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A Small Ice Towing Tank for Conceptual Modeling Part 1: Experimental Setup

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ABSTRACT

The intent of designing and building the small ice tank described below has been to provide in-house prototyping of concept designs, and basic experiments in ice mechanics and similarity when access to a full-service tank has not been possible due to high cost and other obstacles. As this paper shows and as one might suspect, the small tank cannot compete with a full-service tank's superior functionality and precision, and at times struggles to attain even its modest repertoire. Yet with a material cost of only about $8,000 US using standard building products, it has proven extremely useful in melding theory and practice at an introductory to intermediate level and has supported rapid iterations of prototype development including a conceptual model to the point of patenting. In Part 1 of this two-part paper, the tank is described in detail with drawings and evaluated with respect to ITTC Guidelines. The preparation of a two-stage version of EG/AD ice adapted to the tank's limited freezing capacity is also provided. In Part 2, model test runs demonstrate some of the tank's capacity for preliminary studies of macroscopic ice fracture and displacement patterns, and preliminary estimates of properties such as flexural strength, elastic modulus, and characteristic length, but not resistance, propulsion, maneuvering, or cycles of ice pileup.

KEY WORDS: towing tank, EG/AD, model ice, sea ice

INTRODUCTION

Part 1 of this paper outlines the overall arrangement and functionality of the small ice towing tank and its icemaking process (Fig. 1). Evaluation is presented primarily with reference to ITTC General Guidance and Introduction to Ice Model Testing and ITTC Recommended Procedures and Guidelines - Resistance Tests in Ice. Based on this and the results detailed in Part 2, the tank is proposed to be suitable for preliminary studies of macroscopic ice fracture and displacement patterns, preliminary estimates of properties such as flexural strength and characteristic length, but due to insufficient tank size, not studies on resistance, propulsion, maneuvering, or cycles of ice pileup and collapse (Polojärvi, 2022; time stamp 23:10).

Drawings of the tank are shown in Fig. 2 through 5 with typical tank, ice and testing characteristics listed in Table 1. It is comprised of three modules that may be disassembled and transported through standard door openings of 76 cm (30 in.) clear width. It is in a sense a portable cold room. The ambient air temperature of the tank's basin just above the waterline during freezing cycles is around -1.5°, significantly higher than the -18°C noted by Timco (1986), and that of many ITTC member tanks. This yields a best case ice growth rate of around 0.5 to 1 mm/hr – below the 2.5 mm/hr of HSVA and the 2.8 mm/hr noted by Timco (1986). As a result, it is surmised that much of the ethylene glycol (EG) dopant is rejected by the slower crystallization process with EG freely convecting away (Timco, 1986, p. 178), producing relatively pure, overly strong ice with large crystals that is useless for modeling, and is herein termed 'first ice'.

Figure 1. At left, the small ice towing tank with closed basin lid in foreground and packaged freezer unit at rear (For over-clad insulation added in 2024 and not shown, see drawings). At right, the fiberglass lined basin is visible with set up for an ice floe melt rate test.

Since the wet seeding process described by Pratte and Timco (1981) or similar processes such as a sprayed granular form of EG/AD described by Ha et al. (2015) are not feasible without a walk-in cold room (which is out of the question in the present case), a two-stage process was devised in which the dopant-depleted 'first ice' is broken and removed from the basin, ground into a fine slush, broadcast onto the melt (the parent EG/AD liquid) maintained at about 0°C, and then refrozen. The resultant 'second ice' (Fig. 6) freezes more rapidly, presumably due to less liquid phase per unit volume, with the slush initiating the formation of a fine grain microstructure throughout with some columnar graining at times occurring towards the bottom (Fig. 7 and 8). With tempering that often ranges from 120-180 minutes at room temperature, around 10 kPa flexural strength can be achieved as verified with a sequence of in-situ cantilever beam tests. At the end of the tempering process, the window for mounting the model on the carriage and performing the test run is quite short, on the order of 10-15 minutes.

Table 1. Small Ice Towing Tank and Testing Characteristics

Tank Characteristic	Description or Value
Year constructed	2020; Modified: 2024
Location	New York, NY, USA
Ice tank basin interior dimensions	0.94 m x 1.99 m
Model ice type	Two-stage, fine grain EG/AD: 0.7% EG; 0.048% AD[1]
EG/AD solution depth	0.13 m
Model ice target thickness	10 - 20 mm
Typical model scale, λ	80
Typical model ice flexural strength target	10 kPa[2] (at λ80)
Ambient air temperature and relative humidity during model testing	20-35 °C; 30-60% RH
Typical tempering time for target flexural strength	120-180 min.
Towing carriage drive	Hand powered with timer
Typical towing carriage speed	0.1-0.18 m/s (at $\lambda_v = \lambda^{1/2} = 80^{1/2} = 8.94$)
Cooling system	2100 BTU Heatcraft Inc. Pro[3] top mount packaged freezer unit PTN021L6AE; 115V, 1 phase; Run load amps: 12.8;
Models	60 cm long x 33 cm wide (at λ 80) max. 3D printed with PLA
Model ice freezing rate – a two stage process	Stage 1: 0.2 ± mm/hr; Stage 2: 0.5 to 1 ± mm/hr
Instrumentation	GoPro Hero 5 & 8 video cameras
Tests performed	Ice fracture and displacement studies; Model ice property testing; Melt rates

