ASEE 2022 ANNUAL CONFERENCE
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MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022 ASEE

Paper ID #37575

Marine Icing on a Commercial Crabbing Vessel in the Gulf of Alaska: Accident Study

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Abstract

The fishing vessel *Scandies Rose* capsized in heavy spray-icing conditions on December 31, 2019, with the loss of five of seven fishermen onboard. The U.S. Coast Guard and National Transportation Safety Board (NTSB) convened a Marine Board of Investigation to identify causal factors of the vessel's sinking. Testimony identified current vessel regulations under 46 Code of Federal Regulations (CFR) 28.550 may not accurately account for vessel icing on crab pots – a surface consisting of netting and open space where ice can accumulate in a non-uniform pattern. The lack of understanding of icing phenomenon on porous crab pots may put mariners and the environment at undue risk.

This research project, conducted by a team of faculty and undergraduate students, forensically analyzes the vessel's actual loading condition and stability on the day of the sinking to create a vessel model in which sea spray droplet trajectories are analyzed under actual weather conditions. The paper also presents an initial computational fluid dynamics (CFD) analysis of the airflow around the vessel to better understand the likely location and rate of ice accretion. The results indicate that current regulations vastly underestimate the effect and amount of topside icing on vessels and its overall effect on safe vessel operation. Student learning in each stage of the project is described and an overall reflection on student education, in the framework of ABET Engineering Accreditation Commission (EAC) Student Outcomes, is also presented.

Background

The *Scandies Rose*—a crabbing vessel based in the Bearing Sea—sank from heavy weather conditions by the eastern coast of Sutwik Island, Alaska on December 31, 2019. The vessel is shown in Figure 1. The last 40-hour transit is depicted in her Automatic Identification System (AIS) tracking in Figure 2. She left her port on the northeast of Kodiak Island at approximately 2100 (Alaskan time) on December 30, 2019, and transited southwest through the Shelikof Straight where the vessel experienced 20-foot seas and starboard-side winds. At approximately 2200 on December 31, 2019, a MAYDAY was broadcast to the area. The *Scandies Rose* rolled and eventually capsized to starboard side. Five lives were lost out of the seven-person crew. The two survivors, Dean Gribble and Jon Lawler, were rescued by Coast Guard helicopter at approximately 0200 on January 1, 2020. Gribble and Lawler testified as witnesses during the Marine Board of Investigation in February 2021 [1], [2].

This tragedy follows in the wake of another similar event which occurred in 2017 – the sinking of the fishing vessel *Destination*. *Destination* sank off St. George Island, Alaska, under heavy spray icing conditions with the loss of all six crew members onboard [3].

The human toll of accidents such as these, beyond the immediate aftermath, can be crushing. Survivors are never the same and are commonly diagnosed with post-traumatic stress disorder

(PTSD), anxiety, fear, insomnia and panic disorders. Moreover, the commercial fishing industry is a tight-knit group and the passing of a member affects the entire community.

To understand how tragedies such as these may be prevented, the causal factors contributing to this maritime accident was investigated by a team of faculty and students at the U.S. Coast Guard Academy. Marine case studies such as these, especially in the context of undergraduate education, offer students the opportunity to apply classroom knowledge to real-world problems while also experiencing many of the challenges and contradictions in practice. The students were specifically tasked to perform a forensic analysis on the capsizing event, with a focus on vessel stability and what contributions, if any, icing had in the loss of stability. This study also forced the students to engage in self-learning, especially in subjects which are not covered by the program curriculum, e.g., ice accretion.

The five students who participated in the research self-selected into areas of interest, with one focusing on the regulatory framework, two focusing on vessel stability and two focusing on vessel icing. Student learning in each of these focus areas is highlighted throughout the paper and a summary of student learning, evidenced by ABET Engineering Accreditation Commission (EAC) Student Outcomes, appears in the conclusion.

Regulatory Framework and Vessel Particulars

The *Scandies Rose* was a 130 ft vessel built in 1979 with a Gross Regulatory Tonnage of 195 tons. Vessel information for the *Scandies Rose* is shown in Table 1 and a picture of the vessel is show in Figure 1.

Length (ft)	130
Beam (ft)	34
Draft (ft)	11.3
Full Load Displacement (LT)	1055
Gross Regulatory Tonnage (GRT)	195
Propulsion	Detroit Diesel 12V2000 (2)

Table 1. Vessel information for *Scandies Rose* [1].

The *Scandies Rose* was subject to the regulations set forth in Title 46 Code of Federal Regulations (CFR) Subchapter C, Part 28, “Requirements for Commercial Fishing Industry Vessels,” which included equipment, stability, and other safety requirements. Monthly drills and instruction were required of the crew while aboard the vessel and, at a minimum, had to cover procedures for abandon ship, firefighting, flooding, man overboard, donning an immersion suit, launching a survival craft, making a voice radio distress call, and activation of the general alarm. Per 46 CFR Subpart E, “Stability,” as an uninspected commercial fishing vessel 79 feet or more in length that had gone through conversions and alterations after construction, the *Scandies Rose* was required to have stability instructions. However, there are no requirements for the completed stability instructions to be reviewed for accuracy by the Coast Guard or other authorized authority. The vessel was also required to participate in the Coast Guard’s commercial fishing vessel dockside safety examination program, which primarily focuses on lifesaving equipment on board the vessel and confirms the presence of lifesaving equipment and correct documentation, including stability instructions. Commercial fishing vessels like *Scandies Rose* and *Destination* are not subject to oversight by the Coast Guard of construction, stability, maintenance, and other standards that govern inspected vessels [1], [2].

Figure 1. Image of *Scandies Rose* [1].

