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Ice Accretion on Crab Pots

Rapid Evaluation and Analysis of Current Technologies (REACT) Report

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16. Abstract (MAXIMUM 200 WORDS)

In December 2020, a Coast Guard Marine Board of Investigation (MBI) looking into the December 2019 sinking of the Commercial Fishing Vessel (F/V) SCANDIES ROSE requested Coast Guard Research and Development Center (RDC) assistance to study ice accretion and accumulation on fishing pots, specifically crab/cod pots used in the Alaska/Bering Sea fishery.

The MBI noted certain evidence suggesting that vessel icing was a causative factor in the SCANDIES ROSE's loss of stability and ultimate sinking. A previous investigation into the 2017 loss of F/V DESTINATION revealed that icing directly contributed to vessel loss of stability and rapid capsizing. The MBI requested RDC assistance in determining how ice accumulation occurs on the non-solid surface of the pot cage, the netting, and gear within the pot, as well as the added weight of ice accumulation over time.

RDC conducted initial tests with CGC POLAR STAR during an Arctic Winter West patrol. Operating limitations prevented an in-depth analysis, so RDC planned a full series of follow-on tests in a controlled environmental chamber at U. S. Army's Cold Regions Research and Engineering Lab (CRREL). The experiments showed that in certain situations, a single trap could accrete more than its own weight in ice, ice accretion thickness could be a rough indicator of weight gain, and covering a pot or stack of pots with a tarpaulin ("tarp") prevents ice accretion on the frame, mesh netting, warps and floats.

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EXECUTIVE SUMMARY

In December 2020, a Coast Guard Marine Board of Investigation (MBI) requested Coast Guard Research and Development Center (RDC) assistance for a study of ice accretion and ice accumulation on fishing pots, specifically crab/cod pots used in the Alaska/Bering Sea fishery. The MBI was investigating the December 2019 sinking of the commercial fishing vessel (F/V) SCANDIES ROSE, with loss of life. The board noted that initial evidence suggested vessel icing, including the possibility of asymmetrical icing, was a causative factor in the SCANDIES ROSE loss of stability and, ultimately, its sinking. The MBI also noted the investigation into the 2017 loss of F/V DESTINATION revealed that excessive icing directly contributed to the vessel loss of stability and rapid capsizing. Due to the repetitive nature of these accidents, the MBI requested RDC assistance in determining how ice accumulation occurs on the non-solid surface of the pot cage, the netting, and gear within the pot, as well as the added weight of ice accumulation over time.

Initially, Coast Guard Cutter (CGC) POLAR STAR, Seventeenth CG District, the MBI, and an RDC staff (embarked aboard POLAR STAR) attempted to conduct preliminary ice accretion testing during POLAR STAR's Arctic Winter West patrol. The vessel strapped a 1,000 pound (8-foot by 8-foot by 3-foot) pot to the main deck, and rigged a freshwater spray source, and let it accrete ice naturally enroute to the Arctic ice pack. After 2-3 days, POLAR STAR personnel attempted to weigh the pot with a ship's crane, however, the weight exceeded strain gauge maximum capacity of 3,000 pounds. This informal ice accretion study showed that a single crab pot could gain as much as three times its own weight in ice after only a few days in certain winter conditions. Extrapolation of this weight gain led to questions of how this would impact multiple, stacked crab pots, and how this would potentially impact the stability of a ship.

Simultaneously, RDC began to plan for testing at the U. S. Army Corps of Engineers, Engineer Research and Development Center Cold Regions Research & Engineering Lab (CRREL) in Hanover, NH. This included working with the MBI to develop test goals and priorities, and with CRREL to determine facility and staff availability and schedule, test methodology, and potential constraints. The experiment team of RDC, MBI, and CRREL closely coordinated their efforts throughout the experiment duration. Because of limited crab pot availability, RDC found three, 6-foot by 6-foot by 3-foot crab pots outfitted with warps and floats on the open market. With concurrence from the MBI to use the smaller pots, RDC began planning for tests to simulate sea spray striking the three pots, in various configurations, in an environmental chamber kept below 0 degrees Fahrenheit (°F), to track ice thickness and weight throughout the spraying duration.

The team tested ice accretion on combinations of one, two-, and three-pot stacks, in two different facilities. An oscillating wand sprayed the pots at either a corner or a side, with spray arcing downward toward the nearest pot frame members. Experimenters regularly measured ice accretion thickness on the frame members for the duration of each trial.

In different trials, the weight of the ice accreted in the pots equaled or exceeded a pot's original weight. In multiple-pot configurations, the top of the stack generally accreted significantly more ice than the lower pots. Though a primary goal of the project was to determine whether accreted "thickness" could provide an indicator to an associated weight, test conditions, trap pot configurations, and ice consistency did not yield a consistent correlation. Pots covered by new, woven-polypropylene tarpaulins (tarps) and polyethylene sheeting showed significantly lower ice accretion than uncovered pots.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

CG	Coast Guard
CGC	Coast Guard Cutter
CRREL	Cold Regions Research and Engineering Laboratory
cm	Centimeter
deg	Degrees
F	Fahrenheit
°F	Degrees Fahrenheit
F/V	Fishing Vessel
ft	Foot or feet
in	Inch or inches
lb	Pound
MBI	Marine Board of Investigation
MEF	Materiel Evaluation Facility
NTSB	National Transportation Safety Board
PSU	Practical Salinity Units
RDC	Coast Guard Research and Development Center
REACT	Rapid Evaluation and Analysis of Critical Technologies
ROI	Report of Investigation

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1 BACKGROUND

On 31 December 2019, the 130-foot-long, 195-gross-ton steel commercial fishing vessel (F/V) SCANDIES ROSE, while transiting southeast of the Alaskan Peninsula, capsized and sank with the loss of five of the vessel's seven crewmembers. This occurred less-than three years after the capsizing and sinking of the F/V DESTINATION near St. George Island, AK in the Bering Sea.

With the sinking and loss of life, the Coast Guard (CG) convened a Marine Board of Investigation (MBI) to thoroughly investigate the circumstances of the sinking. In December 2020, the MBI requested the CG Research and Development Center (RDC) conduct a study of ice accretion and ice accumulation on fishing pots, specifically crab/cod pots used in the Alaska/Bering Sea fishery. The MBI requested RDC assistance (Appendix A) in determining how ice accumulation occurs on the non-solid surface of the pot cage, the netting, and gear within the pot, as well as the added weight of ice accumulation over time.

1.1 Preliminary Test

In anticipation of an upcoming public hearing scheduled for February 2021, the MBI hoped to get some preliminary data (thickness and weight of accreted ice) beforehand. During this time, the RDC, MBI and Seventeenth Coast Guard District (CGD17) worked to find a crab pot that the Coast Guard Cutter (CGC) POLAR STAR could carry and try to accrete ice during an Arctic Winter West patrol. After locating a pot, a RDC staff engineer embarked on POLAR STAR to lead experiment planning and execution. POLAR STAR loaded a 1,000 pound (lb.), 8-foot by 8-foot by 3-foot pot in Dutch Harbor, AK, strapped it to the deck (Figure 1), and rigged a spray system with a garden hose and mist-gun to simulate sea spray. Personnel weighed the pot at the outset of the experiment. After 48-72 hours into the experiment timeframe, the spray created significant accretion (Figure 2), particularly on the pot mesh netting

Figure 1. 8-ft x 8-ft x 3-ft pot aboard CGC POLAR STAR.

Figure 2. Crab pot on POLAR STAR, 27 January 2021.

When POLAR STAR tried to weigh the pot (Figure 3), the total weight exceeded the load-cell capacity, indicating a total weight of over 3,000 lbs.

Figure 3. Hoisting crab pot to weigh after accretion.

1.2 Controlled Experiment Planning

In early January 2021, RDC began investigative research as a lead-in to experiment planning. RDC identified three major issues that required immediate attention: (1) had anyone looked into commercial fishing vessel icing, specifically crab-pot icing, before, (2) where to find crab pots for testing, and (3) where to conduct the testing. Concurrently, researchers worked with the MBI to develop testing methodology to best-provide the MBI the information they sought.

1.2.1 Review of Available Information

RDC performed a background literature review of vessel icing research. The CG Report of Investigation (ROI) (USCG, 2018) and National Transportation Safety Board Report (NTSB, 2018) on the F/V DESTINATION noted potential similarity to the SCANDIES ROSE sinking, but did not include information on accretion weight or ice thickness. Another ROI on the LADY OF GRACE sinking (USCG, 2008) included estimates of ice accretion thickness based on vessels in similar conditions, but did not have information applicable for stacks of trap pots used in the Alaska/Bering Sea fisheries. The LADY OF GRACE and other vessels noted were New England trawlers with nets rather than pots or traps. The most comprehensive document researchers found was a 2013 Cold Regions Research & Engineering Lab (CRREL) report for RDC, “Icing Management for Coast Guard Assets” (Ryerson, 2013). This extensive document details the intermixed causes of vessel icing-development, and addresses measures to prevent ice accretion on CG vessels, including a discussion on CG operations in the Gulf of Alaska and Bering Sea. Of note, the report included a detailed discussion of using tarpaulin equipment covers to minimize accretion weight on deck-mounted machinery, weapons mounts, and rigging.

1.2.2 Acquiring Crab Pots for Testing

To best simulate icing conditions aboard the SCANDIES ROSE, the research team attempted to find crab pots relatively equivalent in size to the “eight-foot” pots aboard SCANDIES ROSE. In finding a “loaner” pot for POLAR STAR, D17 conveyed the difficulty in doing so, and that “spare” pots were not readily available. If the researchers were able to find the pots in Alaska, the cost and duration of shipping pots to the continental US would be excessive. As an alternative, the team conducted market research for crab pot fabrication, both locally and in the Pacific Northwest. Bids generally exceeded $2000 per pot for pot fabrication and outfitting. Crab pots are not generally “in-stock” items, but RDC did find a supplier that had a number of smaller, 6 ft x 6 ft x 3 ft pots on hand, fully rigged, built for a fisher that did not take delivery. After discussing pot size versus number of pots for testing, the MBI concurred there would be more value in acquiring the smaller pots and testing them in stacked configurations to see how the icing occurs on and in the stack, so RDC purchased three “smaller” pots. (See Figure 4).

The actual purchase occurred in early March 2021, but due to shipping delays, RDC did not receive the pots until April 2021. This delay had significant impact on experiment execution, as the next section will detail.

Figure 4. Outfitted 6' x 6' x 3' crab pots before shipping from Dungeness Gear Works, Arlington, WA.

1.2.3 Venue Selection

The ideal scenario would be to find a location exposed to sea spray, cold temperature, and wind with access to allow researchers to stack and weigh the crab pots. While the team worked to acquire pots, they concurrently researched suitable test locations. The team first considered setting up outdoor testing at a Coast Guard installation in Alaska, with below-freezing temperatures and pier access for pumping and spraying seawater, but this would require RDC researcher travel to Alaska, getting pots and weight-handling equipment to the installation, and burdening operational-unit crewmembers to assist. The impact of the COVID-19 pandemic also influenced experiment-related decisions and requirements to protect personnel during the tests. Researchers also considered conducting the experiment locally in New London, CT, understanding the same considerations, but noting fluctuating New England temperatures might not provide suitable conditions.

Simultaneously, researchers investigated the capabilities for testing at the U. S. Army Corps of Engineers, Engineer Research and Development Center, Cold Regions Research & Engineering Lab (CRREL) in Hanover, NH. Researchers were familiar with CRREL facilities and controlled environmental chambers; as RDC had contracted CRREL for earlier ice-accretion prevention work (Ryerson, 2013), and RDC had been planning for a separate, in-ice testing project at CRREL in April 2021.

As crab pot delivery delays continued, RDC finalized plans for testing at CRREL. This included working with the MBI to develop test goals and priorities, and with CRREL to determine facility and staff availability and schedule, test methodology, and potential constraints.

1.2.4 Test Plan Development

The RDC research team, MBI, and CRREL closely coordinated their efforts throughout test plan development and experiment duration. With input from the MBI, RDC began planning for tests to simulate cold (less than 37 degrees Fahrenheit (°F)) seawater spray (at approximately 33 practical salinity units (PSU)) striking one pot alone, then three pots in various configurations, in an environmental chamber kept below 0°F. The team tracked and recorded ice thickness and weight throughout the spraying duration. Appendix B provides the RDC test plan that was coordinated with CRREL.

The plan called for spraying six configurations of crab pots, including single pots, vertical stacks of three pots, a horizontal row of three pots, and a stack of three pots covered by a tarpaulin. The spray was to replicate “frequent, episodic, salt-water wetting by sea wave and wind interaction.” However, actual experiment constraints, environmental chamber layout, and equipment limitations could result in relatively controlled conditions in order to maximize ice accretion over a short period of time. For example, the experiment could substitute a constant or fluctuating stream of “spray” or “mist” aimed at the crab pot in place of wave-induced spray. The testing could account for “seawater” spray by using a saline solution, replicating oceanic conditions. Though the plan specifically called for suspending the pots and using a tension-load cell scale, the team also discussed whether multiple vehicle scales, positioned under the pot-stack corners would also accurately record weight as ice accreted. As both CRREL and RDC had tension-load cell scales available, the team decided on this method.

Initially, CRREL planned to use their Materiel Evaluation Facility (MEF), a 45 ft × 22 ft space with a 12.5 ft high ceiling and large (11.5 ft high and 11 ft wide) bay doors, which would allow easy access for equipment to stage the various pot configurations (Figures 5 and 6). The MEF had capability to operate at 20°F, which would allow for “cold soaking” the pot stack before spraying. CRREL staff noted that even at -20°F, the relatively warmer water spray (at approximately 30°F) would “heat” the chamber to the point that the saline solution might not further accrete on the pots, and spraying would stop until the chamber got back down to a much colder temperature.

Figure 5. Interior view, CRREL Materiel Evaluation Facility.

To simulate episodic wetting, the team agreed that a high-pressure spray, delivered by an oscillating "wand," could deliver a significant amount of water. CRREL had used this method in previous experiments and had multiple delivery systems available. A portable, commercially available snowmaking machine would deliver pressurized saline solution though an oscillation wand with small-orifice nozzles, mixing with high-pressure air to help disperse the spray. Figure 6 shows the snowmaker with oscillating wand attachment (a) and close-up of the spray pattern (b).

(a) (b)

Figure 6. (a) Snowmaker with wand attachment and (b) close-up of spray pattern.

To simulate the occasional larger wave spray and spume, the team discussed occasional use of a garden hose mounted fan-style soaker nozzle and hand nozzle as shown in Figure 7.

(a) (b)

Figure 7. (a) Garden hose fan-style soaker nozzle and (b) hand nozzle.

1.2.5 Facility Issues, Rescheduling, and Changes

The combined team planned for a 12 July 2021 experiment start date, to include MBI representatives. However, on 9 July, CRREL technicians found a leaking glycol coolant pump and a defroster electrical problem. Before completing repairs, CRREL suffered a catastrophic electrical failure in a summer storm that knocked out power to CRREL's "lower campus" where the MEF is situated. This led to a 45-day delay in beginning the experiment, requiring the experiment team to adjust plans, priorities and procedures.

CRREL identified an alternate cold chamber for interim testing, a 21 ft × 20 ft space with 8 ft vertical clearance (from gantry to entry level deck grating) called the "Cold-Pit." The Cold-Pit could also operate at -20°F. This chamber's one drawback was that the height of the space and its gantry limited the team to testing only one- and two-pot configurations until the MEF regained operating capability. This would allow the team to conduct the first two experiments as per the test plan, and provide additional two-pot testing, not in the original test plan.

2 PROCEDURES

2.1 Single and Two Pot Experiments

2.1.1 Experiment Set-up, Basic Procedures

To conduct the experiments in the Cold-Pit, researchers set up the Cold-Pit (Figure 8) with a 1,000-gallon tank of fresh water to supply the spray water, and added food-grade salt to provide a salinity of approximately 30-33 practical salinity units (PSU). A recirculating pump kept the water moving to prevent freezing as the spray water chilled overnight to approximately 30°F. The team would also move a crab pot to the Cold-Pit on a pallet, for "cold soaking" overnight to approximately -15°F. Cold soaking the pot and components would simulate cold weather conditions as those experienced aboard a fishing vessel in northern regions.