Due to the constricted air convection pathway from the packaged freezer unit to the surface of the EG/AD solution (Fig. 5), air temperature nonuniformity must be managed, in this case with an array of twelve low voltage fans which are able to bring basin thermocouple temperatures to within ±0.5°C of around -1.5°C between defrost cycles (which need to be minimized). A pair of horizontal fine mesh screens positioned side by side just above the EG/AD solution are intended to dampen and more evenly disperse convective turbulence at the surface and provide further throw of cold air out of the plenum (Fig. 4 right, 5 and 13).

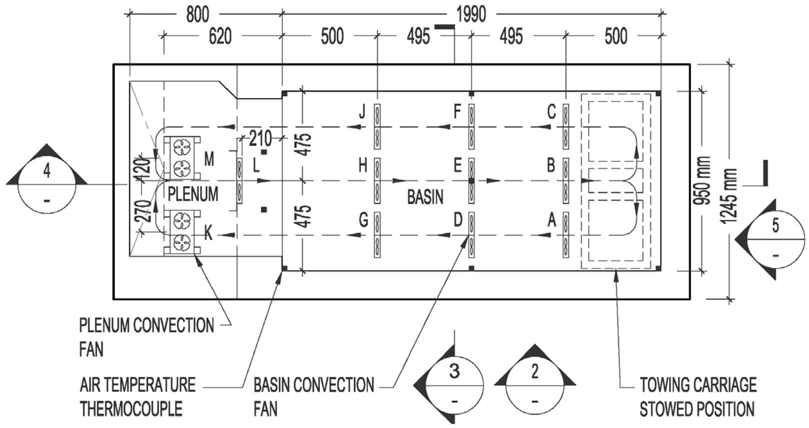

Figure 2. Ice tank plan with schematic diagram of forced air circulation in basin and plenum. Nine thermocouples with datalogging allow adjustment of cooling uniformity.

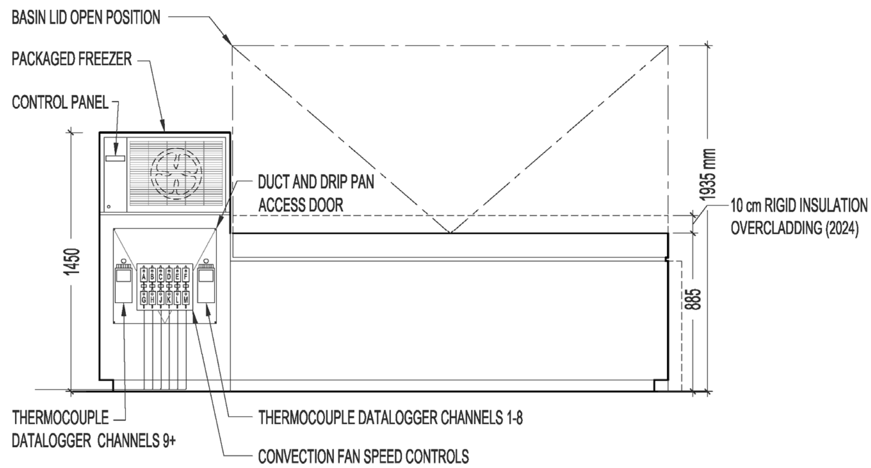

Figure 3. Front view of the small ice towing tank, comprised of three modules: ice basin and housing with lid (center), packaged freezer unit (upper left), and air supply and return plenum with housing, fan controls and data loggers (lower left).