Stability Requirements

Scandies Rose and *Destination* were subject to the stability standards identified in 46 CFR Part 28 Subpart E [1], [2]. Both vessels did not operate on international voyages and thus were not subject to the international regulations and survey requirements of Safety of Life at Sea (SOLAS) set forth by the International Maritime Organization (IMO) [4]. Additionally, these vessels were not subject to the fishing vessel stability rules set forth in the International Code on Intact Stability, or IS Code, to include icing on fishing vessels. It is also important to note that if *Scandies Rose* was subject to meeting the requirements of IS Code, the vessel was operating outside the region required to undergo stability analysis with ice accumulation [5]. IS Code 6.3.2 only requires icing analysis if the vessel operates within specific regions of the world; in the case of the Pacific Northwest, IS Code requires icing analysis when vessels operate within the Bering Sea [5]. *Scandies Rose* sank south of the Aleutian Islands or outside the Bering Sea as identified in Figure 2 [6].

Despite the differences in the location of ice accumulation in the Bering Sea, the maximum assumed icing quantities on fishing vessels are identical between 46 CFR 28.550 and IS Code 6.3 – 30 $\frac{kg}{m^2}$ of ice on horizontal surfaces and 15 $\frac{kg}{m^2}$ of ice on vertical surfaces. The ice accumulation equates to a thickness of 1.3 and 0.65 inches, respectively. The ice loading prescribed in both sets of regulations causes a twofold decrease in vessel stability:

1. weight addition largely on surfaces that are predominantly higher than the vessel's center of gravity (kg) decreases stability
2. parallel sinkage caused by an increase in weight or displacement and subsequent reduction in vessel freeboard or reserve buoyancy.

Both regulatory schemes assume a uniform ice loading and do not consider the effects of listing due to off-center weight additions. The assumption that added weight due to icing is uniform is suspect, as vessels rarely have wind and seas directly off the vessels bow. Additionally, these rulesets assume that icing is applied over the top and sides of the fishing pots, commonly referred to as the “shoebox method.” However, the crab pots are porous, being constructed of steel tubing with netting which enables ice to build up in the interior of the crab pot stack [2].

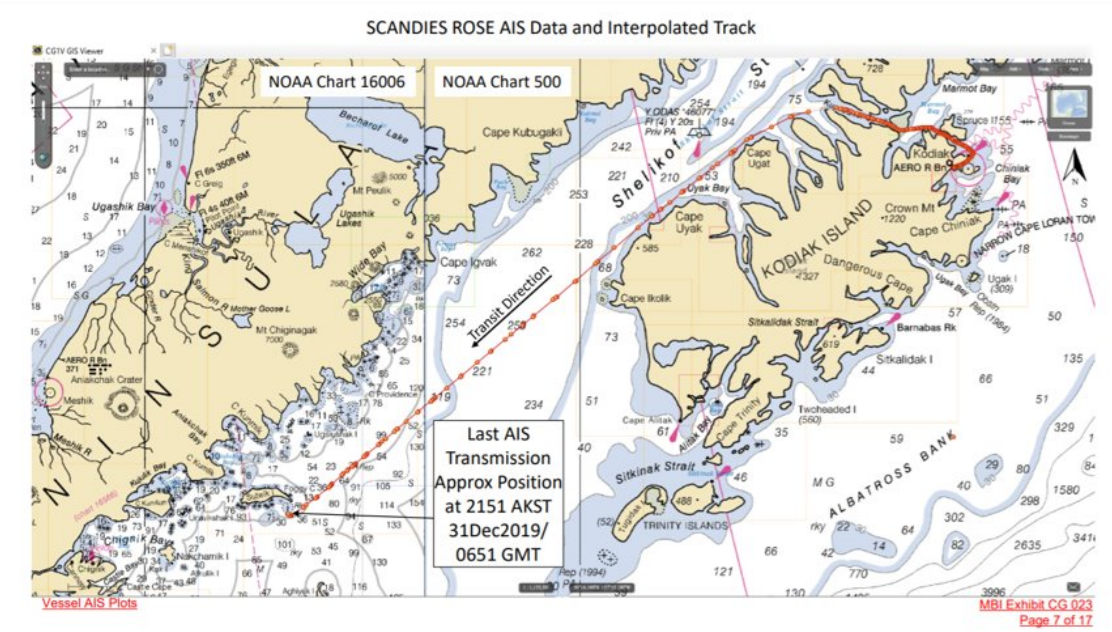

Figure 2. *Scandies Rose* Automatic Identification System (AIS) of the final voyage [6].

Figure 3 shows a commercial fishing vessel loaded with crab pots under similar icing scenarios as *Destination*. Ice build-up is more apparent on the stern of the vessel than the forward sections, indicating the non-uniform nature of sea-icing phenomenon. Ice can also be seen on the interior portions of the crab pots. Expert testimony from a panel of Naval Architects during the *Scandies Rose* Marine Board of Investigation (MBI) also attested to the non-uniform nature of ice and subsequent weight build up associated with sea-icing events [2]. It is also clear from this photo that the thickness of ice is much greater than the most severe icing events required to be analyzed by 46 CFR 28.550 and IS Code. IS Code also states, “For vessels operating where ice accretion may be expected… ice accretion requirements of one-half to twice the required allowance may be applied” (IS Code 6.3.2.6). Multiple masters of fishing vessels operating in and around the time of *Destination*’s sinking report that ice accumulated on the vessel at rates between 0.5 and 1 inches of ice per hour [3].

This indicates that assumed icing phenomenon is known to vary significantly from that required by the rulesets. This also assumes that the rulesets are not conservative in nature. From these experiences and professional testimony, a new icing criterion may be required. This is a very powerful student-generated conclusion. Regulatory requirements are often very difficult summarize, and even more difficult to distill. This type of analysis, e.g., identifying, comprehending, and applying marine regulations to a specific case, illustrates a deep understanding of marine policy, critical thinking and the ability to integrate and communicate different types and sources of information into a succinct and coherent case.