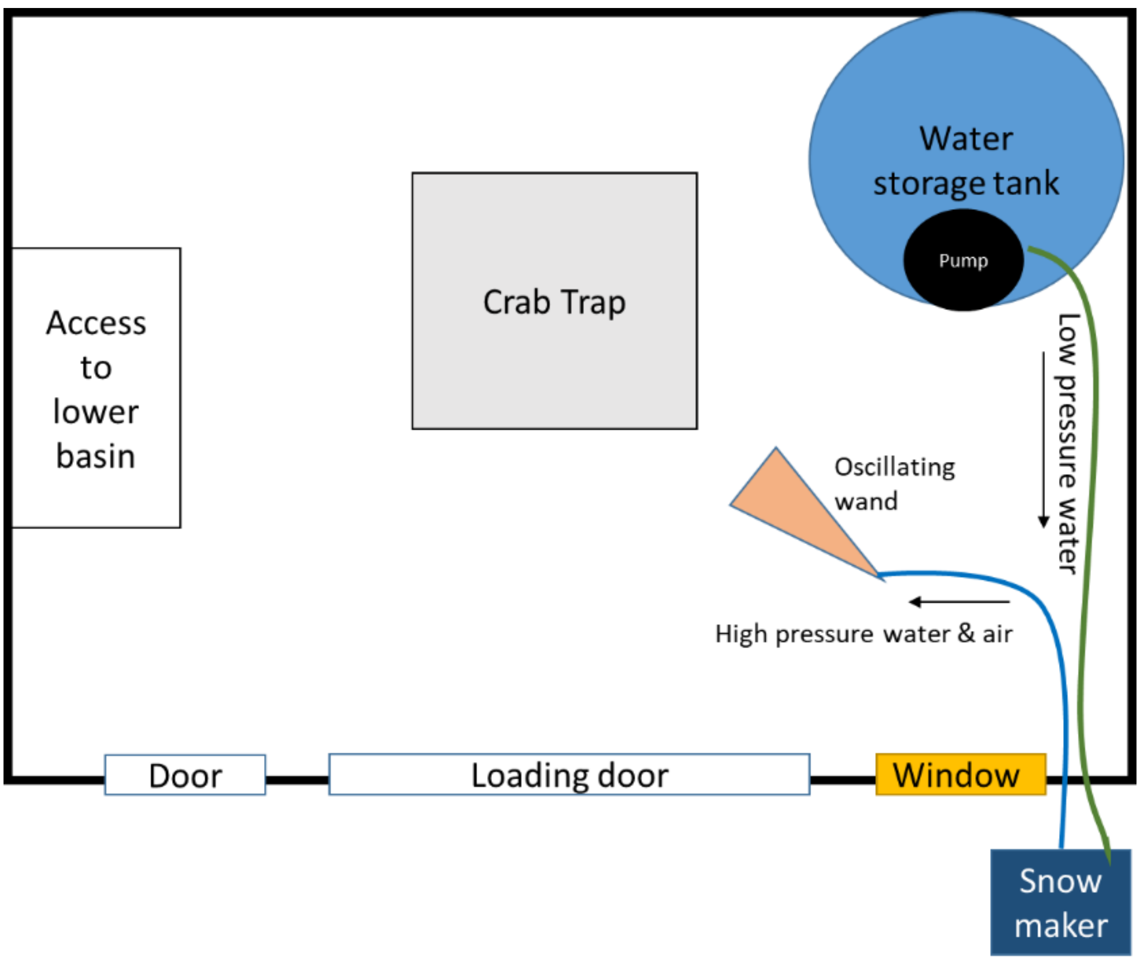


Figure 8. Schematic layout of the Cold-Pit for testing.

Because the experiment used a battery-powered load-cell scale (with the battery impacted by sustained cold temperatures) the team connected the load cell and suspended the pot until just prior to each experiment. Figure 9 shows one pot suspended before testing. Once suspended, researchers connected thermocouple sensors to record pot and ambient air temperature, and made final preparations to begin spraying.

Figure 9. Single pot suspended from load cell prior to trial experiment.

For two-pot stack tests, researchers cold soaked the pots in the Cold-Pit overnight, but would need to maneuver and stack them prior to suspending from the load cell. The team used chain and chain binders to connect the pots for suspending from the load cell. The initial pot/pot stack weight included the bridle, chain, and chain binder weight, so the net weight at the end of the experiment would be the accreted ice weight. Figure 10 (a) shows the pots before stacking, while Figure 10 (b) is during the stacking operation.

(a) (b)

Figure 10. (a) Two pots in Cold-Pit before stacking, and (b) stacking operation.

Immediately before each test, the team put the submersible pump in the water tank, connected the snow maker outside the Cold-Pit, ran the high-pressure hoses to the oscillating spray wand in the Cold-Pit, and started spraying.

Test team members were prepared to monitor spray operations and ice accretion by entry into the Cold-Pit for physical measurement, looking through the external observer window, or by monitoring audible indicators from the snowmaker compressor (change in compressor motor loading). Researchers used three-inch investigator's scales, wire-tied to the pot frame at various measurement points, to show accretion throughout a test, mini-cams inside the pot for continuous recording, and a chamber video camera.

At the completion of each test, the team removed the pots(s) for thawing, refilled and remixed the water supply tank, and staged a replacement pot(s) to cold-soak for the next day's test.

2.1.2 Preliminary Trial Runs

Before actual experiment runs, the team conducted system trials to determine if everything worked as planned and to try to eliminate any potential operating glitches or impediments.

Initially, researchers needed to reconfigure the cold-pit hose arrangement to keep the reservoir tank circulating and submersible pump clear, then set up for spray trials.

The Cold-Pit and pot had been soaked to -10°F. The high-pressure snowmaking spray put a significant amount of moisture in the air, and started to cause frost build-up on the chiller coils. More-importantly, the spray nozzles froze up after 20 minutes, requiring a thaw outside the chamber (Figure 11). In the first 20 minutes, the Cold-Pit temperature stayed below -5°F, indicating the team could restart spraying once the applicator wand thawed or after a change in sprayer.

Figure 11. Snow-maker spray wand nozzle head thawing after 20 minutes of use.

The team also attempted to evaluate the low-pressure fan nozzle and hand spray nozzle (shown previously in Figure 7) and whether the higher volume of water in larger droplets would freeze on the crab pot. Both were at pressure from the supply-tank submersible pump. The adjustable garden hose nozzle clogged internally after four minutes. The team then tried the fan-spray head, which put out a fair volume of water, but at low velocity. The fan-spray head also froze up after six minutes. Additionally, the flow from the spray head was such that it appeared to melt previously accreted ice. At the end of this test, the Cold-Pit temperature approached 0°F. The test team theorized that with the low-pressure flow and even greater pressure reduction due to the two garden-hose nozzle designs, the metal parts of the two nozzles conducted the Cold-Pit temperature to the nozzle flow, allowing internal ice buildup until the nozzle blockage. The test team removed the low-pressure nozzles from further consideration.

Prior to a second trial run, the team set up thermocouples for water, air and crab pot temperatures, then performed data logger initialization and system checks. On this trial, the team learned ice accretion almost immediately obscured the investigator's scales. Though made of smooth plastic, they formed their own accretion targets. Also, the ice build-up caused by the scales did not accurately represent the thickness on the pot framing in close proximity (Figure 12).

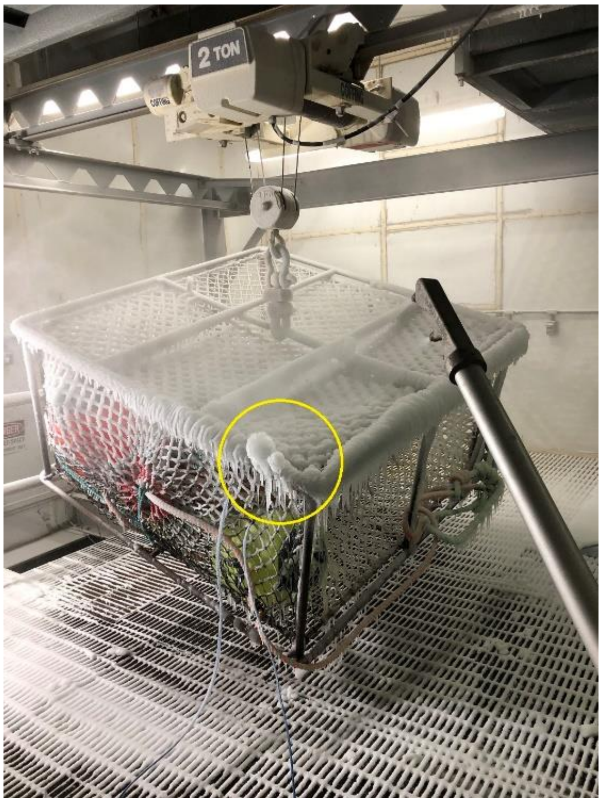


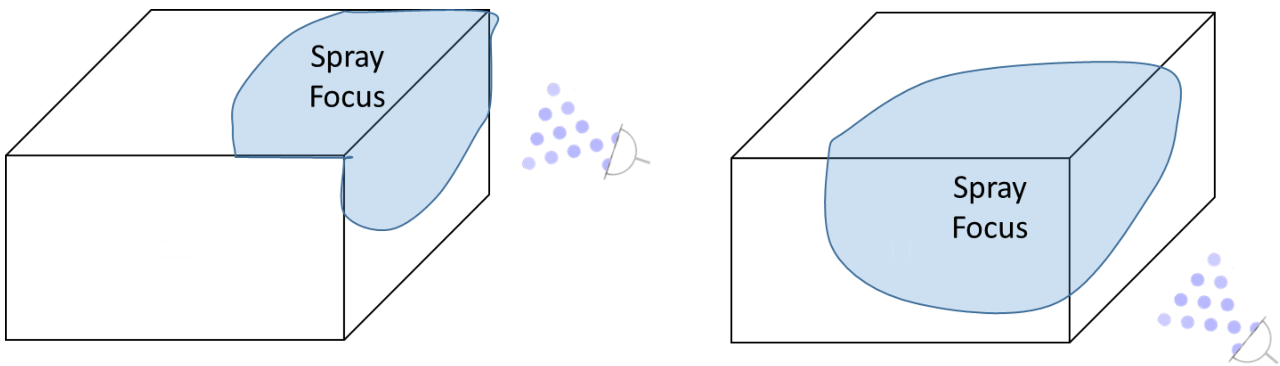
Figure 12. Crab pot in second trial run, highlighting obscured investigator's scale.

During the second trial, the spray covered the closest part of the pot extremely well, but left only a sparse coating farther away, indicating to the test team that the oscillating spray wand might need attention throughout a trial to account for the oscillating sweep coverage (azimuth), vertical angle, and proximity to the pot. In this trial, the pot gained 500 pounds of ice after 1-1/2 hours, but the pot tilted heavily due to the weight on one corner. For the actual experiments, the test team would use a four-leg chain bridle to try to stabilize the pot against "listing" in the direction of the spray. The final take away from the second trial was that the mini-camera inside the pot operated for only ten minutes. Due to the extreme cold temperature and no method to keep the mini-camera relatively "warm," the battery drained from 95% to 15% and shut down. This prevented any determination of ice accretion as viewed from inside a pot.

2.1.3 Single and Double Pot Experiment Tests

As per the experiment test plan the team initially planned to conduct test one (spray perpendicular to the pot side, with the spray arcing toward the top, facing edge) and test two (spray centered on the pot's corner, spray arcing to the top of the corner). Figure 13 depicts the spray "focus areas." Because the spray emanated from an oscillating arm, and the spray nozzles dispersed through an approximate 40-degree angle, researchers expected the spray to "paint," though not evenly, the exposed frame members and mesh.

Once spraying began, the team would measure the ice thickness forming on the pot frame at approximately thirty - to sixty-minute intervals, depending on apparent buildup, and note the weight from the continuous-reading, load-cell scale output. Because the spray water at approximately 30°F was much warmer than the initial Cold-Pit temperature of -15°F, the water would heat the ambient air in the chamber. Researchers expected approximately three hours spraying would bring the Cold-Pit temperature near-to or above 0°F, where additional spray would likely melt the already accreted ice, and the total weight would not increase.



(a) (b)

Figure 13. Focus areas for oscillating spray (a) perpendicular to side of pot and (b) centered on pot corner.

In the first three Cold-Pit tests, the spray system encountered numerous operational interruptions, including submersible pump freeze-up or failure, hose-joint freeze-up caused blockages, oscillating wand spray-head freeze-up, snowmaker overload, and other problems. All test evolutions required troubleshooting, component replacement, component thaw, or other measures. For tests four through seven, the team had overcome the problems and could conduct continuous spraying.

For experiments, researchers needed to devise an effective measurement method besides the investigator's scale. The personnel conducting measurements needed to exercise caution due to the nature of the ice accretion, a granular buildup that would dislodge when disturbed. In the first test, researchers tried using both a small engineer scale (Figure 14) and a folding wooden rule. In some instances, these did not allow accurate measurement from the top of the frame bar, occasionally dislodging accreted ice. Consequently, the team tried measuring from the bottom of the top, 1-1/8" frame bar. The gradations on the engineer scale were hard to read, so the measurer used the folding wooden rule for most readings (Figure 15 (a)). Where obscured by icicles, measurements were taken from the bottom of the bottom frame bar using the folding wooden rule (Figure 15 (b)). This required subtracting the distance from bottom of bottom bar to top of top bar from the gross measurement.

Figure 14. Small engineer scale measurement.

(a)

(b)

Figure 15. Wooden rule measure from (a) bottom of top frame bar, and (b) bottom of bottom frame bar.

For the second and third single pot tests, the measurer used a 12-inch steel square (carpenter's square) as shown in Figure 16. Half-inch colored tape made measurement to the nearest half-inch relatively easy.

Figure 16. Color-taped steel square.

Researchers built a custom measuring tool for the two-pot stack tests, and used it on two additional single pot tests (Figure 17). This tool had small hooks at the base and allowed hooking the base to the bottom frame of either a single pot or a two-pot stack.

Figure 17. Researcher holding measuring tool that could hook onto the pot's bottom frame.

Researchers limited measurements to accretion on the horizontal frame surfaces. Except for photographic records, the team did not regularly measure growth extending horizontally from the pot, ice thickness on the mesh or chain bridle, or length and quantity of icicles. (Images in Section 3 and Appendix C give examples of icicle quantity and size, and extent of ice accretion outward horizontally from the pot frame.)

2.2 Three-Pot Vertical Stack Experiments

2.2.1 Experiment Set-up, Basic Procedures

Researchers conducted the three-pot vertical stack tests in the MEF as originally planned. As with the Cold-Pit tests, the afternoon before a test, researchers set up the MEF (Figure 5) with a 2,000-gallon tank of fresh water to supply the spray water, and added food-grade salt to provide a salinity of approximately 30-33 PSU. A recirculating pump kept the water moving to prevent freezing as the spray water chilled overnight to approximately 30°F. The team would also move the three-pot stack to the MEF, for “cold soaking” overnight to approximately -15°F.

For the three-pot vertical stack tests, the test team used chain and a chain binder at each corner of the stack, connecting the bottom of the top pot to the top of the bottom pot, with the chain reeved through the middle pot’s frame (Figure 18). Instead of the chain bridle used in the single- and two-pot tests, the set-up used an extra-large, screw-pin shackle across the two frame cross-members for connecting to the load cell.

Because the MEF had a solid floor instead of the Cold-Pit’s deck grating over a basin, the team constructed a large plywood “pan” to go under the pot stack, for removing ice buildup under the three-pot stack (Figure 18). This would allow for removing ice buildup during the course of the test (to prevent the stack from “resting” on the ice resulting in a lighter than actual weight on the load cell, and for hastening clearing out the MEF after ice buildup).

For measurements, a researcher made Delrin® angle pieces and affixed rule tape to each (Figure 19). The team thought the Delrin® would shed ice accretion, and with the ruled side facing away from the spray, would facilitate top frame-bar measurement (since the top of the stack would be over nine feet above the floor, and taking measurements would require climbing a movable stair ladder). The team affixed the measurement rules with wire ties to the horizontal, top frame bar. In Figure 18, the measurement rules are visible at the top of the frame. From the more-accessible lower frame bars, an additional rule was used.

Pre-test procedures included lifting the pot stack with a machine, and connecting the load cell between the gantry and the extra-large shackle at the top center of the pot stack. Then, team members retrieved and inserted the snow collection pan beneath the pot stack, connected the thermocouples for internal pot temperature, and prepared for spraying.

Immediately before the test, the team aligned the sprayer, connected all hoses (from tank submersible pump to snowmaker, and snowmaker to spray wand) and began to spray.

Figure 18. Three-pot stack in MEF suspended from load cell before test, with plywood ice removal “pan” underneath.

Figure 19. Delrin® measurement rule used in three-pot stack testing.

As in the single and two pot tests, the test-plan guidance indicated the spray should arc towards the top edge or corner facing the oscillating spray wand, but should also coat the vertical sides as best possible. Figure 20 shows the three-pot stack focus areas for the spray.

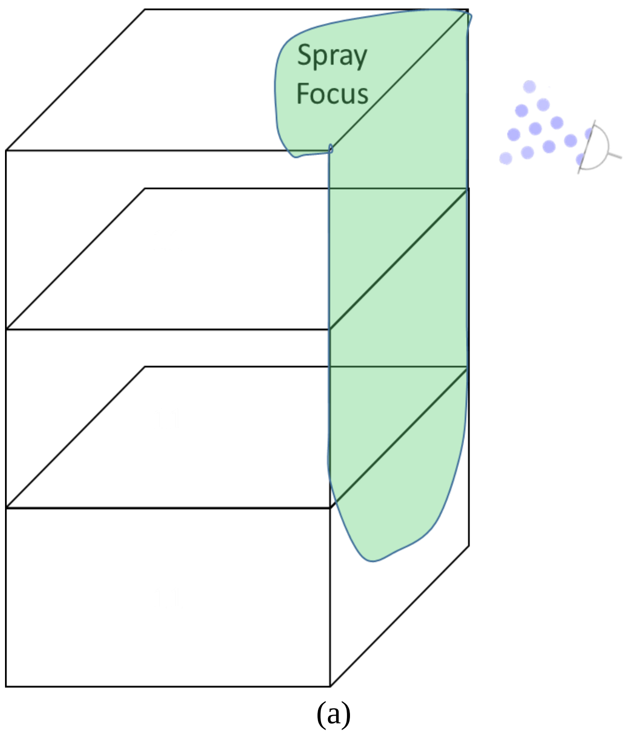


Figure 20. Focus areas for oscillating spray (a) perpendicular to side of three-pot stack and (b) centered on corner of three-pot stack.