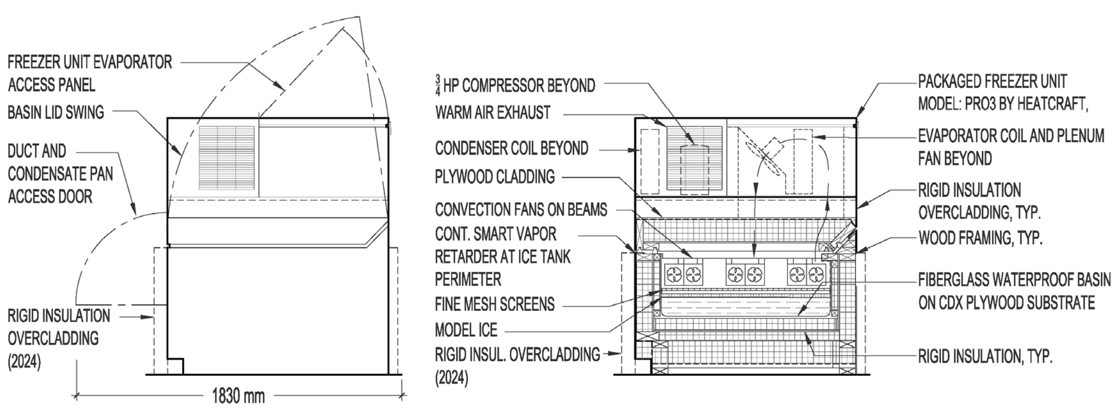

Figure 4. At left, ice tank end view with access panel clearances. At right, ice tank transverse section showing wood framing, insulation, air vapor barrier, fiberglass-lined basin, and packaged freezer unit beyond.

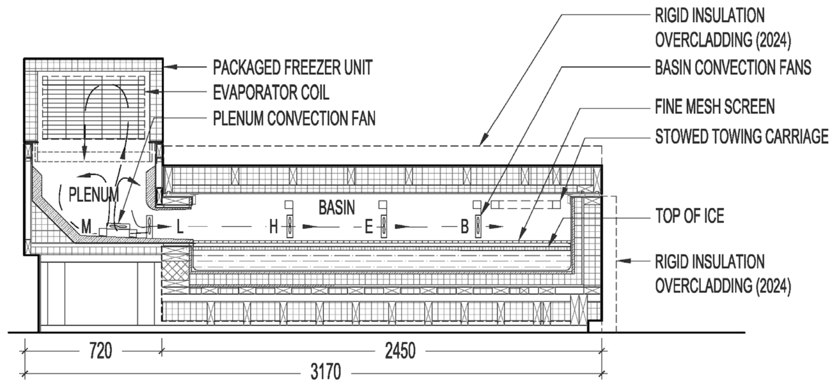

Figure 5. Small tank longitudinal section showing simplified air convection.

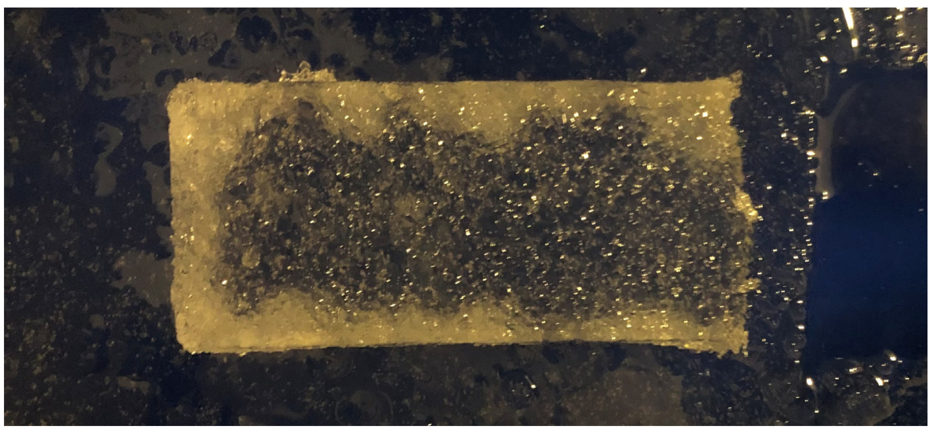

Figure 6. Overhead closeup of a tempered EG/AD 'second ice' cantilever beam placed on top of level ice after loading to failure (~40 mm x 75 mm x 12 mm thick). Some of the fine grain structure of the top surface is visible. 16 Aug. 2024.