Figure 3. Photo of the vessel SANDRA FIVE on February 12, 2017, after a voyage from St. Paul Island to King Cove, AK. The vessel was operating in the same region as *Destination* during the same time [3].

Freezing Spray Experiment

CGC POLAR STAR conducted an icing experiment while underway in the Bering Sea by continuously spraying a standard-size crab pot, 8 feet by 7 feet by 34 inches with water. Prior to the experiment, the crab pot, line and buoy were found to be 1,040 pounds. The pot was sprayed for 72 hours in temperatures which ranged between 5º F and 15º F. At the conclusion of the experiment (Figure 4), the crab pot and associated ice weighed in excess of 3,000 pounds or more than 1,960 pounds of added ice, ultimately exceeding the capacity of the load cell. Significant icing was located inside the pot [1].

By comparison, using the shoebox method on five sides of the crab pot and the rules identified in 46 CFR 28.550, a maximum of 605 pounds of ice added or 1,645 of total weight would be accounted for; a load more than three times the difference.

It is clear from on-scene observations during heavy spray icing events, expert witness testimony, and the experiment on CGC *Polar Star* that the rules governing icing of fishing vessels do not conservatively account for the quantity and location of spray icing [1], [2], [3]. Real-world scenarios have been significantly worse than those required to be simulated by naval architects to evaluate the safety of loading conditions [2]. Further, the rulesets do not account for ice which is known to accumulate inside crab pots or other porous fishing gear. Naval architects also do not have a full understanding of the quantity or location of ice accumulation on crab pots [1], [2], [3].

Verification of Vessel Model

Figure 4. Results of freezing spray experiment by *CGC Polar Star* [1].

The U.S. Coast Guard's Marine Safety Center (MSC) *Scandies Rose* model, which was used in the forensic stability analysis during the Marine Board of Investigation, was verified by comparing the lines drawing from the vessel's owner [7]. The vessel's lines and computer model matched, which was also confirmed by similar hydrostatic data from April 2019 [8]. This verified the underwater volume associated with the vessel.

The engine room ventilations on the port and starboard side were used as the down flooding point [9]. This differs from the original model and the contracted naval architect's work. Other details of the model are discussed in [9].

Deadweight and Inclining Surveys

Prior to conducting a stability analysis, a vessel's lightship weight and location must be determined. ASTM F 1321-92 specifies the procedure for deadweight surveys and incline experiments for vessels [10]; it is required by regulation for both inspected and uninspected vessels as required by 46 CFR 28.535. There is little evidence that the deadweight survey and incline experiment were conducted in accordance with this standard for *Scandies Rose* [9].

A vessel must first undergo a deadweight survey, where weights onboard are categorized as part of the vessel's lightship weight, excess weight is to be deducted, and weights not onboard are added. The procedure then requires the measurement of at least five drafts to determine the vessel's waterline at the time of the procedure. Once a waterline is produced, the volume of the underwater volume is determined and subsequently, the vessel's displacement and longitudinal center of gravity (LCG) is determined [10].

After the deadweight survey is complete, an incline test is conducted to determine the vertical center of gravity or distance from keel to center of gravity (KG) of the vessel using a series of weight movements. If a certified weight is moved a specific distance, a moment is induced on the vessel. The vessel's metacentric height is related to the heeling moment and resultant angle of heel through the equations below. Once weights are moved, the resultant angle is read at three locations on the vessel and then plotted for a total of eight weight movements [10].

Following all weight movement, the heeling moment is plotted versus the tangent of the resultant angle (Equation 1). A straight trend line is plotted from the data and a line with a constant slope is produced. If both tests were performed correctly with little environmental factors, the result should be a straight line [10].

$$GM = \left(\frac{Heeling\ Moment}{\Delta\ \tan\theta} \right) \tag{1}$$

Once GM or metacentric height is obtained, BM and KB are determined from hydrostatic properties based on the hull form and location of the waterplane determined in the deadweight survey. Then, the lightship KG is determined using Equation 2. Like the deadweight survey, non-lightship weights are added or subtracted using a weight-moment balance to find the lightship KG [10].

$$KG = KB + BM - GM \tag{2}$$

The 2019 deadweight and inclining survey was recalculated using the data contained within the MSC Technical Report on *Scandies Rose* [9]. The 2019 data was used in this analysis.

Deadweight and the *Scandies Rose*'s LCG were found using the verified model and the stability analysis software General HydroStatics (GHS). GHS output *Scandies Rose*'s displacement, BM, KB, and LCG; relevant values are shown in table 2. Weight movements were plotted with a trend line. The slope of this line yielded the vessel's GM and ultimately KG. The results of the weight movements and three pendulum readings are shown in Figure 5.

Lightship Comparison			
Location	**Weight (LT)**	**LCG (ft)**	**VCG (ft)**
Naval Architect	548.32	3.3a	14.69
Marine Safety Center	578	0.52a	15.26
This Paper's Result	559.39	3.43a	15.60

Table 2. Comparison of lightship results.

It is important to note that the Naval Architect did not provide an exhaustive list of weights to add or subtract and tank levels that were on board during the experiment, raising doubt as to its accuracy and accounting for the inconsistencies between the three lightship values shown in table 2. Also, two pendulum readings were vastly inconsistent with the others in the data set.

These values were assumed to be swapped with each other; the results of the corrected values are shown in Figure 5.