Though researchers could generally control the oscillating sprayer wand azimuth (horizontal arc), best aligning the fixed, vertical spread of the spray wand was more difficult. Though both wand extension length and vertical angle allowed adjustment, finding the “sweet spot” to best cover both the horizontal top and the vertical sides was challenging. To cover the nine vertical feet on a facing side or corner would mean applying very little spray to the top of the pot stack. Throughout testing, researchers frequently modified both the vertical angle and distance from the pot stack to the motorized sprayer base, and also tried to make limited adjustments to the wand length.

Note: The test plan called for spraying a three-pot horizontal configuration. The actual experiments did not include this test. While handling the pots for both Cold-Pit and MEF testing, researchers realized it was not feasible to rig and support an 18-foot long assembly from the gantry in the MEF.

3 RESULTS

3.1 Daily Testing Results Discussion

3.1.1 Test 1: Single Pot – Side Spray- 1 September 2021

Initial conditions: Water temperature: 29.7°F, air temperature: -14.4°F, single-pot weight: 780 pounds[1].

After 30 minutes spray time, Figure 21 shows a somewhat uneven build-up between left (a) and right (b) on the pot side facing the spray wand. Researchers opted not to try to adjust the spray wand location during this first test, with the final measurement results showing a continued difference after two-hours of spraying. For this first test, only one measurement occurred at the end of the spraying. This first test encountered six incidents of component freeze-up or failure that required troubleshooting and component swap-out.

(a) (b)

Figure 21. Test 1: (a) left half of pot side facing spray (b) right half of pot side facing spray.

[1] The nominal pot weight was 690 pounds per pot. For single and two-pot vertical stack testing, the project used a four-leg chain bridle to try to keep the pot(s) level. The bridle weight was 20 pounds. For the two- and three-pot vertical stack, chain and a chain binder at each corner held the pots together (an additional 20-40 pounds). The initial weights reflect the weight of the pots and rigging, but when the test team would attach the load-cell scale in the extremely cold environment, it would acclimate to the cold and the load before settling. Since the important value is the net accretion gain, researchers did not try to zero-out or calibrate the scale for each test.

As the test progressed, the significant asymmetric weight loading gave concern. The spray angle may have favored the top more than the side. In the later part of the test, as the pot “leaned-in” to the spray due to the asymmetrical load, the accretion on the top mesh continued to increase, with the continued spray fully covering the top and bridle legs (Figure 22). Overhanging ice buildup with icicles is also visible. Test 1 had the greatest weight accretion for single-pot tests.

Figure 22. Test 1: Heavy accretion on top frame, mesh, and bridle.

End conditions: Total spray time: 127 minutes, water temperature: 29.7°F, air temperature: -6.7°F, final weight: 1,620 pounds (840 pounds of accretion).

3.1.2 Test 2: Single Pot – Corner Spray- 2 September 2021

Initial conditions: Water temperature: 29.8°F, air temperature: -15.6°F, single-pot weight: 760 pounds.

Test 2 encountered five sprayer system interruptions similar to Test 1, yielding a 90-minute total spray time. This resulted in a corresponding decrease in accreted weight when compared to Test 1. In Figure 23, note the 1-1/2 to 2-foot icicles adjacent to the corner that faced the sprayer, the 3-1/2 to 4-inch accretion on the top frame bar, and approximately 3-inch accretion on the bridle leg.

Figure 23. Test 2 ice accretion at end of spraying.

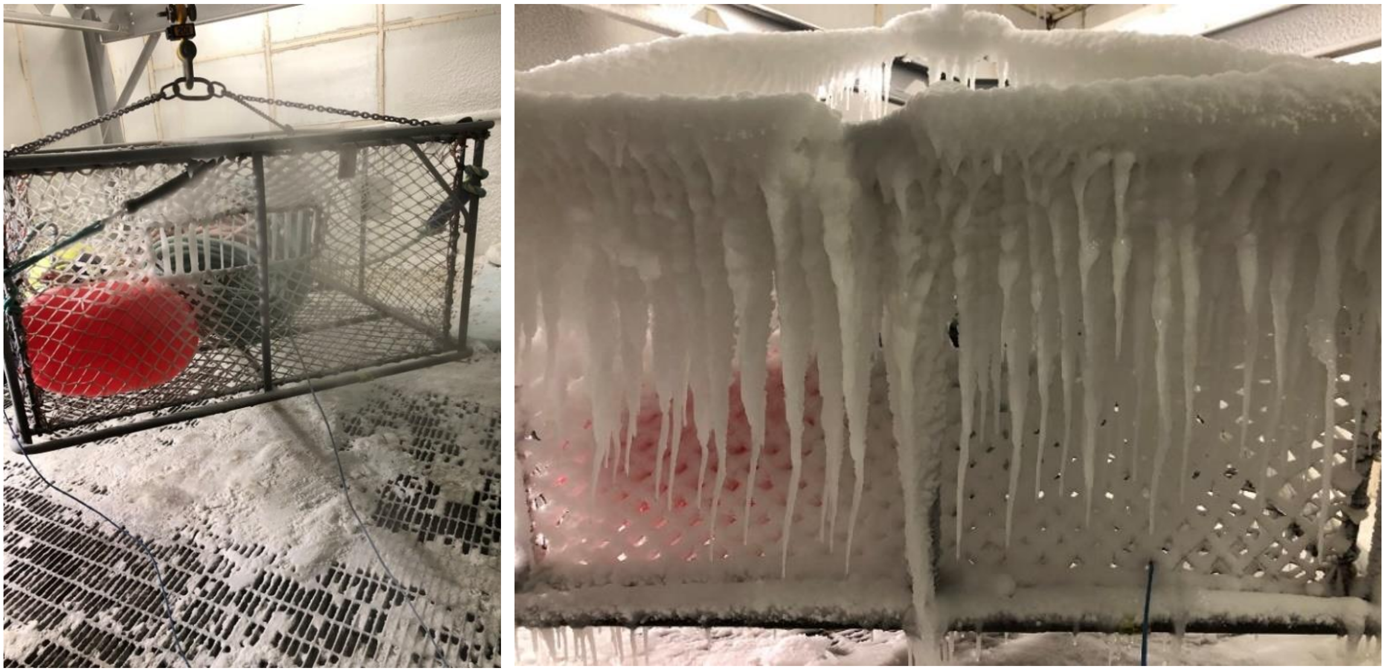
End conditions: Total spray time: 90 minutes, water temperature: 29.4°F, air temperature: -8.5°F, final weight: 1,380 pounds (620 pounds of accretion).

3.1.3 Test 3: Single Pot – Side Spray- 3 September 2021

Initial conditions: Water temperature: 29.7°F, air temperature: -14.3°F, single-pot weight: 760 pounds.

For Test 3, the project lead decided to redo the single-pot spray at the side. This test included the interim measurements (not conducted in Test 1) and tried to have the spray concentrated into the opening of the single pot (Figure 24 (a)). Test 3 had nine interruptions, including three where researchers found the spray nozzles plugged with rust, debris, or paint.

In comparison to Test 1, the total spray times were approximately the same, but Test 3 used 15% less water than Test 1. The resulting accumulation was also 15% less. The biggest difference from Test 1 was on the frame top accretions. Test 1 high-three final accretion measurements were 4.5, 6.5 and 9 inches, while Test 3 high-three measurements were 3.0, 3.0, and 3.5 inches. There was slightly more ice on the lower webbing, warps and floats in Test 3 when compared to Test 1, but the greatest difference was in the number and size of icicles formed on the sprayer-facing side (Figure 24 (b)).



(a) (b)

Figure 24. Test 3 (a) spray targeted more toward pot side rather than pot side, top edge, and (b) resulting heavy increase in icicles on side.

End conditions: Total spray time: 126 minutes, water temperature: 30.0°F, air temperature: 0.9°F, final weight: 1,460 pounds (700 pounds of accretion).

3.1.4 Test 4: Two Pot Vertical Stack – Corner Spray- 7 September 2021

Initial conditions: Water temperature: 28.7°F, air temperature: -15.6°F, two-pot weight: 1,420 pounds.

Ice started accreting within the first 30 minutes of spraying, and at all times the top bar experienced more accretion than the bottom bar. Large icicles formed on the top bar along with granular ice packing onto the mesh netting. As the spray continued, the interior of the pot experienced very little ice accretion in general (Figure 25); very little adhered to the ropes or buoy inside. However, as ice accumulated on the top mesh, icicles formed that hung down into the interior of the pot.

Figure 25. Test 4: Interior of top pot showing icicles and minimal accretion.

Ice accumulation on the top bar created 1 to 1-1/2 foot long icicles that dangled loosely from the top bar. Multiple times when taking measurements, researchers would brush up against the icicles causing them to fall off. These icicles broke off at the slightest touch, and appeared granular as opposed to the smooth, clear icicles one might see hanging from a frozen rain gutter. The corner of the pot stack facing the spray developed large masses of ice that grew outwards (toward the sprayer) and accumulated more ice as spraying continued. The large accumulations proved to be difficult to measure accurately (Figure 26). These large ice masses adhered to the pot better and were denser than the icicles. Researchers used extreme caution when taking measurements from underneath the ice masses in order to avoid the risk of falling ice as well as to ensure the integrity of the added ice for accretion-weight measurements. Researchers only measured the vertical part of these corner accumulations, above the frame top bar.

Figure 26. Test 4: Ice accumulation on top bar with large protrusion from the spray-facing corner.

As ice accreted, the weight of the ice caused the corner closest to the sprayer to lean and later rest on the floor. A support rope (tag-line) was attached to the opposite side of the pot to prevent contact with the floor, which would lead to a lighter-than-actual weight gain.

End conditions: Total spray time: 180 minutes, water temperature: 29.4°F, air temperature: -5.9°F, final weight: 2,500 pounds (1,080 pounds of accretion).

3.1.5 Test 5: Single Pot – Side Spray- 8 September 2021

Initial conditions: Water temperature: 28.9°F, air temperature: -15.9°F, single pot weight: 760 pounds.

Test 5 repeated the single pot experiment from Tests 1 and 3. The test team decided to recreate the single pot, side spray because of the number of problems encountered with the first three tests. This test encountered no interruptions. As in Tests 1 and 3, the sprayer was positioned to oscillate transversely over one side of the pot. The team took measurements once every 30 minutes.

Ice accretion occurred primarily on the pot's spray-facing side, with some accretion happening on the two adjacent sides. Ice built up on the chain bridle fairly-quickly, and later formed a solid mass from the chain to the pot frame and mesh (Figure 27). There was heavy ice accretion along the top, spray-facing frame bar that created a protruding ridge of ice with one- to two-foot long icicles. No real accretion happened inside the pot; only a thin layer of snow formed on the mesh, ropes, and floats on the inside of the pot.

Figure 27. Test 5: Heavy ice accretion on top frame, mesh, and chain bridle, but very little inside.

End conditions: Total spray time: 145 minutes, water temperature: 28.9°F, air temperature: -5.3°F, final weight: 1,560 pounds (800 pounds of accretion).

After Test 5, the experiment team cleared approximately 250 pounds of ice from the pot and wrapped the frame top bar with plastic wrap, secured with electrical tape. This was an on-the-spot idea to attempt to replicate real-world circumstances. A common occurrence in the commercial crabbing industry to help prevent ice accretion is adding a layer of plastic wrap around the pot sides. After an additional 30 minutes of spraying, the pot had accumulated an additional 215 pounds of ice, but had minimal accretion on the wrapped surfaces as compared to the other areas (Figure 28).

Figure 28. Test 5: Top frame bar (closest to camera) wrapped in plastic, showing minimal accretion after 30 minutes spraying as compared to chain bridle (top right of image).

3.1.6 Test 6: Two Pot Vertical Stack – Side Spray - 9 September 2021

Initial conditions: Water temperature: 28.7°F, air temperature: -16.4°F, two-pot weight: 1460 pounds.

Test 6 had a two-pot vertical stack, with a side of the stack facing the sprayer (as in Tests 1, 3, and 5 for the single pot). In this configuration, ice accretion was most-pronounced at the side closest the sprayer, resulting in large ice masses on the facing corners and frame bars, a heavy cover on the mesh that resembled a thick ice sheet, and icicles hanging from the frame bar and corner buildup. Some of the icicles were up to four feet long (Figure 29). Measuring the large buildups proved to be problematic due to uneven growth, and the team was concerned that incidental contact with the accretion would dislodge large pieces or the icicles.

Figure 29. Test 6: Two-pot vertical stack showing heavy ice accretion on spray-facing side with iced-over mesh, large buildups on corners and top bar, and numerous icicles.

Though the mesh on the front was completely iced over, except for some accretion on the side top frame bars with a few icicles, the mesh in the back and sides of the pot experienced little accretion (Figure 30). Because of the extreme, asymmetric ice loading, the two-pot stack required a tag-line (visible in Figure 30 tied to the lower basin guard rail) to keep the bottom pot off the metal grating deck, in order to get an accurate weight.

Figure 30. Test 6: Side of two-pot stack showing minimal accretion on mesh, both pots.

<u>End conditions</u>: Total spray time: 180 minutes, water temperature: 29.6°F, air temperature: -2.1°F, final weight: 2,280 pounds (820 pounds of accretion).

3.1.7 Test 7: Single Pot – Tarped – Side Spray - 10 September 2021

Setup for Test 7 included wrapping a single pot in heavy-duty tarpaulin. The tarp was meant to prevent ice accretion on any of the individual pot components (frame, mesh, warps and floats), but could provide large slick surfaces to possibly shed accretion. The team wrapped the tarp around the body of the crab pot, but left the chain bridle exposed. The sprayer oscillation target was a side, top edge of covered pot

Initial conditions: Water temperature: 29.0°F, air temperature: -15.0°F, pot weight: 780 pounds.

Once spraying began, it was obvious the tarp was repelling the snow on the face of the pot. However, since the chain bridle was exposed, the ice started accreting on the chains. As with the previous testing in the Cold-Pit, the ice around the bridle legs was not measured nor accounted for when calculating ice growth. Over time, the tarp also began to experience ice accretion on the horizontal top bars of the pot. This ice was extremely fragile and would often fall to the ground under its own weight. Figure 31 shows the ice accretion on the lip of the pot and bridle; the void on the facing top-bar shows where ice fell.

Figure 31. Test 7: Tarped crab pot, minimal to no ice accretion on side faces, but ice accretion on chain bridle and lip of tarp at top frame bar.

Over the course of the two-hour test the top of the pot experienced slow but steady ice accumulation. Though a considerable amount of ice accreted on the lifting bridle and the tarps directly above the horizontal frame top bars, the areas between the frame bars above the mesh also accreted a noticeable layer (Figure 32).

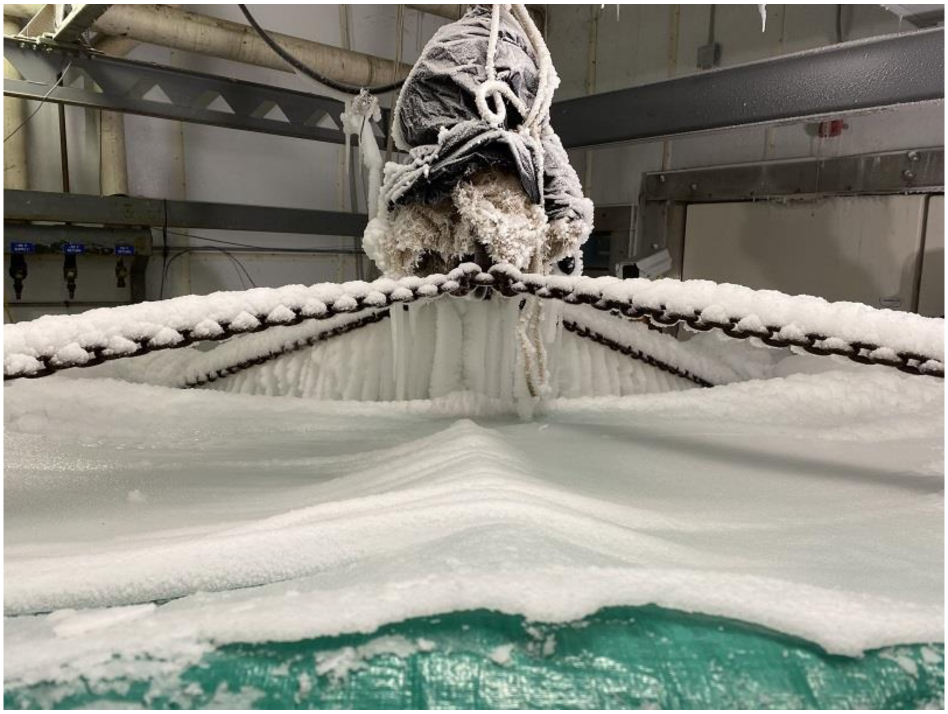


Figure 32. Test 7: View along top of tarped pot showing layer of ice on the tarp over frame and mesh areas.