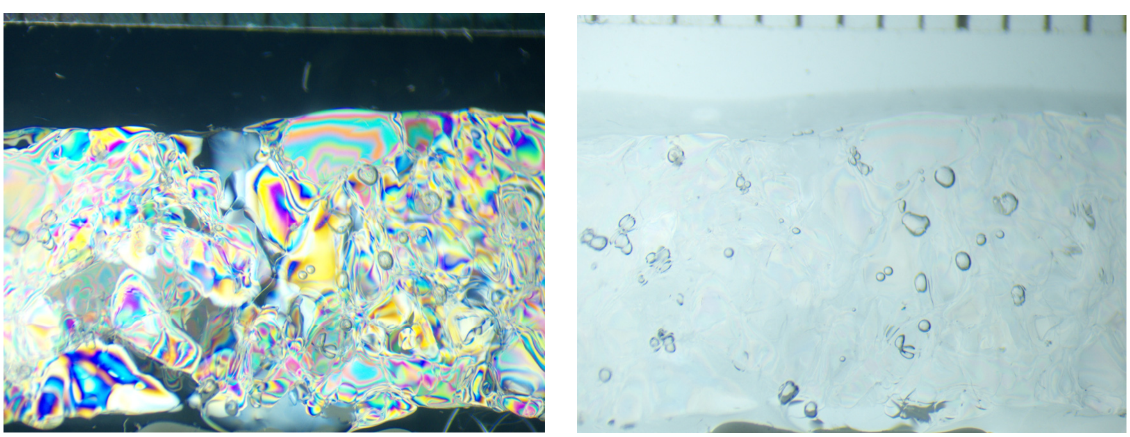

Figure 7. At left, a vertical thin section, 1-2 mm thick, of an EG/AD 'second ice' cantilever beam showing fine grain microstructure under polarized light. Scale at top of image: 1 division = 1 mm. At right, the same section in unpolarized light. 16 Aug. 2024.

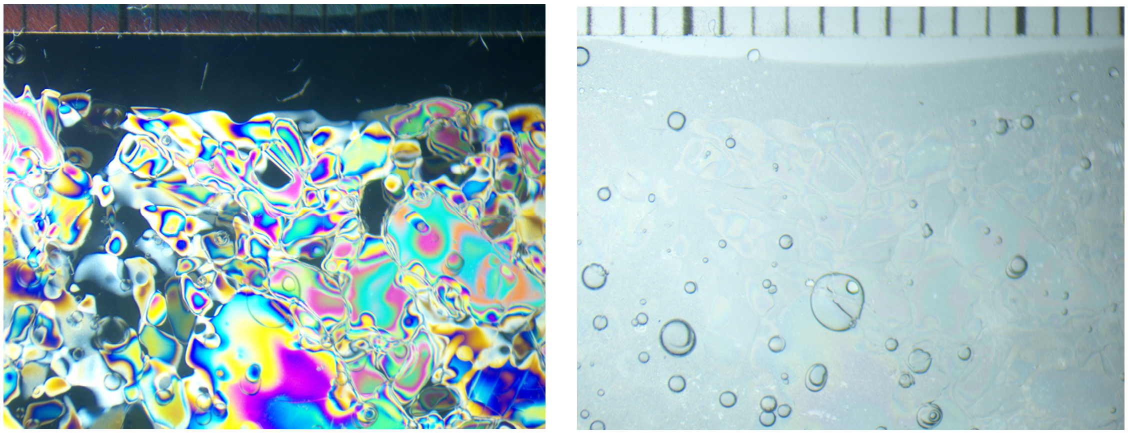

Figure 8. At left, a horizontal thin section of EG/AD ice showing fine grain structure in polarized light. At right, the same section unpolarized. 16 Aug. 2024.

ICE TANK AND MODEL SIZE EVALUATION PER ITTC GUIDELINES

Minimum Distance of Model Loads to Closest Tank Wall[3]

This minimum distance criterion is important for properly simulating level ice sheet deflection and hence ice stress minima and maxima, which in turn determine crack formation. Per ITTC: “The level ice sheet may be considered to have infinite extent if the shortest distance from the point of application of any loads to the nearest tank wall is more than three characteristic lengths.” [4,5] Accordingly, the maximum allowable model width or beam at waterline, B_M, is estimated as follows referring to Fig. 9:

Given the ice towing tank width of D and ice fragment assumed maximum width[6] $\approx \pi\ell_{cM}/4$, then the widest model beam for which the tank can still approximate the behavior of an infinitely wide sheet of ice on either side of the model is:

$D/2 – B_M/2 – \pi\ell_{cM}/8 < 3\ell_{cM}$

$B_M < D – 6\ell_{cM} - \pi\ell_{cM}/4$

$$B_M < D – 6.785\ell_{cM} \quad \text{[m]} \qquad (1)$$

As an example of determining the maximum beam for an icebreaking bow model scaled at λ80 with 15 mm ice in the small tank (again referring to Fig. 9) consider the following:

Given the tank width D of 94 cm, and a model ice characteristic length ℓ_{cM} of 9 cm, the largest model beam permitted is:

$B_M < D – 6.785\ \ell_{cM} = 94 - 6.785(9.0) = \underline{32.9}$ cm

Where characteristic length is calculated as:[7]

$$\ell_{cM} = [Eh^3/12\rho g(1-\nu^2)]^{1/4} \quad \text{[m]} \qquad (2)$$

$\ell_{cM} = [(1{,}933{,}000\ N/m^2)\ (0.015\ m)^3\ /\ (12*1001\ kg/m^3)(9.81 m/s^2)(1 - 0.30^2)]^{1/4}$

$\ell_{cM} = 0.088$ m, rounded up to $\underline{9.0}$ cm;

EG/AD melt solution density is:

ρ = [(1130.75 kg/m^3 EG)(0.700%) + (1020 kg/m^3 AD)(0.048%) + (1000 kg/m^3 water)(99.252%)]/100 = 1001 kg/m^3

E ≈ 1933 kPa (Estimated from Fig. 8 in Part 2 using the three ice thickness curves for 11 and 12 mm at 135 min. of tempering.)