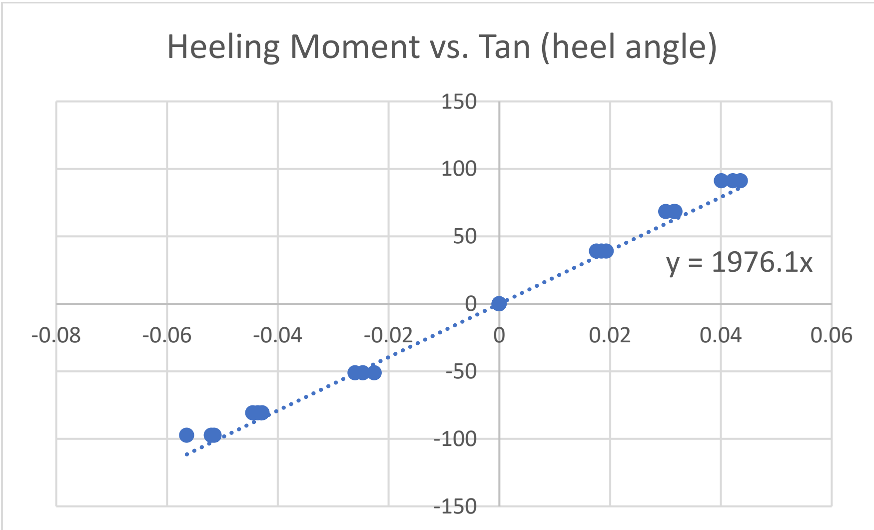

Figure 5. Plot of heeling moment vs. tangent of the heel angle (2019).

It is unclear if the Naval Architect did the same with his data. Also, the Naval Architect conducted this work without regulatory oversight; that is, the work was never prepared or intended to be prepared for outside review. Nonetheless, the results were not able to be replicated by us or naval architects from the Marine Safety Center, otherwise values would be consistent.

Drafts were only taken from one side of the vessel, ignoring the likely trim and list the vessel had at the pier on the day the tests were conducted. ASTM F 1321-92, recommends but does not require freeboard readings on both sides of the vessel. It recommends reading this value specifically for cases where there is no appreciable list. Because readings were not performed on both sides, lightship transverse center of gravity (TCG) must be assumed to be zero, meaning no list would occur in the lightship condition. *Scandies Rose* was not symmetric, as it had different sized cranes on the port and starboard sides and the bait freezer was known to be located on the port side. Additionally, photos indicate that if crab pots were stacked asymmetrically, they often were stacked higher on the port side indicating the vessel may have had an inherent list to starboard which was corrected via external means. This introduces a level of error to any calculations using data related to the deadweight and inclining experiments.

Through this forensic exercise, students understood the importance of accurate, repeatable deadweight and lightship survey data. Students formulated the stability problem, identified and validated the required data and evaluated the stability of *Scandies Rose*. Here, the students surveyed the problems as investigators, identifying errors in the procedure in order to identify problems in the results. This required a thorough knowledge and application of the parent regulation, methodical application of the procedure, and critical thinking to synthesize and translate the naval architect's rough notes.

Loading Conditions

The weight sheet is a rough list of the weights that are assumed to be on the ship at the time of its departure. From the stability booklet it was assumed that the vessel left in condition 1 [8]. This is because it has max consumables and tanks, representing a fully loaded condition. The vessel had been underway for less than 26 hours before sinking it was chosen to analyze the vessel in loading condition 1. Although free surface effect is minimized in this condition, the vessel has the least amount of freeboard in this condition, as all fuel tanks are fully loaded. Additionally, 14,000 pounds of bait stored in the bait freezer on the port side near the bow, was added to the departure condition. Witness testimony identified the location and the quantity of bait onloaded [2]. The addition of this weight resulted in a port list of 4.17 degrees. It is unlikely that the crew would normally operate *Scandies Rose* in such a condition, so the transverse loading is suspect. Either the vessel had an inherent starboard list in its lightship condition or the crew compensated for the off-center loading of the crab pots and bait freezer by not having consistent liquid loads in the port and starboard tanks.

This data were later used to evaluate *Scandies Rose's* stability. Figure 6 depicts the loading scenario of *Scandies Rose* as analyzed. Crab pot loadout is discussed further in depth in the next section.

```
            ----- Likely Departure Condition - Condition 1 w/Bait-----
                           WEIGHT and DISPLACEMENT STATUS
                           Baseline draft: 13.122 @ Origin
                     Trim: Fwd 0.07 deg.,  Heel: Port 4.17 deg.
Part-----------------------------Weight(LT)----LCG-----TCG-----VCG
Lightship                            559.39     3.34a   0.00   15.60
Crew                                   1.00     5.00a   0.00   18.00
stores                                 1.50    15.00a   0.00   16.00
Bait Freezer                           6.66    54.00f   6.50p  22.50
Crab Pots - Total                     73.80     7.41f   0.31p  23.78
  Total Fixed--------->              642.35     1.54a   0.10p  16.62
                Load-----SpGr-----Weight(LT)----LCG-----TCG-----VCG------RefHt
HOLD2.C        0.950    1.025        133.82    12.64f   0.25p   8.66     -14.04
HOLD3.C        0.950    1.025        116.06     6.25a   0.26p   8.54     -13.81
FWDWING.S      0.950    0.870          9.21    29.25f  13.00s   6.51     -10.60
FWDWING.P      0.950    0.870          9.21    29.22f  13.05p   6.51      -8.67
MIDWING.S      0.950    0.870         18.33    12.41f  13.53s   5.85     -10.58
MIDWING.P      0.950    0.870         18.33    12.41f  13.58p   5.85      -8.58
AFTWING.S      0.950    0.870         16.93     6.26a  13.57s   5.75     -10.60
AFTWING.P      0.950    0.870         16.93     6.26a  13.62p   5.75      -8.59
DAYTANK.P      0.950    0.870         12.02    55.47a  10.20p  11.02     -13.43
WATER.S        0.950    1.000         25.88    28.78a  13.65s   8.35     -14.91
WATER.P        0.950    1.000         25.88    28.78a  13.69p   8.35     -12.88
LUBEOIL.P      0.950    0.870          5.50    44.82a   7.12p   9.54     -13.50
SEWAGE.S       0.500    1.025          7.45    55.21a   9.84s   9.50     -12.03
  Total Tanks--------->              415.53     2.56a   0.37p   8.10
  Total Weight-------->            1,057.88     1.94a   0.21p  13.27
                                   Displ(LT)----LCB-----TCB-----VCB
HULL                    1.025      1,057.88     1.94a   0.61p   7.73     -13.09
------------------------------------------------------------------------------
               Righting Arms:                   0.00     0.00p
Distances in FEET.------------------------------------------------------------

                               HYDROSTATIC PROPERTIES
                      Trim: Fwd 0.07 deg., Heel: Port 4.17 deg.

 Origin  Displacement     Center of Buoyancy
  Depth----Weight(LT)----LCB-----TCB-----VCB-----WPA-----LCF------BML-----BMT
 13.088      1,057.88    1.94a   0.61p   7.73    3697    3.68a   104.2    7.85
 Distances in FEET.-----Specific Gravity = 1.025.---True Free Surface included.
```