End condition: Total spray time: 28 minutes, water temperature: 29.3°F, air temperature: -7.6°F, final weight: 1,320 pounds (540 pounds of accretion).

3.1.8 Test 8: Three Pot Vertical Stack – Side Spray - 27 September 2021

NOTE: All three-pot vertical stack tests occurred in the MEF.

Initial conditions: Water temperature: 29.1°F, air temperature: -14.4°F, three-pot weight: 1,960 lb.

On this first test in the MEF, the goal was for maximum accretion with the side of the stack facing the oscillating sprayer. Test 8 experienced two interruptions for water-supply line freeze-up. Figure 33 (a) shows the stack after approximately one hour of spraying. The almost solid icicle/front mesh accretion on the top pot prevents additional internal buildup. Note also the accretion on the Delrin® rules, making a small "tower" at each measurement point. In some instances, this shadowed a portion of the frame top bar from even accretion.

During the test, researchers noted the difficulty of trying to "arc" the spray over the top facing edge, as some of the spray would completely miss the top of the stack, as indicated by the minimal accretion on the far top bar, shown in Figure 33 (b). At the end of Test 8, though the buildup on the facing side almost closed off the top pot, there was some accretion on the internal mesh of the top pot, but very-minimal accretion on the mesh of the lower two pots. As Figure 33 (b) shows, there was a significant amount of icicle formation from the spray-facing bars, even without vertical accretion on those bars. The spray did not provide much accretion on frame surfaces away from the spray and on the lowest pot. In these cases, the team did not record measurements of less than one-half inch.

After approximately two hours of spraying, spray started to drip continuously from the upper pots, resulting in wet "slush" on the chamber floor and snow removal pan.

End conditions: Total spray time 2 hr 38 min, water temperature 29.8°F, air temperature -6.3°F, final weight 2,805 pounds (845 pounds of accretion).

(a) (b)

Figure 33. Test 8: (a) Accretion after approximately one hour spraying; face of top pot almost completely obscured, rules accreting ice well above frame top bar. (b) After 2-1/2 hours spraying, minimal accretion on far, top frame bar.

Up to this point in the testing, all ice accretion imagery was at close range. The MBI raised the issue of how the accretion appeared at a distance, and whether a knowledgeable individual would be able to estimate the depth accretion from that distance. (i.e., try to replicate the view of a person on the bridge of a fishing vessel.) To get such a perspective, researchers carefully moved the three-pot vertical stack to a position suitable for background photography, where a portable scaffold could provide height and distance to view a pot stack. Figure 34 (a) and (b) provides two such views from a distance of 45 feet and height of 18 feet.

(a)

(b)

Figure 34. Test 8: Three-pot stack, outside after spraying (a) normal perspective at 45 ft distance (b) zoom perspective from 45 ft.

3.1.9 Test 9: Three Pot Vertical Stack - Tarped– Side Spray - 28 September 2021

Initial conditions: Water temperature: 30.2°F, air temperature: -6.3°F, three-pot weight: 1,968 pounds.

Due to the time the three-pot stack needed to thaw from the 27 September test, (and the expected thaw time for the corner spray), the team decided to complete the side-spray of the tarped stack as the second test. As the ice on the pots needed to thaw overnight, the team did not start tarping the pots until the morning of 28 September. Bringing the wrapped three-pot stack and catch pan inside the MEF immediately before testing caused the MEF's ambient temperature to rise to -6.3°F, somewhat warmer than the previous tests. There were no interruptions during the approximate 2-1/2 hours spraying.

Throughout the test, icy slush only covered the top of the stack, pooling in tarp sags between frame cross-members as in Test 7. The team took no physical measurements of ice accretion on the top frame bar during this test, as the ice was very unstable and continuously sloughed off throughout the test, occasionally losing 10-30 pound chunks (as noted by the load cell) off the top edge and corners. Figure 35 (a) shows the facing side of the tarped stack with a "clean" break in ice at top left and a pile of ice and slush accumulating on the pan at the bottom. Figure 35 (b) is a close-up of the pooled ice and slush atop the stack. This test stopped due to an increase in MEF temperature to 2.8°F.

(a) (b)

Figure 35. Test 9: (a) facing side of tarped stack with "clean" break in ice at top left and pile of ice and slush accumulation on pan, and (b) close-up view of pooled ice and slush atop the stack.

After spraying, the estimated maximum average depth of the ice and slush mix that filled the tarp's slack areas between the top frame perimeter and cross-members was approximately 2-1/2 inches, the deepest in the forward-right quadrant, and least in the rear-left quadrant. As the test team attempted to remove the snow-pan and pot stack from the MEF, the ice and water mix sloshed over the top frame bar.

End conditions: Total spray time: 2 hr 30 min, water temperature: 29.8°F, air temperature: 2.8°F, final weight: 2,388 pounds (420 pounds of accretion).

3.1.10 Test 10: Three Pot Vertical Stack - Corner Spray - 29 September 2021

Initial conditions: Water temperature: 29.1°F, air temperature: -15.9°F, three-pot weight: 1,930 pounds.

With no accretion on the pot frames after the tarped spray, the pots cold-soaked overnight. Test 10 spray focused on the facing corner, and the team made continuing effort to get spray landing on top, adjusting sprayer height and angle. The goal was to maximize accretion until MEF temperature warmed, then leave the stack in the MEF overnight and resume with the same spray pattern for Test 11, building on Test 10 accretion.

After approximately 30 minutes, the MEF temperature had warmed to approximately -9°F, and the team moved the sprayer farther away from the stack to get a better arc towards the top of the stack while still targeting the leading vertical edge (Figure 36). This did not provide the desired vertical coverage, as the only ice accretion on the facing vertical edge was on the top pot; however, Figure 34 shows that the mesh on both sides of the top pot started to develop significant accretion. Unfortunately, the actuator oscillation pattern now went past the edges of the pot-stack, "wasting" spray and putting moisture into the MEF rather than on the stack.

Figure 36. Test 10: Ice accretion on the top pot of the stack after adjusting sprayer location.

After nearly three hours, the pot accumulated approximately 700 lbs of ice at a maximum accretion thickness of 3 in, but the MEF temperature was at -2°F, leaving heavy wet slush on the ice pan and floor, making measurements challenging. After 3-1/2 hours, as the MEF temperature reached approximately +10°F, much of the spray was not freezing and was dripping off. Thus, the team terminated the test after accumulating 840 lbs of ice at maximum frame-bar vertical accretion thickness of 4 in.

Figure 37 shows the pot stack at the end of Test 10, with significant buildup on the top, spray-facing corner, and icicles hanging from all three pots. The top pot mesh of both spray-facing sides has relatively thick accretion, as compared to the marginal amounts on the bottom two pots. Note the icicles hanging from the gantry due to overspray, and slush on the snow pad around the perimeter of the lower pot. This "wasted" spray contributed to ambient air warming without accretion on the pot stack. During Test 10, the MBI proposed containing the bottom of the pot during Test 11. After continuous checking of the slush on the pad during Test 10, the team decided NOT to try to contain the bottom of the stack for the final test, as there was very little ice or slush directly below or attached to the bottom frame. All the slush and water accumulated from external dripping and spraying.

Figure 37. Test 10: Three-pot stack at the end of spraying.

End conditions: Total spray time: 3 hr 40 min, water temperature: 19.6°F, air temperature: 12.1°F, final weight: 2,803 pounds (873 pounds of accretion).

3.1.11 Test 11: Three Pot Vertical Stack- Corner Spray (continued) - 30 September 2021

Initial conditions: Water temperature: 28.7°F, air temperature: -15.7°F, three-pot weight: 2,829 pounds.

Test 11 built on the previous day's accretion, following the same procedures with spray at 45 degrees to the pot and concentrating at the upper corner, adding to the hardened Test 10 ice layer. The team moved the oscillating wand applicator closer to the stack to minimize lateral overspray encountered in Test 10. As the stack had a forward tilt due to the previous day accretion, the spray easily reached the top of the stack (Figure 38). Test 11 had one interruption when the sump pump float failed, shortly after starting the spray.

After approximately 1-1/2 hours, the MEF temperature was approaching -1°F. Already, an additional 400 lbs of ice, with approximately five inches maximum height on the top horizontal frame sections, had accreted. A vertical mass at the leading corner edge from the previous day had become much larger, though an indent was visible, having taken the spray most-directly. This mass was extremely fragile, and the team estimated it to have a horizontal extent of 10-12 inches outward from the corner. (Figure 39).

Figure 38. Test 11: Thirty minutes into continuation of spraying adding to Test 10 accretion.

Figure 39. Test 11: Large ice accumulation extending 10-12 inches from the spray-facing corner.

After approximately three hours, the load cell weight had plateaued, though spraying continued. The team realized the bottom corner of the stack facing the sprayer was resting on the snow pad. In removing the pad, the load cell registered a 150 lb increase over 1-1/2 minutes. In removing the snow pad through the open bay doors, the ambient temperature rose, and the chiller units could not overcome the warm air introduced while removing the platform. After 3-1/2 hours spraying, the MEF temperature was rising through +5°F, with much dripping from the stack, so researchers ended the test.

At the end of Test 11 and the 2-day accumulation, there were multiple measures of 7 inches accretion on the top frame-bars, along with the large, extremely fragile vertical masses, some 3 feet long, extending 8-15 inches horizontally from the frame (Figure 40 (a) and (b)).

(a) (b)

Figure 40. Test 11: At completion of spraying (a) left side facing sprayer and (b) right side facing sprayer.

<u>End conditions</u>: Total spray time: 3 hr 40 min, water temperature: 18.9°F, air temperature: 6.3°F, final weight: 3,610 pounds (781 pounds of accretion; 2-test combined accretion 1,654 pounds).

As after Test 8, the team carefully moved the three-pot stack outside for photos at a 45-ft distance. (Figure 41).

(a) (b)

Figure 41. Test 11: Three-pot stack, outside after spraying (a) normal perspective at 45 ft distance (b) zoom perspective from 45 ft.

3.2 Results Summary

For each set of laboratory test series (single pot, two-pot stack, and three-pot stack), the maximum accretion in a single spraying showed a variance across parameters (number of pots & direction of spray).

The single pot with side spray had three tests with varied results. Test 1 gained 840 lbs, Test 3 gained 700 lbs, and Test 5 gained 780 lbs.

In terms of maximum accreted weight in one spraying, the ranking for the top three tests from high to low was Test 4, 1080 lbs (two-pot vertical stack, corner-spray); Test 10, 873 lbs (three-pot stack, corner-spray); and Test 8, 845 lbs (three-pot stack, side-spray). Of note, the next highest was Test 1, 840 lbs (single-pot side spray).

Test 9 and Test 7, the tarped pot stacks, had the lowest amounts of ice accretion; 420 lbs for the three-pot stack and 520 lbs for the two-pot stack.

Average measured accretion thickness did not show a direct relation to weight increase.

Appendix C includes a series of full, daily measurement records and accompanying photographs. Table 1 gives daily record excerpts that include experiment spray duration (spray time), change in weight (Δ weight), and ice thickness (in inches) at individual measurement points on the pot frame(s) at the end of each day's trial.

Table 1. Daily ice accretion summary.

Date			1-Sep-21	2-Sep-21	3-Sep-21	7-Sep-21	8-Sep-21	9-Sep-21	10-Sep-21	27-Sep-21	28-Sep-21	29-Sep-21	30-Sep-21
Trap Configuration			Single	Single	Single	Two vertical	Single	Two vertical	Single Tarped	Three vertical	Three vertical tarped	Three vertical	Three vertical
Spray Position			Side	Corner	Side	Corner	Side	Side	Side	Side	Side	Corner	Corner
Spray Time			2h 07m	1h 30m	2h 06m	3h 00m	2h 25m	3h 000m	2h 20m	2h 38m	2h 30m	3h 40m	7h 03m
Weight Δ			840	620	700	1080	800	820	520	845	420	873	1654
Measure Point Thickness Top of stack	1	A	2.5	4.5	1.0	5.0	4.0	2.5	3.5	1.0	No Individual measurements	0.5	0.5
	2	B	4	4	3.0	4.0	4.0	2.0	4.5	1.0		1.0	1.0
	3	C	3.5	7	2.5	3.0	4.5	2.5	5.5	3.0		2.0	3.5
	4	D	9	3.5	2.5	0.5	2.5	2.0	3.5	3.0		3.0	5.5
	5	E	6.5	4	3.5	0.0	0.8	0.5	1.5	2.5		4.0	7.0
	6	F	4.5	1.5	3.5	1.0	0.5	0.0	0.0	3.0		3.5	7.0
	7	G	1.5	0.5	1.0	4.0	2.0	0.0	0.5	2.5		2.5	7.0
	8	H	1	2.5	0.5	5.5	3.0	1.5	2.5	0.5		1.0	2.0
Measure Point Thickness Bottom of top trap	1	I				2.5		3.0		3.0		1.5	5.0
	2	J				2.0		4.5		3.0		3.0	5.0
	3	K				2.0		4.0		3.0		1.5	3.0
	4	L				1.0		1.0		1.0		1.5	5.0
	5	M				0.0		0.5		0.5		2.0	5.0
	6					1.0		0.5		0.0		0.0	0.0
	7					1.0		0.0		0.0		0.0	0.0
	8					2.0		0.8		0.0		0.0	0.0
Average Accretion	TOP		4.1	3.4	2.2	2.9	2.7	1.4	2.7	2.1		2.2	4.2
	Bottom					1.4		1.8		1.3		1.2	2.9

Note: For 30 September, testing started with the finished accretion and weight from 29 September.

4 CONCLUSIONS

4.1 Conclusions Relating to Methodology

While the experiment made best efforts to replicate conditions that would simulate "winter like conditions," the methods used in this experiment did not replicate storm-wind driven spray and spume as a vessel would encounter in the Alaska fishery or in other open-water, high wind and sea, freezing temperature conditions. Understanding that, the methods used were able to induce a targeted level of ice accretion that may allow scaled representation of accreted depth to accreted weight.

4.1.1 Single Test aboard CGC POLAR STAR

This single opportunity provided what could be the most realistic ice accretion simulation during testing. Thorough and repeated application of water yielded a pot weight in excess of 3,000 lbs., or a net accretion of 2000 lbs., allowing for an approximate "dry" pot weight of 1,000 lbs. This test did not include measuring the height of accretion, but allowed for a somewhat homogenous application of water to the pot, allowing buildup on the pot mesh, warps, and floats.

4.1.2 Directed, Oscillating-Wand, Spray Loading

Though initial plans called for a multiple element spray, including larger, occasional dousing, the snowmaker and oscillating wand provided significant accretion in most of the tests. In all but the two tests where the pot and pot stack were tarped, the oscillating wand spray yielded asymmetric accretion and loading, with the pots tilting, top towards the spray.

The team had a challenge in trying to get the proper spray coverage as noted in the test plan. The goal was to “arc” the spray to hit the top facing edge or corner of the pot. However, with the limits of chamber height and gantry, and oscillating sprayer arm length, there was a small “sweet spot” between spraying over the top of the pot or pot stack, and spraying too low, with concentration solely on the forward face.

The ice that formed was extremely granular. In some measurement locations, the granular nature was evident as chunks of ice fell off the frame during measurement. The icicles that formed were extremely susceptible to breakage. The team attributes this to both the salinity of the water (approximately 31-33 PSU) and the size of the droplets from the sprayer nozzles.

4.1.3 Measurement Techniques and Photographic Comparison

Measurement techniques improved throughout the testing, but did not address multiple issues. Reliance on horizontal frame-bar accretion did not account for extensive outward ice growth from the pot frame, the number of icicles (including thickness and length), and accretion on the pot mesh.

Use of fixed scales or rules created their own local accretion and shadowing inconsistencies. The high-points stick out (literally) in the photos associated with the three-pot stack tests.

When measurers used a yardstick, carpenter’s square, or wooden rule to measure from the top of the frame-bar, they occasionally dislodged chunks of the granular ice. Measuring from the bottom of the frame-bar required judgment to prevent measurement parallax error, but firmly holding a measuring device to the frame-bar would again, knock loose a section of ice.

The team took an extensive amount of photographs. Appendix C relates particular time intervals and measurements to photographs. From photographic review, the amount of non-measured ice accretion (icicles, horizontal protuberances, mesh accretion, and chain bridle accretion) likely contributed to a significant portion of the total accreted weight.

4.1.4 General

Use of the chain bridle to try to prevent excessive tipping in the single-pot tests resulted in significant ice accretion on the bridle, and icicles connected the space between the bridle and the pot mesh. This had a factor in increasing the measured weight.