For relating sea ice thickness to characteristic length, Tatinclaux (1988) notes that characteristic length of first year sea ice typically ranges from 10-15 times thickness. For 15 mm model ice (1.2 m at λ80), a characteristic length with credible similarity would be 15 to 22.5 cm, which is significantly higher than 9 cm noted above, which includes about 135 minutes of tempering to achieve 10 kPa flexural strength. Assuming the EG/AD ice of the small tank could be improved to achieve an ℓ_{cM} of 15 cm, tank width would need to be increased to 135 cm to accommodate the 33 cm model noted above, and E would need to reach 16.2 MPa, achieving an E/σ_f ratio of about 1600.

Since the 3ℓ_{cM} limit applies in all directions radiating out from a load imposed on the ice, the leading edge of the model should also stop short of the tank walls by 3ℓ_{cM}. This has not been complied with during test runs in the small tank, and it remains unclear how important this is when not conducting resistance testing. As shown in Fig. 9, ice sheet dimensions during test runs is typically about 1.57 m long x 0.94 m wide, allowing one test run per sheet. During tests, only the upper portion of the ice sheet is used, with cantilever beams (dashed in Fig. 9) occupying the lower portion.

Minimum Distance of Model to Tank Walls in Resistance Testing

Though resistance testing is not part of the proposed test repertoire, one aspect is hypothetically considered here for the sake of comparison and possible future improvements. Per Eqn. 2 of ITTC (2021) 7.5-02-04-01, Rev 03, the minimum distance from the model vessel or platform to the closest tank wall for resistance testing is limited by: $\ell_{cM} \leq (D\text{-}B_M)/6$.

Solving for model width as in (1) above yields:

$$B_M \leq D - 6\ell_{cM} \quad \text{[m]} \qquad (3)$$

By inspection , constraint (3) is less stringent than (1) and no increase in tank width is needed for resistance testing.

Minimal Traversal into Level Ice to Start Resistance Testing

In tandem with the limits on minimum wall distance, ITTC Guidelines require that at least “two vessel lengths” of incursion into the model ice take place prior to starting a test run to minimize transient disturbances.[8] Given that the present tank length is too short for testing full-length vessels or platforms, this criterion cannot be met, but could be with an extended basin length.