Figure 6. Loading condition 1 – estimated departure condition with lightship values from this study and naval architect's loading configuration. Note that the bait freezer was also added as a point weight on the port side.

Crab Pot Loadout

The crab pot loadout has a significant impact on the overall stability of the vessel. Unfortunately, a bona fide record of the typical number and configuration of crab pots loaded aboard *Scandies Rose* does not exist. The departure loadout was estimated by combining witness testimony with departure pictures and operational practices. A key survivor, testified there were 198 pots aboard and that they were stacked higher on the port side of the vessel, partially blocking the bridge [2]. Vessel photographs, such as those shown as Figure 7, illustrate the crab pot configuration during typical fishing operations. Of note, which corroborates witness testimony, are the six tiers of crab pots with the sixth tier on the port side and the entire first tier placed on end (often to accommodate crew passage along the centerline of the vessel).

Figure 7. *Scandies Rose* underway and at the pier [11].

Utilizing these sources, in conjunction with the ship lines drawing, a 3D model of the vessel in the assumed departure condition was created. Figure 8 shows a rendered version of the model using Rhinoceros software.

Figure 8. 3D Model of the *Scandies Rose*

While the Rhino model serves as a visual for the estimated crab pot arrangement, it has several additional uses. First, it allows the KG and weight of the pots on deck to be calculated for the departure condition. Second, it allows the surface area of the crab pot stack to be calculated so that an accurate estimation of icing can be obtained as required by regulation.

Using an estimated weight of 835 pounds per crab pot, the number and location of the crab pots, the most likely departure loading condition for *Scandies Rose* on its final voyage is shown as Table 3 [9].

Condition	Displacement (LT)	KG (ft)
Full Load without Crab Pots	977.42	12.41
Crab Pots	73.80	23.78
Full Load	1,057.88	13.27
Full Load with Regulatory Icing	1,077.41	13.57
Full Load with Probable Icing	1,121.20	14.42

Table 3. Most probable loading condition of *Scandies Rose* on the final voyage.

Due to the lack of concrete evidence, the seemingly simple, yet extremely important, task of identifying the layout of crab pots on deck was a real challenge. Students assimilated data from a variety of sources to arrive at a reasonable crab pot layout. Using sources such as pictures, deck layouts, survivor testimony, mariner interviews and engineering judgement, students constructed the most probable crab pot loadout for *Scandies Rose*. Students recognized the professional responsibility inherent in accepting the fundamental assumptions or "givens" in a problem – specifically the vessel loading condition. In the case of *Scandies Rose*, this was unknown as exact records of vessel loading were not kept. This emphasized the importance of understanding the fundamentals of a problem and not making even basic assumptions with a forensic case.

Stability Analysis

GHS was used to analyze the vessel's stability in the likely departure condition: the departure condition with icing as prescribed by 46 CFR 28.550 and likely ice weight as discussed in the icing section. A righting arm was plotted using GHS with deck edge immersion and downflooding points annotated. Initial stability (GM) and righting energy was compared. Figures 9 and 10 show the results.

With regulatory icing applied, there is significantly less initial stability (GM) – 2.29 feet in departure as compared to 0.73 feet in the icing condition. Righting energy at downflooding was also decreased severely – 9 foot degrees versus 5.5 foot degrees. Righting energy describes the vessel's ability to absorb the effect of wind and waves before capsizing.

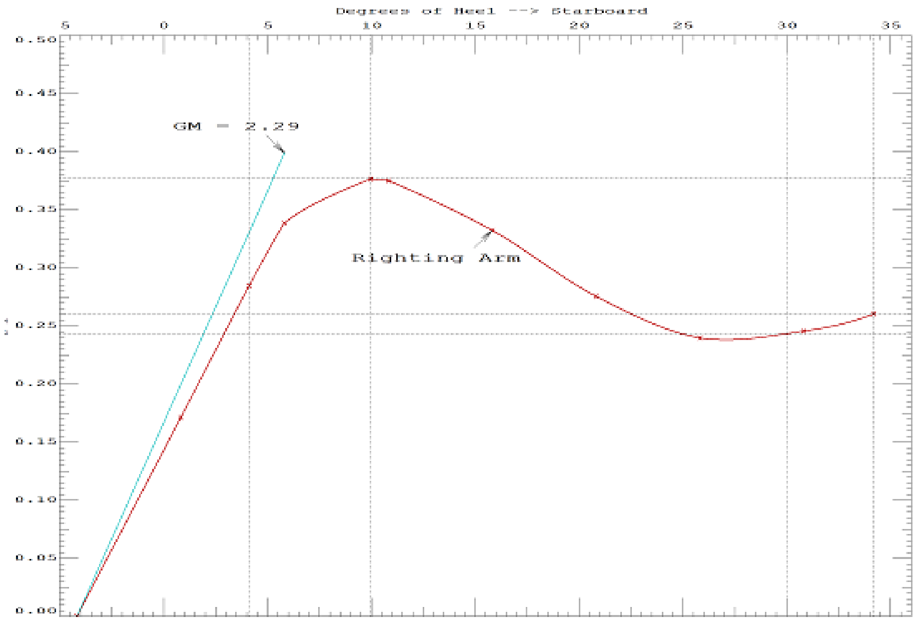

Figure 9. *Scandies Rose's* righting arm for the vessel's departure condition without ice. Deck immersion occurs at 10 degrees heel; downflooding occurs at 30 degrees.