Researchers had numerous discussions as to whether suspending the pots from a load cell for weight measurement had benefit over using multiple industrial floor scales. The one drawback to using the gantry-suspended load cell was the pot or pot-stack “tipping” into the spray. On occasion, the spray-facing side or corner contacted the floor, but researchers quickly took measures to keep the pot or pot stack free-hanging.

4.2 Conclusions Relating to Results

4.2.1 Crab Pots with Tarpaulins

Covering the crab pots with tarps prevented ice accretion on the mesh, warps, floats, and much of the pot frame. Ice did not stick to the vertical sides of the pots. In the single, tarped pot test, a significant amount of ice formed on the chain bridle, with additional ice pooling in the slack areas of the tarp, in the quadrants made by the pot’s top frame. In the three-pot vertical stack tarped test, the only ice accretion was a mix of ice and slush in those same slack areas of the tarp, atop the stack. Accretion on the outer edge of the frame was extremely unstable and regularly slid down the tarped sides.

4.2.2 Total Amounts of Ice Accretion

The preliminary test aboard POLAR STAR showed that **severe icing could triple the weight of a crab pot**.

Though the laboratory procedures did not accurately simulate real-world conditions, researchers were able to accrete a significant amount of ice on the different configurations of crab pots, when not tarped, in a relatively short amount of time (two to four hours). For the four single-pot tests, **researchers more than doubled the single pot weight in two of the tests**, with the remaining two tests being at 180% and 190% the starting, single-pot weight. (Note: In these single-pot tests, the chain bridle used to try to prevent tipping incurred large amounts of unmeasured ice accretion.)

In the lab tests, there was asymmetric loading on the crab pots: the side of the pot facing the spray had up to three times the accretion as the other side of the crab pot. Though it was beyond the scope of the lab testing, if researchers changed the pot orientation, even slightly, for additional spraying, the accreted weight could be different.

In all but the tarped pot tests, icicle formation was a significant addition to the accumulated weight. Analysis did not include icicle categorization as to number or size. Further, in numerous instances, horizontal ice built-up away from the pot, contributing to additional, unmeasured vertical growth. A review of photographs from this work for multi-pot stacks indicates most of the ice accretion, horizontal growth, and icicle formation was on or extended from the top pot. This resulted from the “top corner” spray focus.

The results of this testing did not provide enough information to allow a visual “rule-of-thumb” estimation of added weight based on depth of ice accretion.

5 RECOMMENDATIONS

The Marine Board of Investigation into the sinking of the F/V SCANDIES ROSE should determine whether this report provides information that could begin to explain the issues associated with ice accretion encountered by vessels in cold temperatures, high winds, and heavy seas. If found to be relevant, the MBI should include this report as an adjunct to its Report of Investigation into the sinking of the F/V SCANDIES ROSE.

In light of the amount of ice accretion found possible in this experiment, the MBI should also consider recommending to the Coast Guard Office of Design and Engineering Standards an examination of regulatory stability requirements pertaining to deck loading of frame and mesh fishing pots when a vessel can expect icing conditions.

If additional research into the dynamics of vessel ice accretion is warranted, the Office of Design and Engineering Standards should request research and development support.

6 REFERENCES

National Transportation Safety Board. Marine Accident Brief, Capsizing and Sinking of Fishing Vessel *Destination* NTSB/MAB-18/14, Washington, DC. June 2018.

National Transportation Safety Board. Marine Accident Report, Capsizing and Sinking of Commercial Fishing Vessel SCANDIES ROSE, Sutwik Island, Alaska, December 31, 2019, NTSB/MAR-21/02. Washington, DC. June 2021.

Ryerson, Charles C. Icing Management for Coast Guard Assets, ERDC/CRREL TR-13-7. U. S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, NH. April 2013.

U. S. Coast Guard. Report of Investigation into the Sinking and Loss Of Four Crewmembers Aboard the Commercial Fishing Vessel LADY OF GRACE in Nantucket Sound, January 26, 2007. Washington, DC. January 2008.

U. S. Coast Guard. Report of the Marine Board of Investigation into the Commercial Fishing Vessel DESTINATION Sinking and Loss of the Vessel With all Six Crewmembers Missing and Presumed Deceased Approximately 4.4 NM Northwest of St. George Island, Alaska on February 11, 2017. Washington, DC. February 2018.

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APPENDIX A. MARINE BOARD OF INVESTIGATION REQUEST

U.S. Department of Homeland Security
United States Coast Guard

Commander
Eleventh District

Coast Guard Island, Bldg 50-7
Alameda, CA 94501-5100
Staff Symbol: dp
Phone: 510-437-2955
Fax: 510-437-5793
Email: Karen.Denny@uscg.mil

16732
21 Dec 2020

MEMORANDUM

From: G. A. CALLAGHAN, CAPT
CGD ELEVEN (dp)

Reply to
Attn of: CDR K. Denny

To: D. P. KEANE
CO CG R&D CENTER

Subj: Request for a REACT project – ice accumulation on crab pots

Ref: (a) Telephone conversation between CDR K. Denny (CGD11) and Mr. Lewandowski (RDC) on 16 Dec 2020

1. As discussed in reference (a), request Coast Guard Research and Development Center (RDC) assistance to an ongoing Marine Board of Investigation (MBI) into the 31 December 2019 sinking of the commercial fishing vessel (F/V) SCANDIES ROSE. The MBI requests a study of ice accretion and ice accumulation on fishing pots, specifically crab/cod pots used in the Alaska/Bering Sea fishery. Five of the SCANDIES ROSE seven crew members were never recovered and the vessel currently sits on the ocean floor.

2. While this investigation is ongoing, certain evidence suggests that vessel icing was a causative factor in the SCANDIES ROSE's loss of stability and, ultimately, it's sinking. This is not the first time icing has been identified as a causative factor for catastrophic fishing vessel accidents. The 2017 loss of F/V DESTINATION investigation revealed that icing directly contributed to the vessel loss of stability and rapid capsizing. Due to the repetitive nature of these accidents, we request RDC assistance in determining how ice accumulation occurs on the non-solid surface of the pot cage, the netting, and gear within the pot, as well as the added weight of ice accumulation over time.

3. We are conducting a public hearing on 22 February through 5 March, 2021, so having even initial data would be optimal, but not critical to have by the hearing. After the public hearing, the MBI team will be analyzing evidence and testimony and will be writing a Report of Investigation to include safety recommendations. The ice accumulation study data would be incredibly important to support potential regulatory changes and may have significant impacts the way Naval Architects calculate maximum pot loading for stability tests on commercial fishing vessels.

4. My investigation team and I are ready to assist in providing information that would help develop a study or experiment that would most closely simulate the conditions the vessel likely experienced at the time of the casualty. Should you have any questions or concerns, please contact Commander Karen Denny at karen.denny@uscg.mil or at (510) 437-2955.

#

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APPENDIX B. PRELIMINARY TEST PLAN

Test Plan-Crab Pot Ice Accretion Experiment

Purpose: Determine and document ice accretion rate over time for an Alaska/Bering Sea crab pot and its included gear in support of a marine casualty investigation. Documentation to include tabulated record and sequential, time-stamped photos (and videos) of ice accretion over the experiment duration.

Discussion: In F/V Scandies Rose and F/V Destination casualties, investigators suspect a possible, vessel loss of stability due to ice accretion on stacked crab-pots because of below-freezing air temperatures and the vessel taking spray. In the F/V Scandies Rose incident, surviving crewmembers may be able to identify a level of ice accretion on a crab pot associated with the proximate time of the vessel's capsize. Other vessel operators will be included to look at the ice accretion that they have experienced to get a larger field of witnesses that have experienced ice loading.

Information on increased weight due to ice accretion on a) an individual crab pot, and b) on a stack of pots may provide naval architects with a tool to estimate change in a vessel's metacentric height and, potentially, change in righting moment, due to severe risks to fishing vessels associated with crab/cod pot stack icing. The resulting information may also provide input for future regulatory changes. At this time, icing regulations are interpreted by industry to apply a "shoebox" standard with weight accumulating on the top and sides of the pot stack. The current regulations (46 CFR 28.550) provide a minimum standard for weight of assumed ice. This is specified to be 6.14 lb/ft^2 (30 kg/m^2) of horizontal projected area and 3.07 lb/ft^2 (15 kg/m^2) of vertical projected area which corresponds to a thickness of 1.3 in/33 mm of ice and 0.65 in/16.5mm of ice, respectively. This measurement does not include or factor in ice that is asymmetrically loaded on the pot stack or ice accumulating inside of crab pots.

The experiment objective is to replicate the frequent, episodic, salt-water wetting by sea wave and wind interaction, however, actual experiment design may use relatively controlled conditions to maximize ice accretion over a short period of time. E.g., the experiment could substitute a constant or fluctuating stream of "spray" or "mist" aimed at the crab pot in place of wave induced spray. "Seawater" spray is the objective, however, freshwater spray is threshold. If the experiment uses freshwater, evaluate and note any potential differential ice density compared to freezing salt water. While the freezing process of salt water should remove salt, it is unknown if the mass per volume reflected in the regulations appropriately reflects the phenomena of freezing salt water as opposed to freshwater.[1]

Part of the experiment requires that ice accretion continue until there is up to two inches of ice on the exterior of the pot or until the interior of the pot is considerably filled with ice.

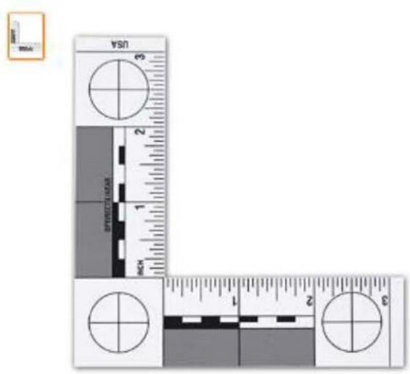
[1]Since, technically, salt water doesn't freeze under normal conditions. There is a possibility that pockets of dense brine are entrapped in the ice structure as liquid droplets. This may increase the density. Language reflects this unknown.

Method:

RDC provides three Alaska/Bering sea 6' x 6' x 3 crab pots, outfitted in "normal" set configuration (2 shots synthetic rope, 2 floats, less "bait") (Figure 1).

Figure 1. Stack of three, 6' x 6' x 3' crab traps as supplied by Dungeness Gear Works

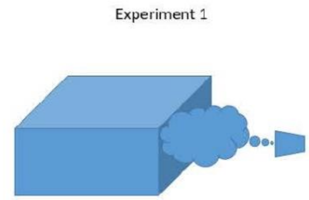
Weigh and photograph each pot, individually. Affix an investigator's crime scene scale (Figure 2) to the interior and exterior of each trap to provide visual reference in inches/millimeters for showing visual extent of ice accretion. Provide visual reference in terms of common photographer's scale in inches to show visual extent of ice .



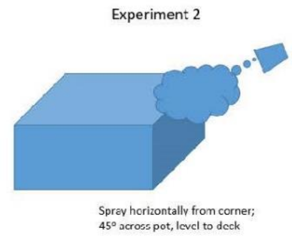
Roll over image to zoom in

Figure 2. Investigator's Crime Scene Scale

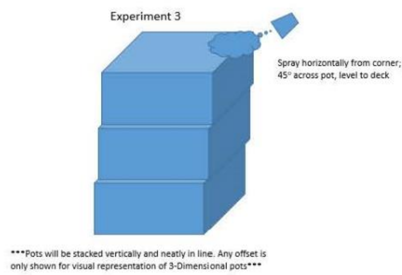
A. **Test one** will be the experiment base line. Suspend one trap from a load cell. Record the weight before the start of the test. Orient trap square to the water spray source at a distance suitable for the spray to arc towards the top-facing edge of the pot. Apply the spray to the pot at a constant rate, monitoring the weight throughout the test and taking periodic photos and video documenting weight gain over time and capturing the depth of ice using reference scale.



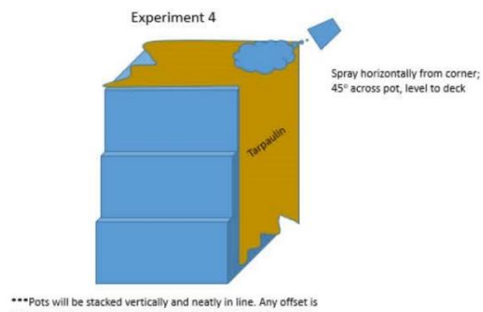
B. **Test two** will repeat test one except with the pot at a 45 degree angle horizontal to the spray. Target arc of spray to top-facing corner of pot. Apply the spray to the pot at a constant rate, monitoring the weight throughout the test and taking periodic photos and video documenting weight gain over time and capturing the depth of ice accretion using reference scale.



C. **Test three** will use three crab pots stacked on top of each other (roughly nine ft high stack) on a semi-permeable or permeable surface. Weigh each crab pot while stacking before the start of the test. As in test two, orient the stack at a 45-degree angle to the water spray source at a distance suitable for the spray to arc towards the top-facing edge of the top pot. Apply freezing spray at a constant rate over the test period. Monitor the weight throughout the test and take periodic photos and video documenting weight gain over time and capturing the depth of ice accretion using reference scale. At the end of the test, log the weight of the stack as a whole and then the individual traps.

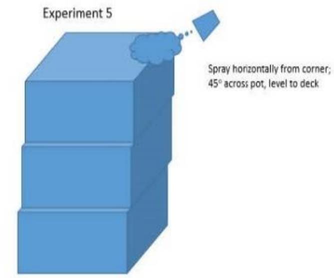


D. **Test four** will tarp the top and sides of the three-pot stack with a common plastic tarp securely fastened at each edge. As in test two, orient the stack at a 45-degree angle to the water spray source at a distance suitable for the spray to arc towards the top-facing edge of the top pot. Apply freezing spray at a constant rate over the test period. Monitor the weight throughout the test and take periodic photos and video documenting weight gain over time and capturing the depth of ice accretion using reference scale. At the end of the test, log the weight of the stack as a whole. Secure the experiment when the top icing reaches 1.3 inches on the top of



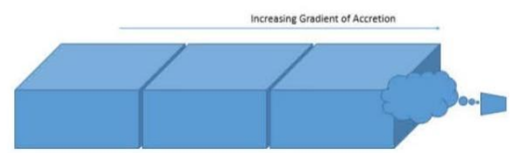
the tarp and .65 inches on the sides. This is the existing regulatory framework for stability and icing considerations.

F. **Test five** will use three crab pots stacked on top of each of other (approximately nine feet high stack) on a semi-permeable or permeable surface. As in tests two and four, orient the stack at a 45-degree angle to the water spray source at a distance suitable for the spray to arc towards the top-facing edge of the top pot. Apply freezing spray at a constant rate over the test period. Attempt to examine if ice coating will reach 1.3 inches on top surface of topmost pot and .65 inches on the side of the stack. Document over time with photos and video the point where these parameters are reached and *what is happening inside the three-pot stack in terms of ice accretion inside the pot stack to determine the vertical development of ice inside each pot*.



Pots will be stacked vertically and neatly in line. Any offset is only shown for visual representation of 3-Dimensional pots

G. **Test six** will use three crab pots arranged in a line horizontally, adjoined along the 6 foot edge. During this test, the water spray should be directed perpendicularly at the center of the side of the pot instead of aligned at the top. Apply the spray at a constant rate over the test period. Document over time with photos and video that point at the horizontal line of pots from the back and record observations of what is happening inside the three pots that are lined up. At the start and end of the experiment, weigh each pot individually to determine the distribution of weight and relative accretion rate through the permeable netting of the pot.



Experiment is to determine distribution and ingress of water to central pots in a stack.

H. Record all tests with time-lapse video from a point near the water spray source and at 90 degrees to the source. Record continuous strain gauge measurements for tests one and two. Weigh the individual pots in tests three, four, five and six hourly (or time increments based on accretion rates determined in tests one and two). Include measurements of ice thickness using pre-positioned investigator's reference scale which is being documented with videos and photos. While the request is for hourly measurements, depending on the rate of ice accretion, the frequency of observations could change.

NOTE: Due to the formation of ice, it will be difficult to get individual pot weights during the testing. If individual pot weights cannot be achieved during the test period, weigh the entire stack at the end of the test, then carefully break pots apart and then weigh the pots one by one, noting the position of each pot in the stack during the experiment and adding if possible any ice that was broken off an individual pot in the process of separating the pots. Total weight will be monitored at a constant interval.

APPENDIX C. DAILY ICE ACCRETION MEASUREMENT RECORDS

C.1 Description of Daily Records

On each daily record's first page, the upper left figure is a key to ice-thickness measurement locations with an icon representing the aspect of the spray (Figure C. 1.).

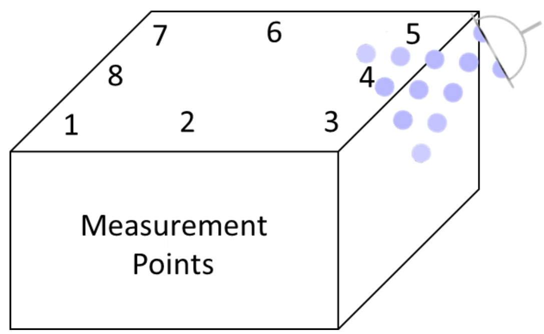


Figure C-1. Example key to ice thickness measurements.

