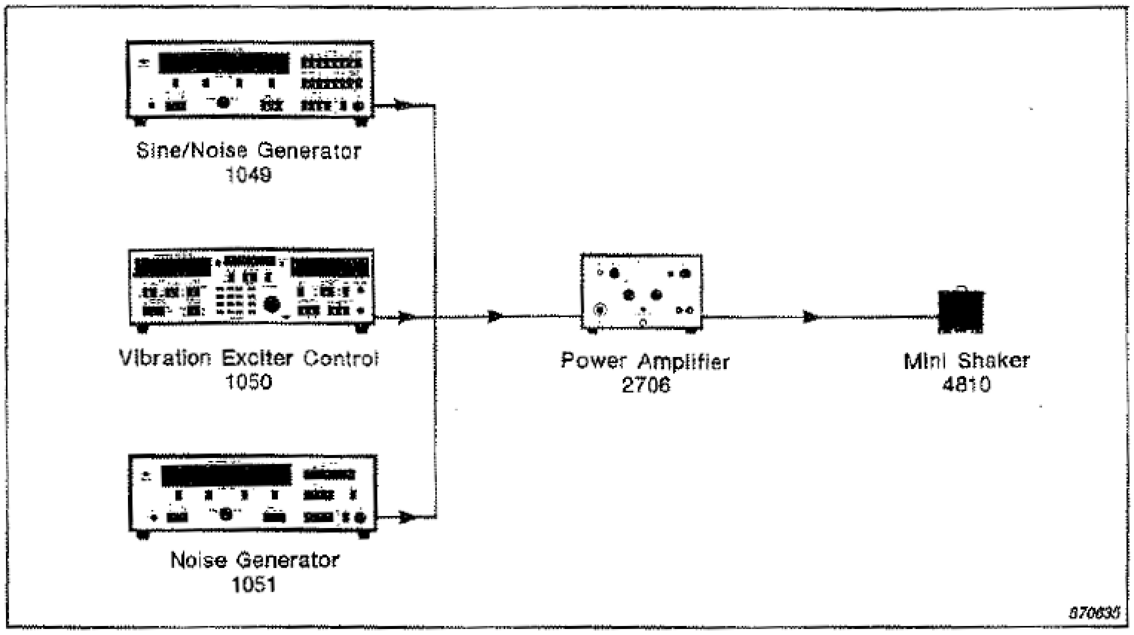

Figure 3. General connection arrangement possibilities for vibration testing (Brüel & Kjær 1987).

Table 4. Equipment to be used for the vibration testing

Manufacturer	**Model**	**Description**	**Quantity**
Generic	Europallet	Standard EU-pallet	1
Cipax	10200	200-litre polyethylene container, with lid	1
Generic	NA	Bungee cord with hooks	4
Generic	NA	Hook to attach bungee cord to pallet	4
Unknown	Unknown	Vibrator controller	1
Brüel & Kjær	2712	Power amplifier for vibrator(s)	1
Brüel & Kjær	4805 + 4814	Large vibration exciter body + head	1
Brüel & Kjær	4809	Vibration exciter	1

3.3 Test procedure

The main aim of this study is to understand the effects and effectiveness of vibration as an ice breaking means. The following procedure for testing contains parts which are not essential or can be modified as necessary, but the general idea would remain the same.

1. Fill container
    a. Designated container is 210 L, fill to about 200 L.
2. Allow partial natural freezing of contents
    a. Freeze rate of ice is on average about 1 mm/h @ -1 – -3 °C and with wind speeds of 0.5 – 3 m/s (John 2016).
    b. Ice freezes on the top first, followed by the sides and then bottom. Decreasing thickness as it gets deeper.
3. Apply removal method
    a. Vibration: Induce vibration, start at low frequencies and increase until resonance causes the ice to break, problems are encountered or the equipment reaches its limit.
4. Analyse results of removal
    a. Consistency of results
    b. Ice thickness relation with frequency
    c. Freeze temperature relation to frequency

d. Freeze time relation to frequency

The running of this simple procedure will result in one of several possible outcomes, the desired outcome is broken ice of a uniform and manageable size with no remaining ice on the container walls. This may not be realisable without adjustment during testing.

4 ANALYSIS

Testing the ability of vibration to break ice is potentially a simple task, at least to get some result. However, there are numerous potential problems and pitfalls to be encountered.

It is entirely possible that the ice will not break at all. The equipment available for the test may not be able to provide enough force to the oscillation to break the ice. Alternatively, the remaining water in the system and the drum's flexibility may lead to any vibration being damped enough to protect the ice from breaking.

The resonant frequencies of the barrel/ice system will not remain static and when the situation with the ice changes (cracking happens, water seeps from one location to another, the ice ceases to be bonded to the container wall, etc.) In this case the frequency of testing would have to be changed often during the test.

The running of the simple testing procedure will result in one of several outcomes, including the below undesirable outcomes:

- Ice fails to form on the walls of the container
- Ice does nothing
- Ice merely cracks but fails to break
- Ice breaks but in inconsistent/incomplete ways
- The container is damaged because of the test
- The test equipment is damaged or broken

In addition to these undesirable outcomes there is the possibility of the desired outcome. The desired outcome is that all ice is removed from the container walls and broken into manageable sized pieces. These results would have to be consistent over multiple test runs and ice conditions.

5 CONCLUSION

The previous text described one possible way to test the viability of vibration to break ice formed in a container. It answered the question regarding the kind of system required to test the viability of using vibration to break containerised ice. The method which was contrived, involved the use of a small container which is allowed to freeze partially and is then excited by vibrations from two vibration exciters places 180 degrees apart.

The act of inducing some activity in the ice should be a simple one and some kind of result should be forthcoming. However, the complexities of ice as a medium and of the container/ice/water system as a whole, mean that effective ice breaking will likely require a little more than just a simple test at a single rate of vibration.

The tests proposed in this work are at risk of being the victim of numerous variables out of reasonable control. For better understanding to be gained of the behaviour of ice when exposed to vibration, it may be necessary to perform more controlled tests. Tests using fixed geometry test pieces and model ice which has had its freeze carefully controlled in laboratory conditions, would perhaps enable a better utilisation of vibration as a means of ice breaking.

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