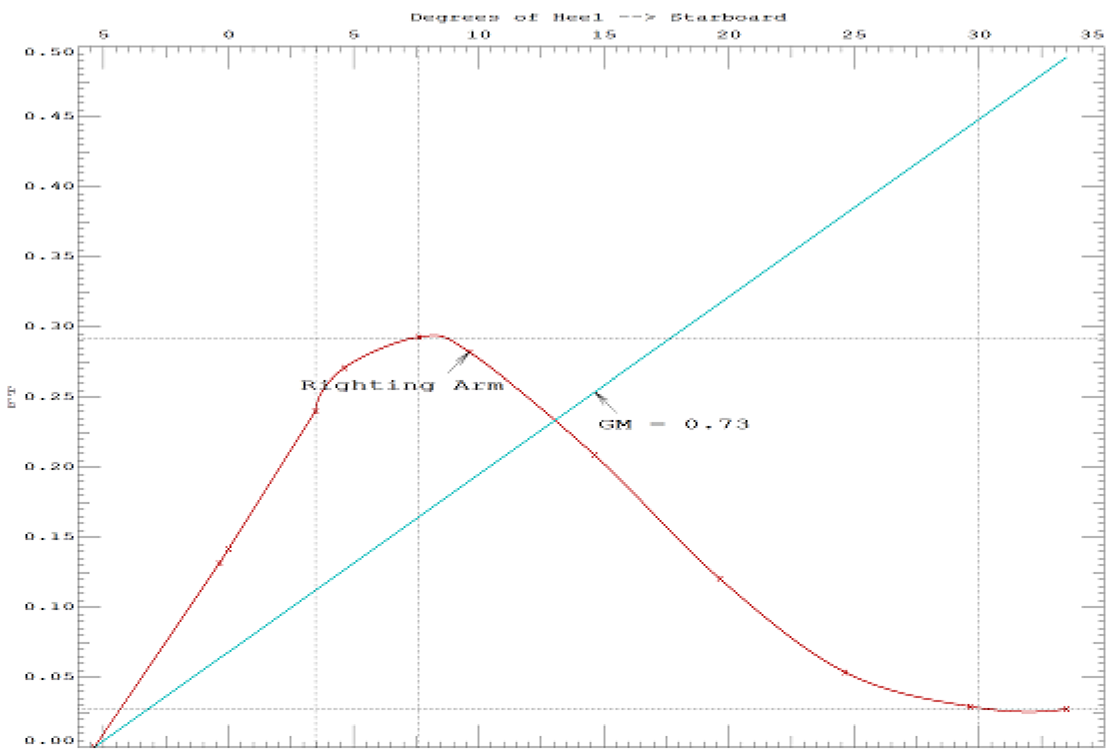

Figure 10. *Scandies Rose's* righting arm in the departure condition with worst-case icing specified in 46 CFR 28.550. Deck edge immersion occurs at 7.5 degrees heel; downflooding occurs at 30 degrees.

When actual icing weights were applied, the vessel capsized due to the large increase in the vessel's center of gravity. *Scandies Rose's* condition with approximated icing only left a freeboard of six inches, severely degrading both the vessel's reserve buoyancy and waterplane area when heeled. It is important to note this is a simplification of actual icing weight on *Scandies Rose*. The next section indicates icing loads may have been significantly higher than analyzed in this scenario.

Students were most comfortable and experienced in this area of the research. These are fundamental skills taught during sophomore level Naval Architecture courses: evaluating a vessel's righting arm to a set of stability criteria required by a specific ruleset. Nonetheless, the reapplication of these principles, especially in the context of an actual marine incident, reinforces the skill set and helps to build their confidence in applying it.

Vessel Icing

Ice accumulation on marine vessels is a long-standing issue for mariners working in cold weather [12]. The industry subjected to the greatest risk of ice accumulation is commercial fishing vessels operating in extreme weather conditions at high latitudes. Commercial fishing vessels, with limited open seasons (as short as 4 days) in treacherous operational areas with the potential of huge financial windfall often motivate fisherman to take higher risks during otherwise hazardous conditions.

Although there are several types of marine icing, the most common and dangerous encountered by marine vessels is sea spray icing. Unfortunately, this type of ice accumulation can be difficult to predict because a number of physical and environmental factors influence its rate of accretion. The most important factors include water temperature, air temperature, wind speed, relative direction of winds and waves, wave height, and wave period. The minimum meteorological conditions for the formation of sea spray ice are shown in Table 4.

Wind Speed (kts)	≥ 17
Air Temperature (°F)	$0 < T_a \leq 28$
Water Temperature(°F)	$28 \leq T_w \leq 28$

Table 4. Required meteorological conditions for sea spray icing

It is important to note the lower cutoff for both the air and sea temperatures. For air temperatures below 0 degrees Fahrenheit, sea spray icing does not often occur because the sea spray droplets freeze before reaching the vessel. When sea temperatures are below 28 degrees Fahrenheit, seas are typically frozen and do not cause sea spray icing.