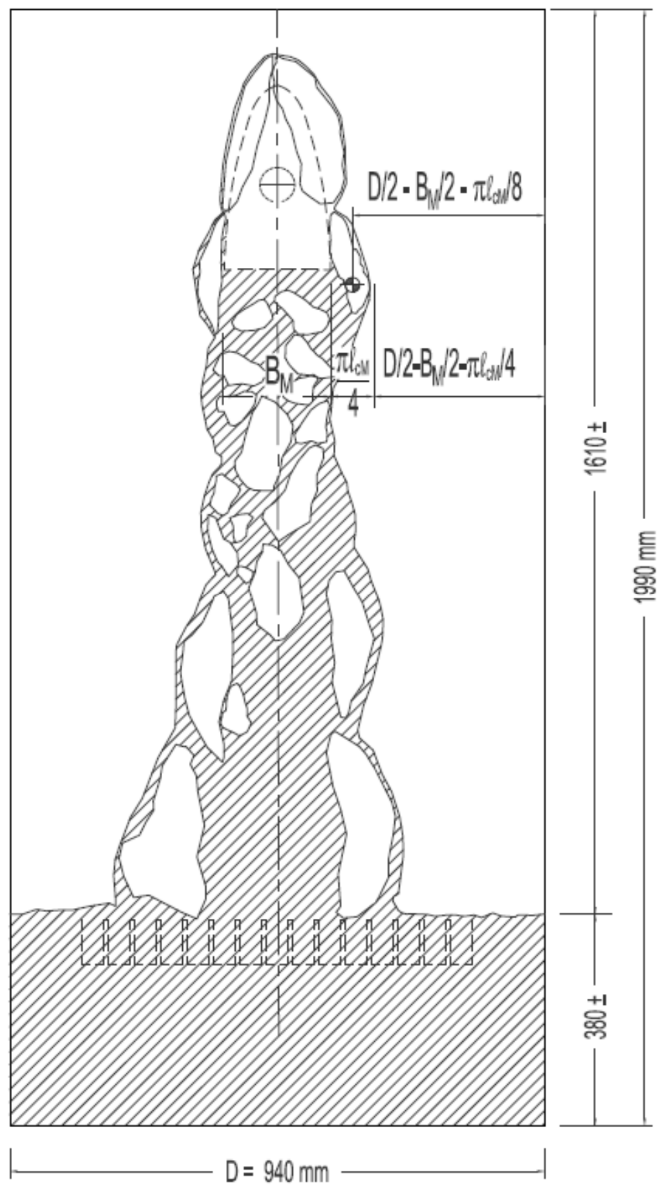

Figure 9. Idealized illustration adapted from the test of an icebreaking bow of width B_M =18 cm in 15-20 mm level ice. Assuming ice fragments with $\pi\ell_c/4$ maximum width are broken off and occasionally deposited beyond the channel edge as shown at upper right, the distance from the side wall of tank to centroid (⊕) of the $\pi\ell_c/4$ wide ice floe load is $D/2 – B_M/2 – \pi\ell_{cM}/8$.

MODEL ICE PRODUCTION AND PERFORMANCE

The process of ice production begins with initial freezing of the EG/AD melt solution to produce ice about as thick as the final or ‘second ice’ target depth. As noted, this ‘first ice’ will often have a horizontal grain pattern, at times with large and overly strong crystals randomly scattered about (Fig. 10, left), which is entirely contrary to the columnar microstructure developed by Timco (1986) and sea ice in general. In a process that takes about 45 minutes to 1 hour, the first ice is broken up in the basin with a small ice axe, successively placed in a 10 liter container with the aid of a handheld fine mesh net, and ground in a blender[9] (Fig. 10, right) to produce slush with crystals ranging from 1 to 5 mm in diameter (Fig. 11, left).

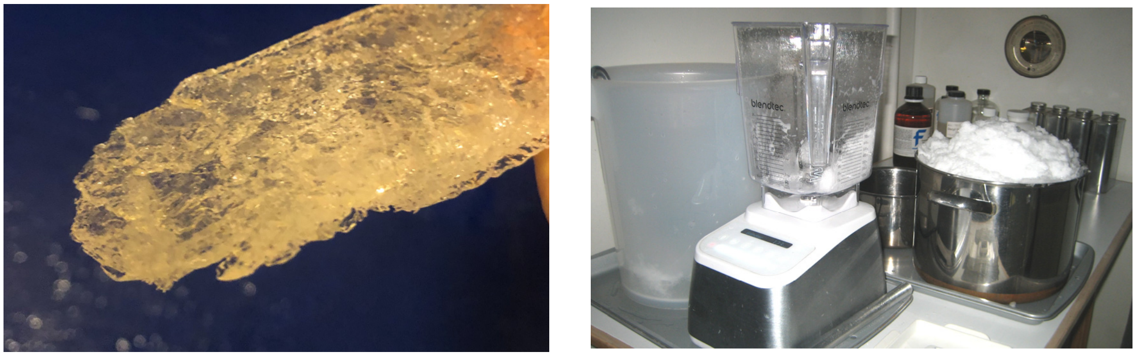

Figure 10. At left, example of the horizontal laminar structure and fracture pattern of a 'first ice' cantilever beam loaded to failure. At right, breaking up and grinding of the 'first ice' in the container at left with a blender (Designer 725 model by Blendtec) to produce fine grain slush at right. Short-lived foaming occurs even with low suds detergent.

The slush is then placed back into the melt and dispersed manually with a small rake, followed by a handheld mixer[10] using three full passes over the basin area for more uniform distribution. It is then lightly troweled with a magnesium or stainless steel float, which seems to aid in coalescing the initial jumble of floating crystals closer to the surface (Fig. 11, right). The depth of the troweled slush is spot checked with a stainless steel skimmer by lifting out portions, measuring, and blending them back in place (Fig. 12, left). One method is to start with troweled slush that is slightly too thick, and then let it melt in place over the course of a few hours to about two-thirds of the target depth.