Next to the measurement location key is a tabular summary of the day's ice accretion, repeating the spray location and including the starting conditions and conditions throughout the spray testing (Figure C. 2.). "Spray time" is the actual duration of spraying. Because of numerous instances where certain components of the spray apparatus froze, failed, or otherwise were unable to provide spray, the total elapsed time of the test may vary greatly from the spray time. The weight delta is directly above the measurement thickness (in inches).

Date		**3-Sep-21**					
Spray Position		**Side**					
Time		845	1000	1100	1240	1300	1330
Spray Time		**0m**	**0h 29m**	**0h 57m**	**1h 27m**	**1h 49m**	**2h 06m**
Air Temp F°		-14.3	-11.5	-9.8	-4.4	-2.7	-1.0
Water Temp F°		29.8	29.4	29.7	29.6	29.7	30.0
Weight		760	940	1100	1240	1400	1460
Weight Δ		**0**	**180**	**340**	**480**	**640**	**700**
Measure Point Thickness	1	0	0.5	0.5	1.0	1.0	1.0
	2	0	1.0	1.5	2.5	2.5	3.0
	3	0	1.0	2.0	2.5	2.5	2.5
	4	0	1.0	2.0	2.5	2.0	2.5
	5	0	1.0	3.0	3.0	4.5	3.5
	6	0	0.5	2.0	2.5	3.0	3.5
	7	0	0.0	0.0	0.5	1.0	1.0
	8	0	0.0	0.0	0.0	0.5	0.5

Figure C-2. Example of tabular ice accretion summary.

Following the measurement position and tabular summary is a series of images depicting the measurements (inches) and a photograph of the ice accretion at approximately the same time as the measurements (Figure C. 3.). As the actual measurements took anywhere from 5-10 minutes, photos generally align with completion of measurements.

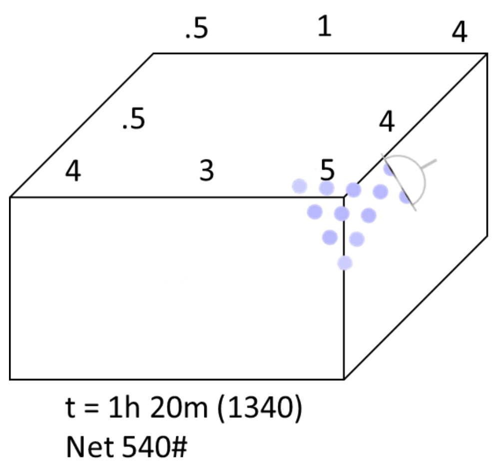
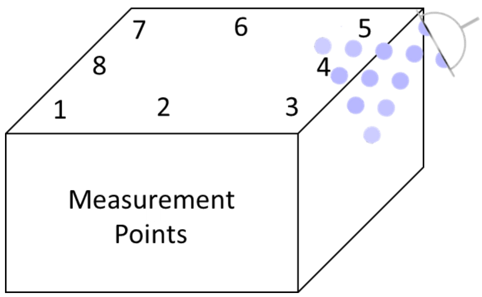


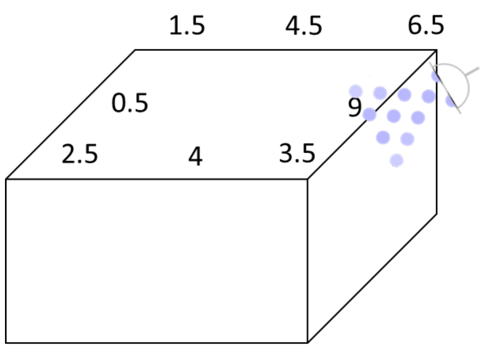
Figure C-3. Example of measurement depiction and corresponding photo.

Table C-1. Test 1: 1 September 2021.

1 Sep 2021 (page 1 of 1)



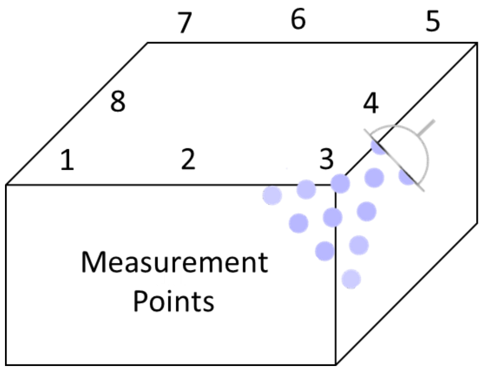
Date		1-Sep-21	
Spray Position		**Side**	
Time		945	1514
Spray Time		0	**2h 07m**
Air Temp F°		-14.4	-6.7
Water Temp F°		29.5	29.7
Weight		760	1620
Weight Δ		0	**840**
Measure Point Thickness	1	0	2.5
	2	0	4
	3	0	3.5
	4	0	9
	5	0	6.5
	6	0	4.5
	7	0	1.5
	8	0	1



t = 2h 07m (1514)
Net 840#

Table C-2. Test 2: 2 September 2021.

2 Sep 2021 (page 1 of 2)



Date		**2-Sep-21**			
Spray Position		**Corner**			
Time		856	1240	1340	1400
Spray Time		**0**	**50m**	**1h14m**	**1h30m**
Air Temp F°		-14.0	-14.6	-10.4	-8.0
Water Temp F°		30.2	29.5	29.1	29.3
Weight		760	1140	1300	1380
Weight Δ		**0**	**380**	**540**	**620**
Measure Point Thickness	1	0	3	4	4.5
	2	0	3	3	4
	3	0	3.5	5	7
	4	0	3	4	3.5
	5	0	3.5	4	4
	6	0	1	1	1.5
	7	0	0.5	0.5	0.5
	8	0	0.5	0.5	2.5

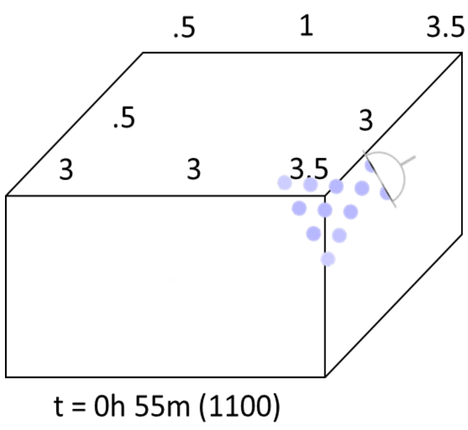


Table C-2. Test 2: 2 September 2021 (Cont'd).

<table>
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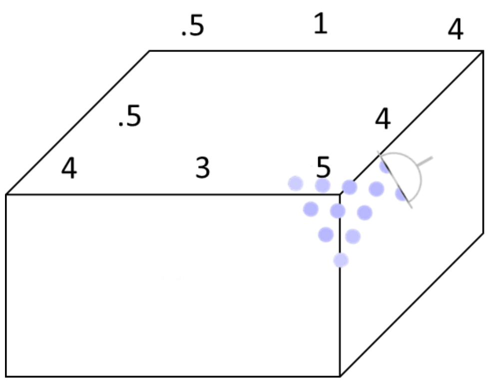
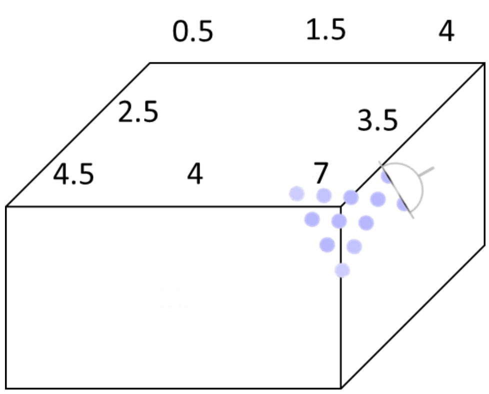
<tr><td>

t = 1h 20m (1340)
Net 540#</td><td></td></tr>
<tr><td>

t = 1h 36m (1400)
Net 620#</td><td></td></tr>
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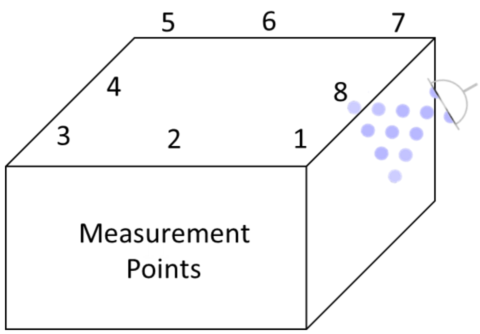
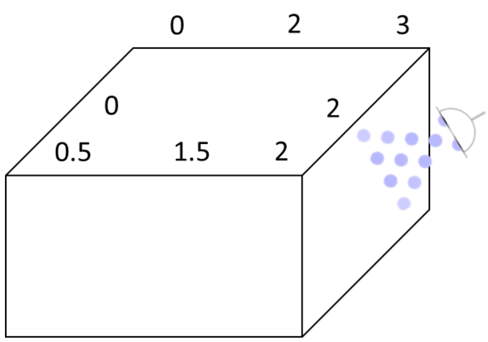
Table C-3. Test 3: 3 September 2021.

3 Sep 2021 (page 1 of 2)



Date		**3-Sep-21**					
Spray Position		**Side**					
Time		845	1000	1100	1240	1300	1330
Spray Time		**0m**	**0h 29m**	**0h 57m**	**1h 27m**	**1h 49m**	**2h 06m**
Air Temp F°		-14.3	-11.5	-9.8	-4.4	-2.7	-1.0
Water Temp F°		29.8	29.4	29.7	29.6	29.7	30.0
Weight		760	940	1100	1240	1400	1460
Weight Δ		**0**	**180**	**340**	**480**	**640**	**700**
Measure Point Thickness	1	0	0.5	0.5	1.0	1.0	1.0
	2	0	1.0	1.5	2.5	2.5	3.0
	3	0	1.0	2.0	2.5	2.5	2.5
	4	0	1.0	2.0	2.5	2.0	2.5
	5	0	1.0	3.0	3.0	4.5	3.5
	6	0	0.5	2.0	2.5	3.0	3.5
	7	0	0.0	0.0	0.5	1.0	1.0
	8	0	0.0	0.0	0.0	0.5	0.5



t = 0h 57m (1100)
Net 340#

Table C-3. Test 3: 3 September 2021 (Cont'd).

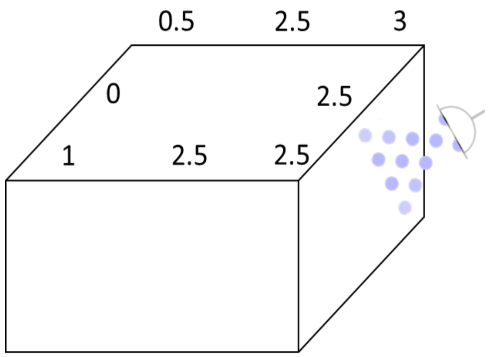
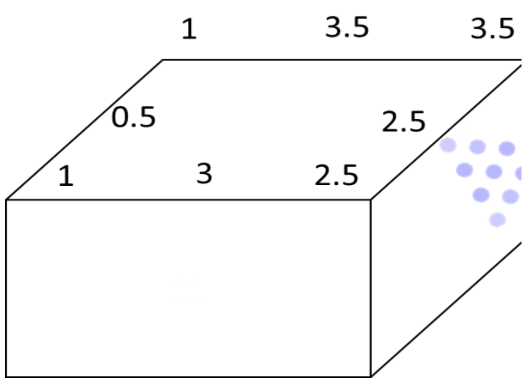
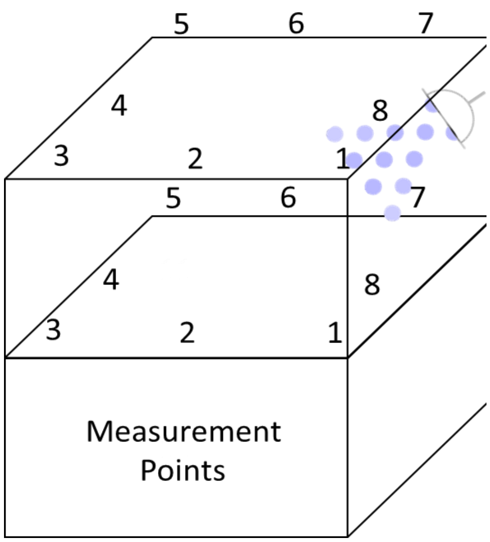
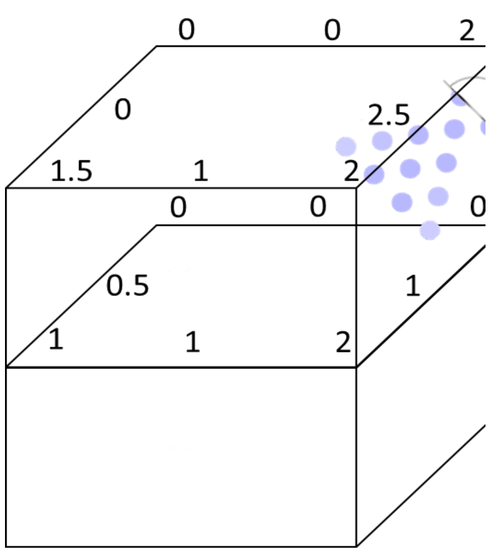
3 Sep 2021 (page 2 of 2)	
 t = 1h 37m (1240) Net 520#	
	

Table C-4. Test 4: 7 September 2021.

7 Sep 2021 (page 1 of 2)

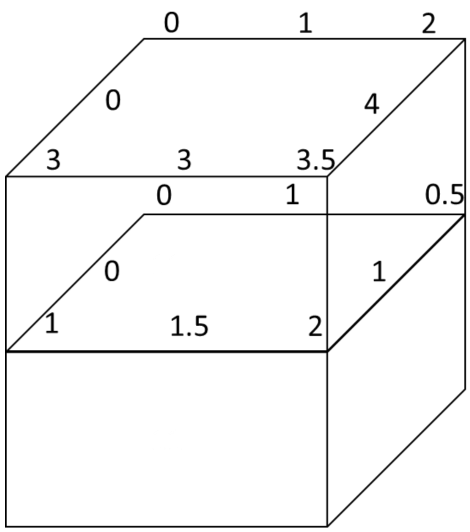


Date		7-Sep-21			
Spray Position		**Corner**			
Time		1121	1230	1330	1421
Spray Time Δ		0	69	129	180
Air Temp F°		3.9	16.5	21.5	29.2
Water Temp F°		83.7	84.3	85.0	85.1
Weight		1420	1800	1980	2500
Weight Δ		0	380	560	1080
Top of Trap					
Measurement Point Thickness	1	0	2.0	3.5	5.0
	2	0	1.0	3.0	4.0
	3	0	1.5	3.0	3.0
	4	0	0.0	0.0	0.5
	5	0	0.0	0.0	0.0
	6	0	0.0	1.0	1.0
	7	0	2.0	2.0	4.0
	8	0	2.5	4.0	5.5
Bottom of Trap					
Measurement Point Thickness	1	0	2.0	2.0	2.5
	2	0	1.0	1.5	2.0
	3	0	1.0	1.0	2.0
	4	0	0.5	0.0	1.0
	5	0	0.0	0.0	0.0
	6	0	0.0	1.0	1.0
	7	0	0.0	0.5	1.0
	8	0	1.0	1.0	2.0

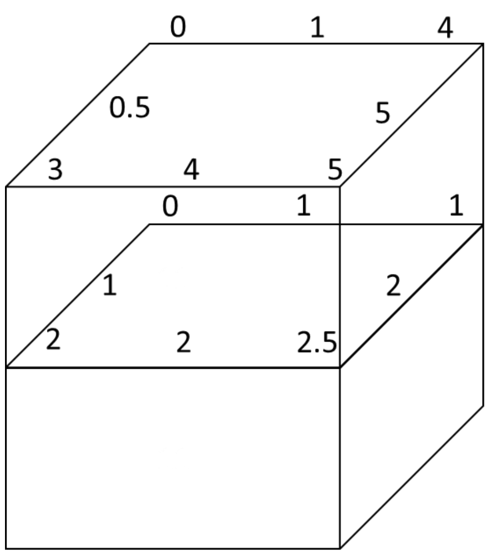


t = 1h 09m (1230)
Net 380#

Table C-4. Test 4: 7 September 2021 (Cont'd).

<table>
<tr><td>7 Sep 2021 (page 2 of 2)</td><td></td></tr>
<tr><td>


t = 2h 09m (1330)
Net 520#
</td><td>

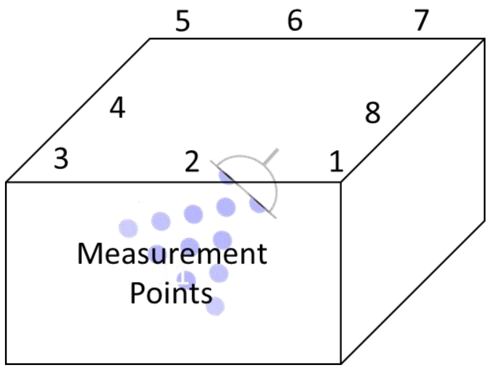
</td></tr>
<tr><td>


t = 3h 00m (1421)
Net 1080#
</td><td>

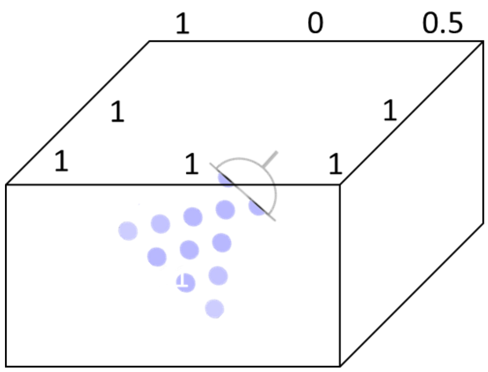
</td></tr>
</table>

Table C-5. Test 5: 8 September 2021.