Generally speaking, the worst sea conditions for sea spray icing occur when a vessel experiences bow-wave collisions, high winds, listing towards the exposed side with heavy beam winds, high waves, and seas between 15 and 45 degrees off the bow – all prevalent and factors on the evening of the *Scandies Rose* sinking.

Theoretical icing accumulation predictions have ranged from observation nomograms to droplet size, spray flux, and dozens of complex heat transfer equations. However, for the purposes of this study, a simpler, and much more often used icing prediction tool is applied. The Overland

Method is a method used by the National Oceanic and Atmospheric Association (NOAA) to predict the likelihood of sea spray icing and the associated accretion rates [13], [14]. The model only requires four variables: wind speed (V_a), the freezing point of seawater (T_f), the air temperature (T_a) and the sea temperature (T_w). The Overland method generates an icing predictor (PPR) shown as Equation 3.

$$PPR = \frac{V_a(T_f - T_a)}{1 + 0.3(T_w - T_f)} \tag{3}$$

The PPR predicts the icing as “light”, “moderate”, “heavy”, and “extreme” based on the range of predicted ice accumulation thickness, shown in Figure 11.

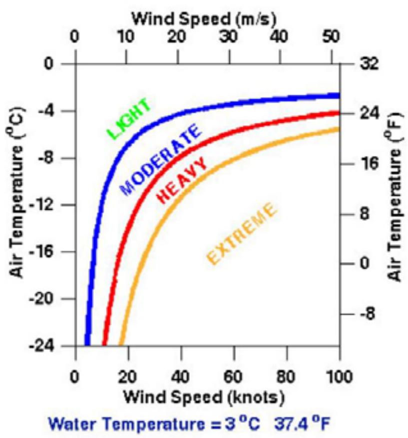

Figure 11. Overland PPR [14]

This method was applied to the *Scandies Rose* because there was sufficient weather data from NOAA buoys close to the last known position of *Scandies Rose.* The nearest weather buoys, 46077 and 46078, are highlighted in Figure 12.

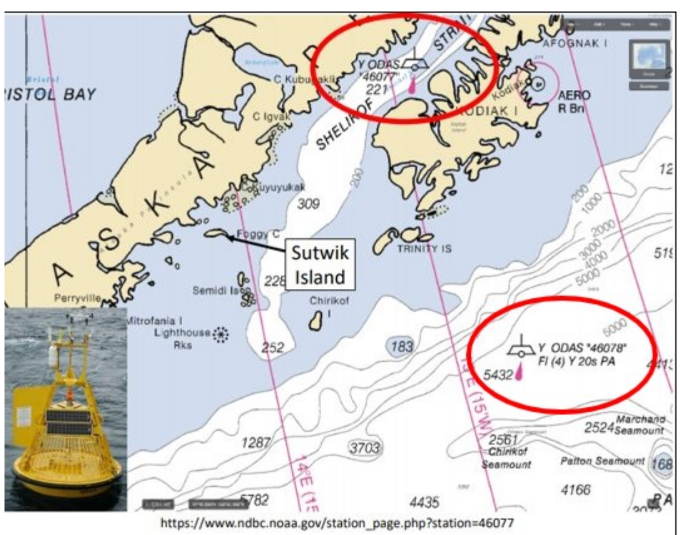

Figure 12. Weather buoys closest to *Scandies Rose*

During the evening on December 31, 2019, the general conditions recorded from both buoys indicated that there were winds from the northwest with decreasing air temperatures throughout the day into the evening hours. Weather data from buoy 46077 was used for the first 60% of her voyage, indicative of sheltered transit, while buoy 46078 was used to best match the final hours of her voyage, matching conditions in open water. The NOAA buoy data provided for the *Scandies Rose*'s voyage was split into six-hour sections and either summarized by a range or average over those six hours shown in Table 5.

	DEPARTURE: 2041 ASKT (0541 GMT)								CAPSIZE: 2141 ASKT (0651 GMT)	
BUOY 46077										Final Conditions:
Time (ASKT)	2100 29Dec-0300 Dec	0300-0900 30Dec	0900-1500 30Dec	1500-2100 30Dec	00 30Dec-0300 31D	0300-0900 31Dec	0900-1500 31Dec	1500-2100 31Dec	2100 31Dec -0300 01	2150 01Jan
Time (GMT)	*0600-1200 30DEC*	*1200-1800 30Dec*	*1800-2400 30Dec*	*2400 30Dec -0600 31De*	0600-1200 31Dec	1200-1800 31Dec	*1800-2400 31Dec*	*2400 31Dec-0600 01Ja*	*0600-1200 01Jan*	*0650 01Jan*
Winds (+-10kts)	20-27	17-7	06-18	09-14	09-17	15-22	22-27	28-32	26-30	26
Wind direction (degT, first-last)	270-240	240-310	050-040	030-170	180-245	245-235	245	245-260	260-250	260
Max wind gust (kts)	32	22	21	17	21	23	24	40	38	33
Wave height (+-2ft)	5-7	3-4	2-4	3-4	4-5	5-6	7-9	9-10	8-9	8.4
Wave direction (degT)	*250	240	245	220	235	245	240	240	235	233
Avg wave period (sec)	5	5.5	6	5.5	6	6	6	6	6	6
Water temp (degF)	42	43	43	*40	43	43	43	43	43	43
Air temp (degF, first-last)	34-30	30-33	33-37	44	40	30	21	23-16	15-10	15
ICING conditions	light, low	light, low	light, low	below light	below light	light	moderate	moderate	heavy	
Ice accum, rough avg (in)	1.2	1.2	1.2	0	0	1.8	3	3	4.8	
BUOY 46078										Final Conditions:
Time (ASKT)	2100 29Dec-0300 Dec	0300-0900 30Dec	0900-1500 30Dec	1500-2100 30Dec	00 30Dec-0300 31D	0300-0900 31Dec	0900-1500 31Dec	1500-2100 31Dec	2100 31Dec -0300 01	2150 01Jan
Time (GMT)	*0600-1200 30DEC*	*1200-1800 30Dec*	*1800-2400 30Dec*	*2400 30Dec -0600 31De*	0600-1200 31Dec	1200-1800 31Dec	1800-2400 31Dec	*2400 31Dec-0600 01Ja*	*0600-1200 01Jan*	*0650 01Jan*
Winds (+-10kts)	17-19	18-20	18-21	20-23	21-23	19-24	20-30	31-34	33-38	33
Wind direction (degT, first-last)	250-210	215-205	200-195	190-185	185	180-290	300-275	280	285	285
Max wind gust (kts)	25	25	26	28	28	29	30	42	50	40
Wave height (+-2ft)	15-17	13-15	12-14	14-16	16-17	15-17	14-15	17-21	21-25	21
Wave direction (degT)	200	200	210	220	230	225	230	285	285	284
Wave period (sec)	8.5	8	8.5	9	9	9	8	8	9	8.4
Water temp (degF)	43	43	43	43	43	43	43	43	43	42.4
Air temp (degF, first-last)	40-44	44	44	44	44	44-36	34-30	28-24	24-22	23.5
ICING conditions	below light	below light	below light	below light	below light	below light	light	light	moderate	
Ice accum, rough avg (in)	0	0	0	0	0	0	1.8	1.8	3	