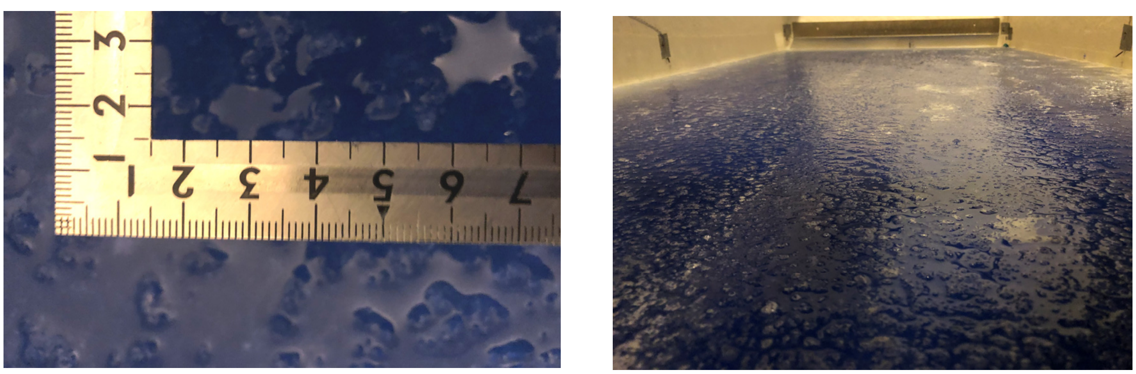

Figure 11. At left, overhead closeup of EG/AD slush ice crystals floating on the EG/AD melt. Nearly all foam due to blending has dissipated. At right, the troweled surface of slush is ready for the second stage of freezing.

Prior to refreezing, installation of two fine mesh screens (Fig. 13, left) is followed by three pairs of convection fans (Fig. 13, right). The 'second ice' freezing process takes 14-20 hours depending on target thickness and ambient air temperature of the room. The initial precooling of the EG/AD solution from about 13°C (NYC tap water temperature) to produce 'first ice' may take over two days. On completion of tempering, a sheet of rather uniform thickness and flexural strength is produced. There is currently some thickening of the ice sheet within a few centimeters of the basin walls, which may have to do with the slush being attracted to the fiberglass basin finish, or the imperfect placement and troweling of the slush. The ice sheet perimeter does adhere to the fiberglass basin as is required for simulating an infinite sheet. An example of a 'second ice' cantilever beam is shown in Fig. 12 at right.

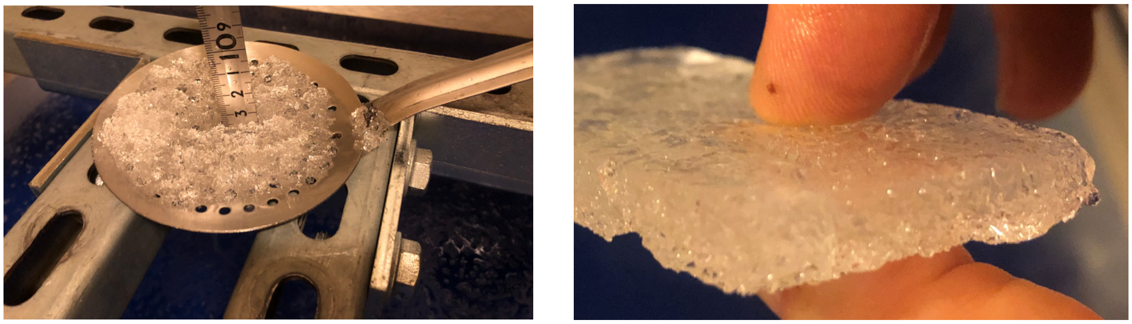

Figure 12. At left, spot checking the depth of EG/AD slush floating on melt solution with a stainless steel skimmer. In this case, slush thickness is ~5-10 mm. A tighter range has not yet been achieved, though does not appear essential. At right, a fine grain EG/AD 'second ice' beam. Thickness ≈ 12 mm. 16 Aug. 2024.