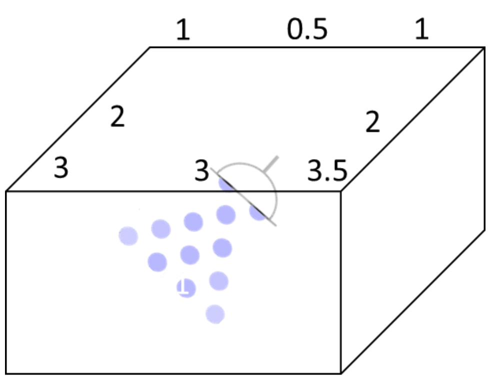
8 Sep 2021 (page 1 of 2)



Date		8-Sep-21					
Spray Position		**Side**					
Time		900	930	1000	1030	1100	1130
Spray Time Δ		**0**	**25m**	**55m**	**1h 25m**	**1h 55m**	**2h 25m**
Air Temp F°		-15.9	-11.4	-9.4	-8.1	-7.0	-5.3
Water Temp F°		28.9	28.2	28.4	28.7	28.8	28.9
Weight		760	940	1100	1260	1420	1540
Weight Δ		**0**	**180**	**340**	**500**	**660**	**780**
Measurement Point Thickness	1	0	1.0	2.0	3.5	4.0	4.0
	2	0	1.0	2.5	3.0	3.5	4.0
	3	0	1.0	2.0	3.0	3.5	4.5
	4	0	1.0	1.0	2.0	2.5	2.5
	5	0	1.0	1.0	1.0	1.0	1.0
	6	0	0.0	0.0	0.5	1.0	0.5
	7	0	0.5	0.5	1.0	1.5	2.0
	8	0	1.0	2.0	2.0	3.0	3.0

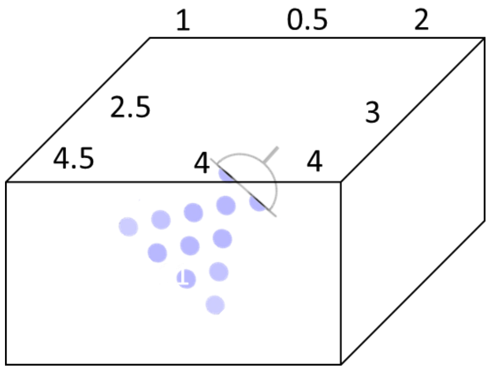


t = 0h 30m (0930)
Net 180#



t = 1h 25m (1030)
Net 500#

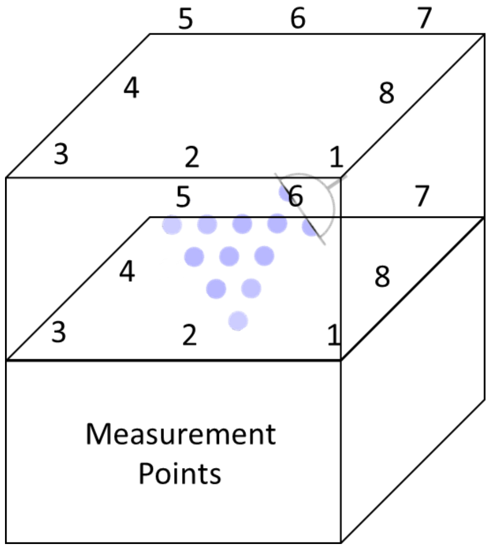
Table C-5. Test 5: 8 September 2021 (Cont'd).

<table>
<tr><td>8 Sep 2021 (page 2 of 2)</td><td></td></tr>
<tr><td>

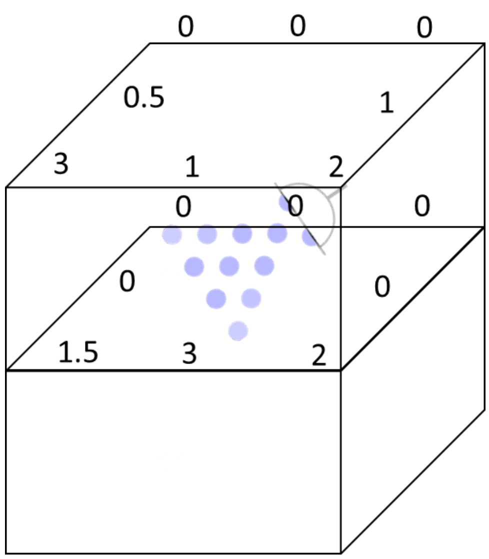
t = 2h 25m (1130)
Net 780#</td><td></td></tr>
</table>

Table C-6. Test 6: 9 September 2021.

9 Sep 2021 (page 1 of 2)

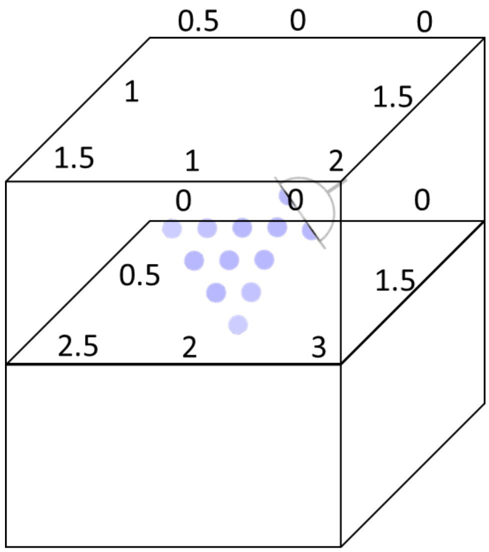


Date		**9-Sep-21**						
Spray Position		**Side**						
Time		900	930	1000	1030	1100	1130	1200
Spray Time Δ		**0**	**0h 30m**	**1h 0m**	**1h 30m**	**2h 0m**	**2h 30m**	**3h 0m**
Air Temp F°		-16.4	-9.9	-8.2	-6.7	-5.7	-4.6	-2.1
Water Temp F°		28.7	28.9	29.0	29.7	29.4	29.2	29.6
Weight		1460	1660	1800	1920	2000	2160	2280
Weight Δ		**0**	**200**	**340**	**460**	**540**	**700**	**820**
Top of Stack								
Measurement Point Thickness	1	0	0.5	2.0	3.0	2.0	3.0	2.5
	2	0	0.5	1.0	1.5	1.0	2.0	2.0
	3	0	1.5	3.0	4.0	1.5	2.0	2.5
	4	0	0.0	0.5	1.0	1.0	1.5	2.0
	5	0	0.0	0.0	0.0	0.5	0.0	0.5
	6	0	0.0	0.0	0.0	0.0	0.0	0.0
	7	0	0.0	0.0	0.5	0.0	0.5	0.0
	8	0	1.0	1.0	1.0	1.5	1.5	1.5
Bottom of top Trap								
Measurement Point Thickness	1	0	1.0	2.0	1.5	3.0	3.0	3.0
	2	0	1.0	3.0	4.0	2.0	4.0	4.5
	3	0	1.0	1.5	4.0	2.5	4.0	4.0
	4	0	0.0	0.0	0.5	0.5	0.5	1.0
	5	0	0.0	0.0	0.0	0.0	0.5	0.5
	6	0	0.0	0.0	0.0	0.0	0.0	0.5
	7	0	0.0	0.0	0.0	0.0	0.0	0.0
	8	0	0.0	0.0	1.5	0.5	0.5	0.8

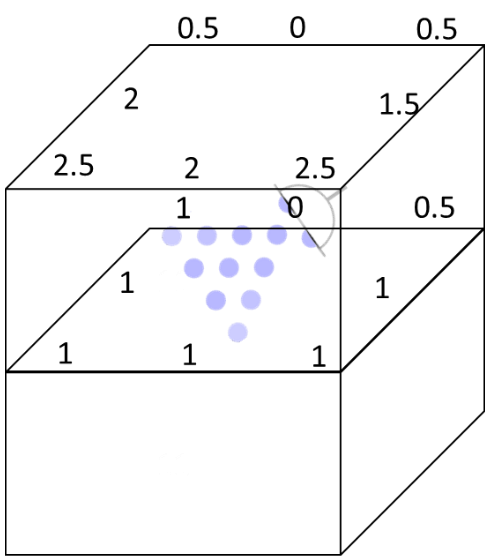


t = 1h 00m (1000)
Net 340#

Table C-6. Test 6: 9 September 2021 (Cont’d).

<table>
<tr><th>9 Sep 2021 (page 2 of 2)</th><th></th></tr>
<tr><td>


t = 2h 00m (1100)
Net 540#
</td><td>

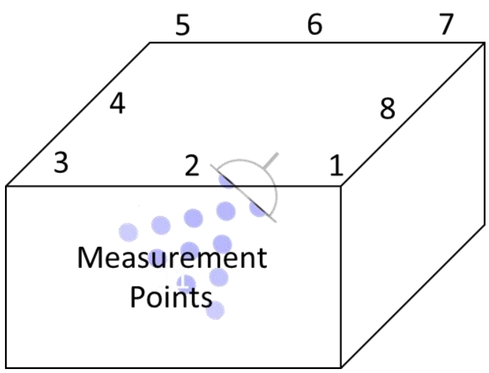
</td></tr>
<tr><td>


t = 3h 00m (1200)
Net 820#
</td><td>

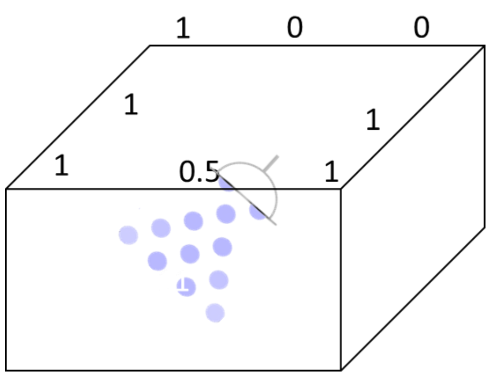
</td></tr>
</table>

Table C-7. Test 7: 10 September 2021.

10 Sep 2021 (page 1 of 2)

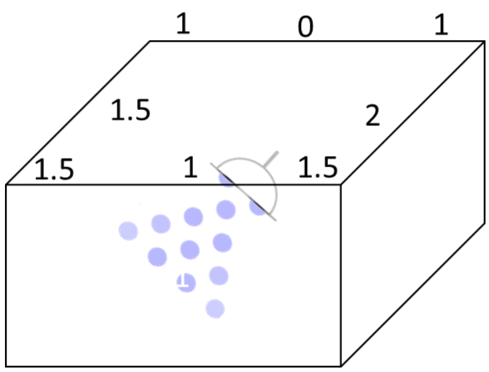


Date		**10-Sep-21**					
Spray Position		**Side, tarp cover**					
Time		830	900	930	1000	1030	1100
Spray Time Δ		**0**	**0h 20m**	**0h 50m**	**0h 80m**	**1h 50m**	**2h 20m**
Air Temp F°		-15.4	-10.8	-9.9	-9.1	-8.6	-7.6
Water Temp F°		29.6	28.8	29.5	29.2	29.5	29.3
Weight		780	880	1000	1000	1200	1300
Weight Δ		**0**	**100**	**220**	**220**	**420**	**520**
Measurement Point Thickness	1	0	1.0	1.0	1.5	1.5	3.5
	2	0	0.5	1.5	1.0	1.0	4.5
	3	0	1.0	0.5	1.5	1.5	5.5
	4	0	1.0	1.0	1.5	1.5	3.5
	5	0	1.0	0.5	1.0	1.0	1.5
	6	0	0.0	0.0	0.0	0.0	0.0
	7	0	0.0	1.0	1.0	1.0	0.5
	8	0	1.0	1.0	2.0	2.0	2.5

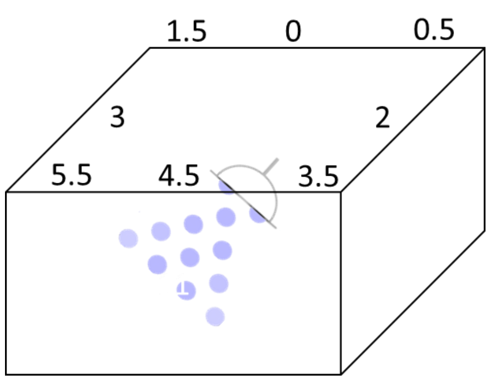


t = 0h 20m (900)
Net 180#

Table C-7. Test 7: 10 September 2021 (Cont'd).

<table>
<tr><th>10 Sep 2021 (page 2 of 2)</th><th></th></tr>
<tr><td>


t = 1h 20m (1000)
Net 220#
</td><td>

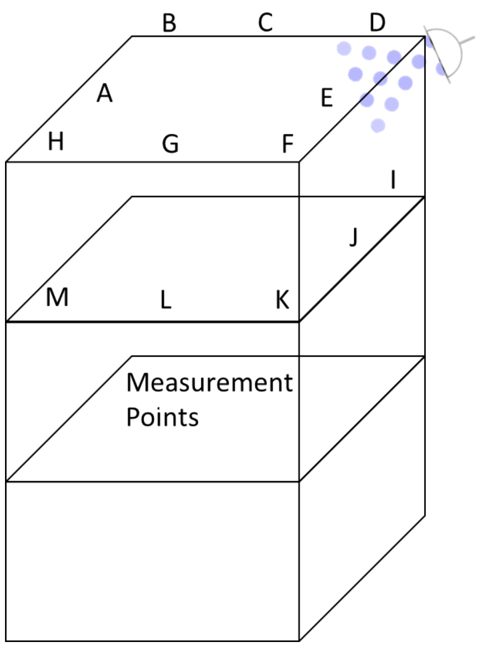
</td></tr>
<tr><td>


t = 2h 20m (1100)
Net 520#
</td><td>

</td></tr>
</table>

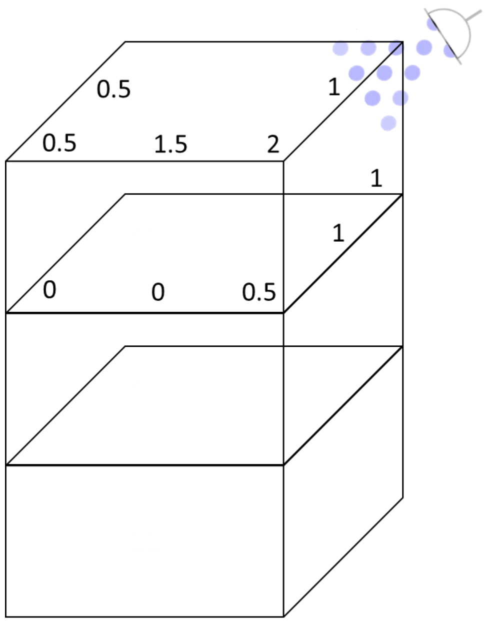
Table C-8. Test 8: 27 September 2021.

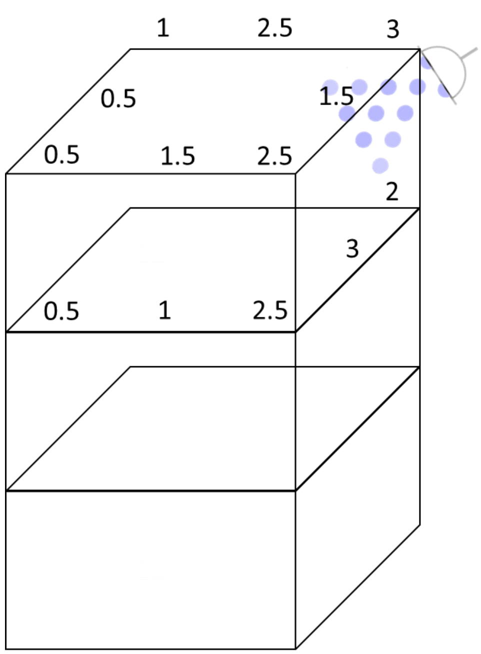
27 Sep 2021 (page 1 of 3)



Date		**27-Sep-21**			
Spray Position		**Side**			
Time		1250	1503	1545	1658
Spray Time		**0**	**43m**	**1h 25m**	**2h38m**
Air Temp F°		18.0	15.1	12.7	20.6
Water Temp F°		85.8	86.7	87.4	87.9
Weight		1960	2629	2789	2805
Weight Δ		**0**	**669**	**829**	**845**
Top of Stack					
Measurement Point Thickness	A	0	0.5	0.5	1.0
	B	0	0.5	1.0	1.0
	C	0	1.0	2.5	3.0
	D	0	2.5	3.0	3.0
	E	0	1.0	1.5	2.5
	F	0	2.0	2.5	3.0
	G	0	1.5	1.5	2.5
	H	0	0.5	0.5	0.5
Bottom of top trap					
Measurement Point Thickness	I	0	1.0	2.0	3.0
	J	0	1.0	3.0	3.0
	K	0	0.5	2.5	3.0
	L	0	0.0	1.0	1.0
	M	0	0.0	0.5	0.5

Table C-8. Test 8: 27 September 2021 (Cont'd).