Table 5. NOAA buoy data summary table.

Combining the NOAA buoy data with the Overland prediction method, the *Scandies Rose* experienced no icing to "very light" icing conditions for most of her final voyage, however, the last 12 hours she experienced moderate to heavy icing conditions. During the last three hours of her voyage, she bordered "extreme" icing conditions. Based on this data, a conservative estimate of her icing is just over four inches, much greater than the expected estimation.

The weight of ice assumed in the stability booklet for the *Scandies Rose* was 16.08 LT. After calculating the horizontal and vertical surface areas of the vessel, the corresponding ice weight in accordance with the geographical location of the *Scandies Rose* at the time of the accident was 9.77 LT. Accordingly, the vessel was within the stability assumptions for icing.

However, based off the analysis of the weather and sea state, the ice accumulation on *Scandies Rose* on the night of the incident was much greater than 9.77 LT. Using the NOAA weather predictions and the Overland method, the weight of ice accumulation was calculated to be 63.33 LT.

Source of Icing Estimate	Horizontal Weight (lb)	Vertical Weight (lb)	Total (lb)	Total (LT)
46 CFR 28.550 - South of 66°30' north	12,393	9,483	21,875	9.77
46 CFR 28.550 - North of 66°30' north	24,784	18,996	43,750	19.53
Stability Booklet	--	--	36,019	16.07
Overland Method - Buoy Weather	80,326	61,531	141,857	63.33
Overland Method - On scene Weather	106,697	81,856	188,553	84.18

Table 6. Comparison of icing estimations

Furthermore, *Scandies Rose* is unique because the survivors and rescue team could attest to the weather conditions on the day of the incident. Using on-scene weather reported from the survivor and by helicopter rescue team, the total weight of the ice would be 84.3 LT or 88% more than anticipated by the regulations.

Ice accretion was a new topic for students in this research project. This focus area required self-learning in areas of types of icing (sea spray), icing predication methods and meteorological parameters influencing the rate of ice accretion. Students were also required to analyze and interpret weather data from two buoys in the general location of the capsize event. Lastly, students quantitatively compared icing estimates across five different sources to illustrate the inconsistency in the current methods, and conclude that the initial claim that a new icing criterion is warranted.

Localized Ship Geometry

The rate of ice accretion is extremely sensitive to localized weather conditions. A cursory investigation into the airflow around the vessel, specifically through the crab pots, also offered insight into the role of ship geometry in the formation of ice. Orca3D Marine CFD, a combination of the Orca3D marine design plug-in for Rhino and the Simerics-MP (Multi-Purpose) CFD software, was used to model airflow across the deck of the vessel.

Figure 13 shows 20 knot streamlines across the deck of *Scandies Rose* in a head wind. Figure 13 shows areas of localized vortices inside of the crab pot positioned on the bow of the vessel and aft of the stepped deck forward. This behavior warrants further investigation and will be investigated by students in a follow-on research project.

Figure 13. Simplified CFD analysis of *Scandies Rose* without crab pots.

Conclusions

It is clear both from the *Destination* and *Scandies Rose* case studies that a new icing criterion should be created to provide a conservative weight estimate and stability assessment of vessels operating in icing regions. The IMO and United States standards do not account for worst-case topside icing conditions accurately – both in terms of quantity and location of ice build-up on the vessel.

This case study, in the context of undergraduate education, allowed students to demonstrate attainment of the following ABET EAC Criterion 3: Student Outcomes:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives

7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Although the students didn’t design an experiment per se, elements of Student Outcome six, specifically “… analyze and interpret data, and use engineering judgment to draw conclusions,” were also achieved. Case studies such as these can provide additional evidence that ABET EAC Student Outcomes are achieved and should be used more frequently in undergraduate engineering programs.

Additionally, the case study not only reinforced specific naval architecture concepts and their importance, but also exposed students to the statutory Prevention mission of the U.S. Coast Guard. Students learned about the investigation process, specifically how the Coast Guard works with the NTSB to conduct an investigation on significant marine casualties. Through their involvement in this project, students have been exposed to a critical engineering challenge for the Coast Guard in regulating commercial fishing vessels. Research projects such as these have been deemed a high priority for the program; this project married academic research into a real-world problem with student engagement with benefits for the U.S. Coast Guard and U.S. Coast Guard Academy.

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