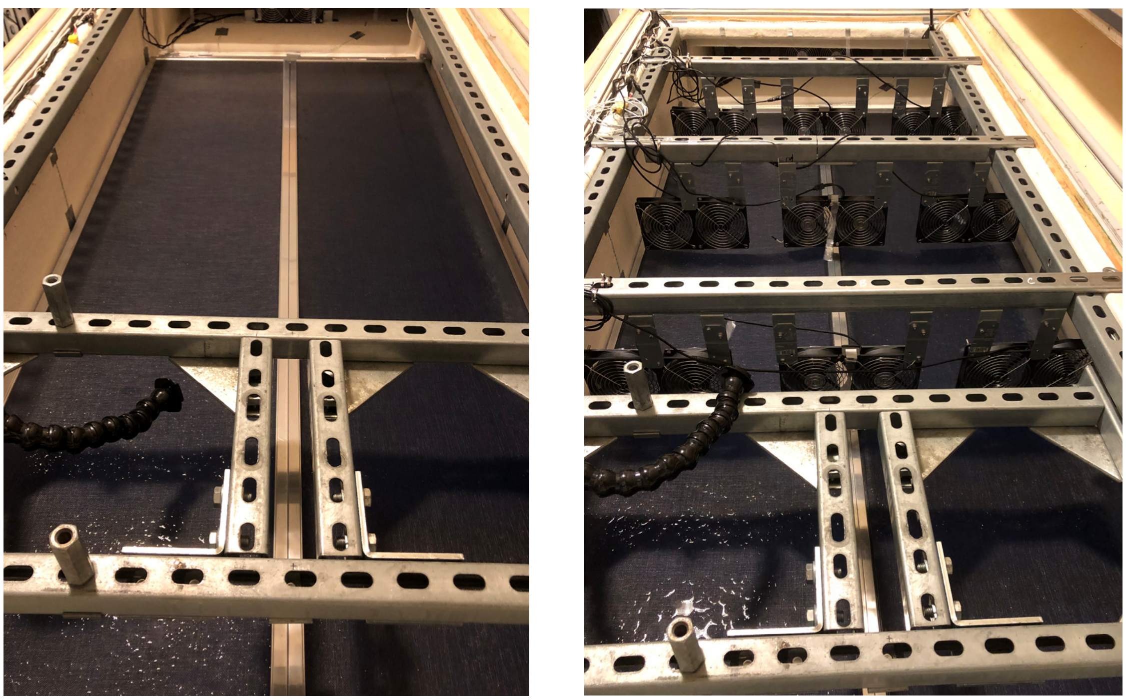

Figure 13. At left, ice tank basin with the two fine mesh screens placed a few centimeters above the troweled EG/AD slush, which is partially visible through the left screen. At right, view with convection fans suspended over screens in preparation for freezing of second ice.

DISCUSSION AND CONCLUSIONS

As may be inferred from the preceding description, the two-stage EG/AD ice adapted to work with the small tank's limitations requires a set of compensating skills, perhaps analogous to those that were required to prepare and place molten paraffin-based synthetic ice on ice tank water surfaces over fifty years ago (Michel, 1978, p. 459). Looking back on four years of experience with the small tank, the process can seem alternately a painstaking chore, an irreplaceable tool, and on occasion uniquely beautiful, which may intrigue a few and hold no interest for those that truly need higher precision and can afford the cost and scheduling of a full-service system. The intent is not to oversimplify the complex science and art of ice tank testing, but to increase access and clarify the precision needed at each phase.

Being able to run one or more tests per day working alone while attending to other tasks has made it possible to rapidly step through novel concepts, and I have often been forced to think through processes and failures that might have remained unexamined wrong thinking or matters of faith if it had been delegated to others. For those learning the basics or some finer points of ice mechanics and wanting to acquire a more confident hands-on feel for ice, or test their own designs on a tight budget and schedule, a small ice tank may be helpful.

ACKNOWLEDGEMENTS

Development of the small ice tank and this paper have been self-funded. The paper is based on a confidential unpublished report by this author to provide validation of testing for an ice rafting device as described in the patent application noted in Part 2, and as part of a master of engineering thesis detailing its prototyping. The author gratefully acknowledges the expertise of Lucas Kriz, Director of Research and Development at Central Solutions, Kansas City, KS in the selection of a suitable low suds aliphatic detergent and for a sample donated for use. The author also thanks Prof. R.U. Franz von Bock und Polach, Technische Universität Hamburg, for encouragement and preliminary review of the confidential report. None of this is to be construed as endorsement of the tank or this paper, any errors being entirely mine.

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ENDNOTES

[1] 'T-Det LF 460' - CAS 68603-25-8; 8-ethoxyoctan-1-ol;methane – nonionic surfactant by Harcros, 5200 Speaker Rd., Kansas City, KS, USA. Lot# ORG-LB-20049; Samples courtesy of Central Solutions.

[2] Some ITTC member ice tanks list 10 kPa flexural strength and 10 mm level ice as the bottom range of their modelling. Lau et al. (2007) also states: "It is noted that the practical minimum flexural strength is more than 10 kPa, in order to avoid unusual failure with significant residual strength."

[3] ITTC - Recommended Procedures: General Guidance and Introduction to Ice Model Testing. 7.5-02-04-01, Rev 03. Section 2.1.

[4] Ibid.

[5] Hetényi & Hetbenyi, 1971, p.4.

[6] Daley, 2020, pp. 85-86, assuming that the broken ice width is determined by the maximum hogging moment according to floating plate theory.

[7] Eqn. 1, ITTC 7.5-02-04-02, 2021, Rev 03.

[8] ITTC (2021). ITTC - Recommended Procedures: General Guidance and Introduction to Ice Model Testing. 7.5-02-04-01, Rev 03. Section 2.1. "Usually, it is recommended to allow the ship to proceed at least two ship lengths in level ice of uniform thickness to get a reliable resistance value."

[9] For the blender model noted in this paper, its container is filled with broken up 'first ice' to within 50 mm of the top and then saturated with EG/AD melt solution, again to within 50 mm of the top. This is mixed on the lowest speed setting: 5 ("STIR') for at least 20 seconds.

[10] KitchenAid 9-Speed Digital Hand Mixer. Initial passes are at speed 7; final pass at 3.