<table>
<tr><th>27 Sep 2021 (page 2 of 3)</th><th></th></tr>
<tr><td>

t = 0h 43m (1503)
Net 669#</td><td></td></tr>
<tr><td>

t = 1h 25m (1545)
Net 829#</td><td></td></tr>
</table>

Table C-8. Test 8: 27 September 2021 (Cont'd).

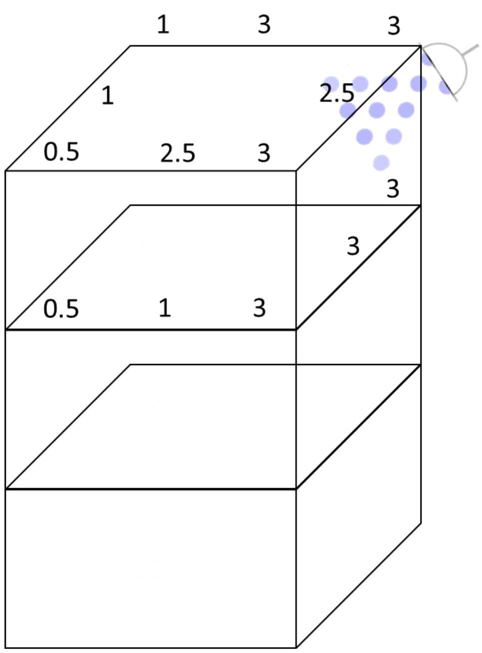
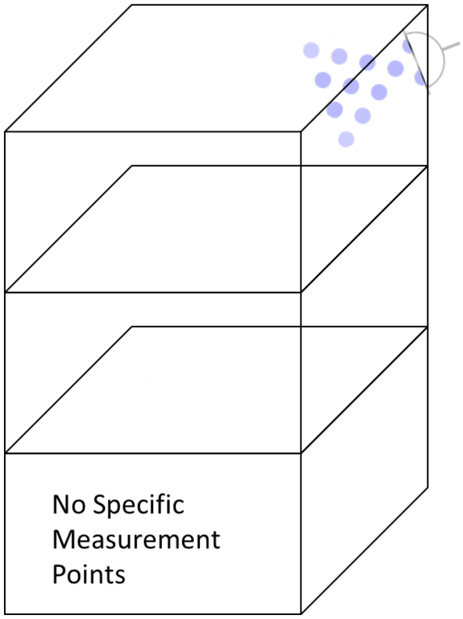
27 Sep 2021 (page 3 of 3)	
 t = 2h 38m (1658) Net 845#	
Post-test, 45 ft distance 	Post test, 45 ft distance, zoom 

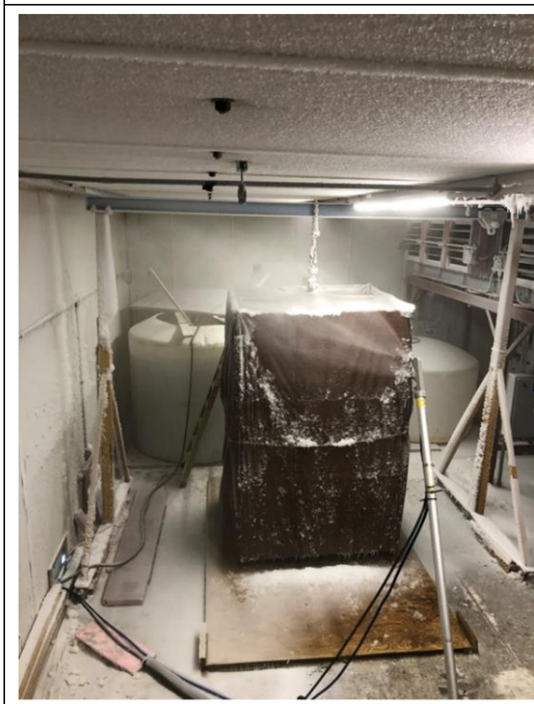
Table C-9. Test 9: 28 September 2021.

28 Sep 2021 (page 1 of 1)



Date	28-Sep-21					
Spray Position	Side-Tarped stack					
Time	1030	1100	1120	1140	1245	1300
Spray Time	**0**	**0h 30m**	**0h 50m**	**1h 10m**	**2h 15m**	**2h 30m**
Air Temp F°	-5.0	-4.2	-4.4	-3.8	2.8	2.7
Water Temp F°	31.3	31.2	30.9	31.0	31.3	31.3
Weight	1968	2080	2150	2222	2347	2388
Weight Δ	**0**	**112**	**182**	**254**	**379**	**420**

Note: For the tarped stack, the team did not take direct measurements due to extreme instability of slushy ice accreted on upper-trap frame that fell when disturbed. Due to the "relatively" warm ambient air temp, the pictures show ice/slush mix that filled the tarp's slack areas bewteen the upper-frame perimeter and cross-members. The *estimated* maximum depth of ice/slush at trial completion was ~3" (forward left quadrant as viewed from sprayer), ~4" (forward right), ~`2" (rear right), and 1" (rear left). At 64 pounds per cubic foot density of salt water, the final net weight of 420 # would be equivalent to a 2.2 inch think, solid, even layer of ice across the 6 x 6 trap.



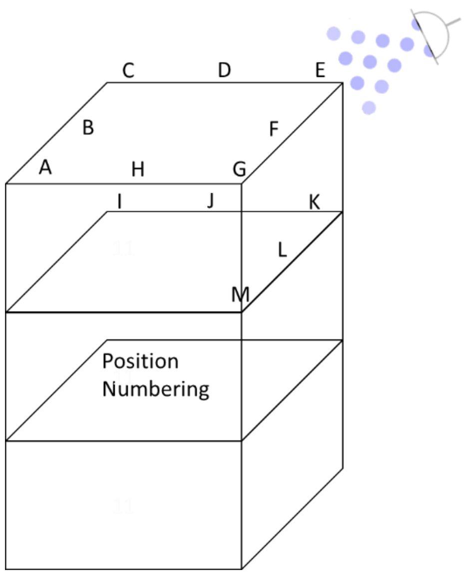
t = 0h 50m (1120)
Net 182#

t = 2h 30m (1300)
Net 420#

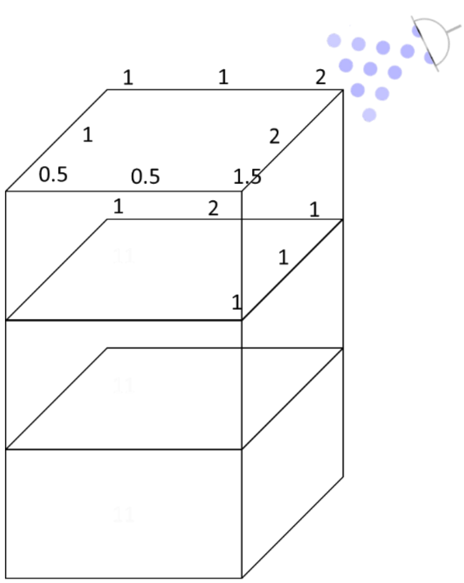
s

Table C-10. Test 10: 29 September 2021.

29 Sep 2021 (page 1 of 2)



Date		29-Sep-21			
Spray Position		Corner			
Time		905	1041	1144	1250
Spray Time		**0**	**1h 36m**	**2h 39m**	**3h 40m**
Air Temp F°		4.1	27.9	24.7	48.0
Water Temp F°		85.6	88.0	87.8	69.2
Weight		1930	2422	2621	2803
Weight Δ		**0**	**491.9**	**691.1**	**873.1**
Top of Stack					
Measurement Point Thickness	A	0	0.5	0.5	0.5
	B	0	1.0	1.0	1.0
	C	0	1.0	2.0	2.0
	D	0	1.0	2.5	3.0
	E	0	2.0	3.0	4.0
	F	0	2.0	3.0	3.5
	G	0	1.5	2.0	2.5
	H	0	0.5	1.0	1.0
Bottom of top trap					
Measurement Point Thickness	I	0	1.0	1.5	1.5
	J	0	2.0	2.5	3.0
	K	0	1.0	1.5	1.5
	L	0	1.0	1.0	1.5
	M	0	1.0	1.5	2.0



t = 1h 36m (1041)
Net 492#

Table C-10. Test 10: 29 September 2021 (Cont'd).

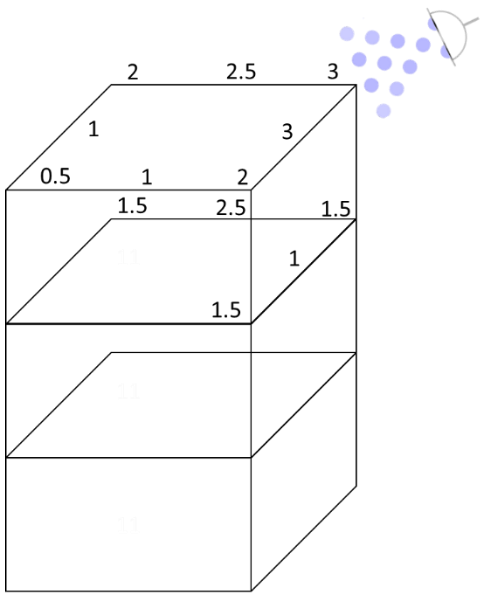
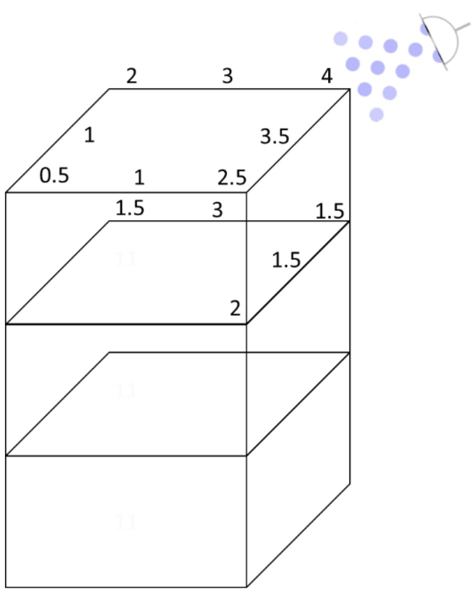
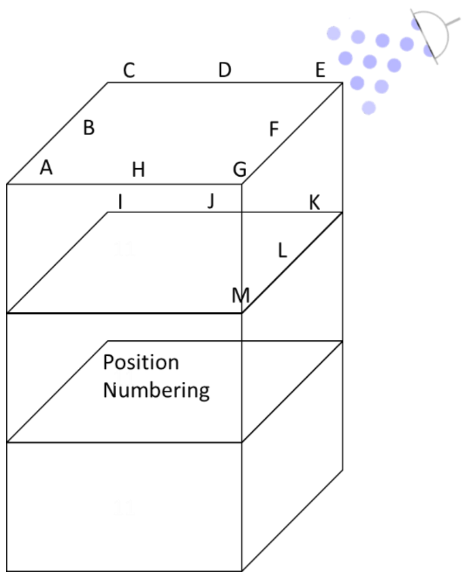
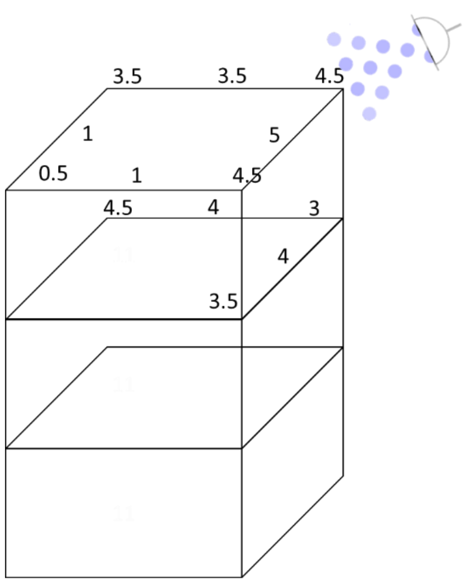
29 Sep 2021 (page 2 of 2)	
 t = 2h 39m (1144) Net 691#	
 t = 3h 40m (1250) Net 873#	

Table C-11. Test 11: 30 September 2021.

30 Sep 2021 (page 1 of 3)



Date		**30-Sep-21**			
Spray Position		**Corner**			
Time		842	1017	1115	1230
Spray Time		**0 m**	**1h 08m**	**2h 08m**	**3h 23m**
Air Temp F°		-13.2	-5.6	-6.2	-4.5
Water Temp F°		30.7	19.3	17.5	16.6
Weight		2829	3083	3284	3610
Weight Δ		**0**	**253**	**455**	**781**
2-day Δ		**873**	**1126**	**1328**	**1654**
Top of stack					
Measurement Point Thickness	A	0.5	0.5	0.5	0.5
	B	1.0	1.0	1.0	1.0
	C	2.0	3.5	3.5	3.5
	D	3.0	3.5	5.0	5.5
	E	4.0	4.5	6.0	7.0
	F	3.5	5.0	5.5	7.0
	G	2.5	4.5	4.5	7.0
	H	1.0	1.0	1.0	2.0
Bottom of Top Trap					
Measurement Point Thickness	I	1.5	4.5	5.0	5.0
	J	3.0	4.0	5.0	5.0
	K	1.5	3.0	3.5	3.0
	L	1.5	4.0	5.0	5.0
	M	2.0	3.5	4.0	5.0



t = 1h 08m (1017)
2-day Net 1126#

Table C-11. Test 11: 30 September 2021 (Cont'd).

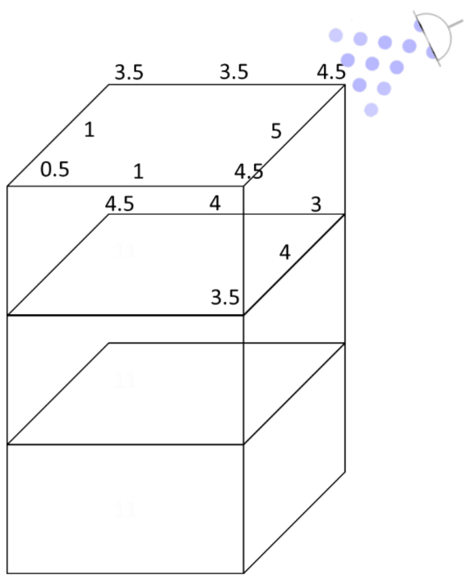
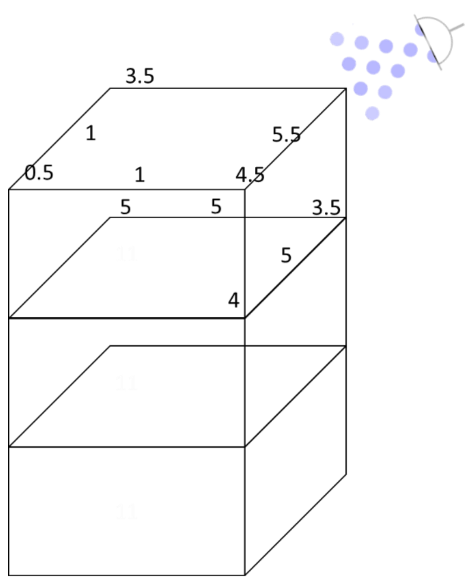
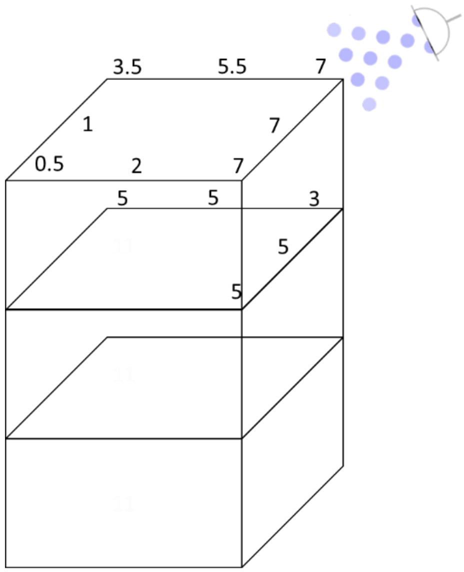
30 Sep 2021 (page 2 of 3)	
 t = 1h 08m (1017) 2-day Net 1126#	
 t = 2h 33m (1115) 2-day Net 1328#	

Table C-11. Test 11: 30 September 2021 (Cont'd).

<table>
<tr><th>30 Sep 2021 (page 3 of 3)</th><th></th></tr>
<tr><td>

t = 3h 23m (1230)
2-day Net 1654#</td><td></td></tr>
<tr><td>Post-test, 45 ft distance
</td><td>Post test, 45 ft distance, zoom
</td></tr>
</table>