FINAL REPORT

Development and Evaluation of Reduced Breaking Strength Rope to Reduce Large Whale Entanglement Severity

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EXECUTIVE SUMMARY

Entanglements of endangered North Atlantic right whales *(Eubalaena glacialis)* occur frequently, can lead to compromised health and sometimes death and are resulting in a conservation crisis. As rope technology advances, manufacturing improvements have resulted in stronger ropes and has escalated entanglement issues dramatically in recent years. Using ropes with a strength of 1,700 lbf has been recommended as one mitigation option to help reduce life threatening entanglements. With support from the Office of Energy and Environmental Affairs we have had 1,700 lbf prototypes developed and tested both in a lab and at sea. The most promising prototype is the *Novabraid* sleeve design initially developed by the South Shore Lobster Fishermen's Association in collaboration with rope manufacturer Novatec Braid, Ltd. Both our lab and field testing showed the sleeves break at just below 1,700 lbf and are feasible during normal fishing activity as only 11.8% of experimental endlines were reported broken/missing in comparison to 8.5% of reported broken/missing control endlines. There is time involved (~ 5 minutes per sleeve) to integrate the sleeves every 40 feet into the endlines but the cost per sleeve is relatively low at just over $2 per sleeve and would allow fishermen to use their existing ropes. Efforts to build fully formed 1,700 lbf ropes were unsuccessful, however initial testing of the most recent sample provided by a rope manufacturer seems promising. With this sample arriving in the coming weeks we aim to further assess the breaking strength (independently) and overall properties of this developed rope.

Modeling work was carried out to assess the tensions placed on ropes when hauling gear in normal fishing operations and to evaluate what forces a whale might put on gear during an entanglement provided a better understanding of what parameters influence rope tensions. Using results of at-sea testing integrated into *OrcaFlex* software showed that during the hauling of gear, the drag coefficient and the weight of gear in the water column had the most influence on endline rope tensions as water velocity and wave height increased. Operational changes such as increasing the groundline distance between the first and second pot, reducing hauler speed in high sea states and keeping the vessel over the top of the gear during hauling were all approaches that could be used to minimize rope tension. The Whale Entanglement Simulator, developed by BelleQuant Engineering to measure rope tensions when a whale gets entangled and rolls in response showed similar findings in that the weight of gear attached and the speed of the whale increased the simulated tensions in the three scenarios tested.

Based on the at-sea testing and the modeling studies, using 1,700 lbf ropes represent a suitable option that will allow fishing to occur without increasing gear loss but give whales the chance to more quickly part the entangling gear thereby reducing the negative impacts of entanglement. *NovaBraid* sleeves have been manufactured and could be deployed broadly into fixed gear fisheries to help address the right whale entanglement issue that is driving this species towards extinction.

OVERVIEW

Fishing gear entanglements involving endangered North Atlantic right whales occur often with 85% of the assessed population showing signs of entanglement interaction (Knowlton et al. 2012; Knowlton et al 2017). Also of concern is the finding that the rate of serious entanglements, i.e. whales with attached gear or with severe injuries from entanglement, has increased significantly over the 30-year period of assessment (Knowlton et al. 2012).

In 2015, New England Aquarium researchers and collaborators published a paper in Conservation Biology titled *Effects of fishing rope strength on the severity of large whale entanglements* in which we showed that rope strength was playing a significant role in the occurrence and outcome of large whale entanglements (Knowlton et al. 2016, accepted version published online in 2015). Clear patterns emerged that showed that small species such as minke whales and young right whales of 0-2 years of age were found in significantly lower breaking strength ropes than larger species and adult right whales respectively. As a result of that study, we recommended that rope strengths of 1,700 pound-force (lbf) breaking strength or less, a.k.a. "Whale Release Ropes" be used in fixed gear fisheries to reduce the impacts of entanglements on large whales.

In June 2016, the Office of Energy and Environmental Affairs awarded a contract to researchers from the Anderson Cabot Center for Ocean Life at the New England Aquarium to carry out the following tasks:

Collaborate with fishermen, polymer engineers, and rope manufacturers to develop a 1700 lbf breaking strength rope based on discussions with fishermen about their desired rope properties (stiffness, ease of coiling, durability, others).
Work with three rope manufacturers to develop a total of six prototypes of reduced breaking strength ropes with better abrasion resistance, and possibly a better "whale avoidance" color scheme than ropes presently used for fishing.
Lab test prototype ropes for abrasion resistance and breaking strength before and after abrasion testing.
Work with Bellequant Engineering to simulate right whale entanglements in the existing Whale Simulator, in order to test interactions with ropes of various breaking strengths, and assess how different rope strengths will impact the entanglement configuration and severity.
Work with lobster fishermen along the coast of Massachusetts to test these prototypes while they are actively fishing to assess how the ropes handle in comparison to standard ropes. All findings will be shared with the Massachusetts Office of Energy and Environmental Affairs and NOAA Fisheries.

This is our final report on this work plan. Our report is presented in five sections. We first describe our efforts to work with rope manufacturers to build 1,700 lbf rope prototypes and the associated laboratory testing. Our next section provides methods and results of at-sea testing of whale release ropes. We then describe a separately funded project where at-sea testing and OrcaFlex software were used to evaluate the tensions placed on gear during hauling and what variables would impact the ability to effectively haul gear using 1,700 lbf rope strength. Next we describe the use of the Whale Entanglement Simulator to further inform our understanding of how whale release ropes will help right whales. And lastly, we provide our conclusions and ideas for next steps.

SECTION 1: DEVELOPMENT OF WHALE RELEASE ROPE PROTOTYPES

Efforts on fully formed 1,700 lbf ropes

The first step in our efforts to get whale release rope prototypes manufactured was to develop criteria for the desired properties of such rope. The goal was to have rope manufactured at ⅜-inch diameter that had similar or better degradation resistance as presently used ropes that would meet the 1,700 lbf breaking strength. We conferred with fishermen to gain an understanding of rope handling properties needed for their work and we also integrated the idea of using fluorescent red or orange coloring to make it more visible to right whales. Previous work carried out by Scott Kraus at the Anderson Cabot Center and others showed that right whale vision is monochromatic but more sensitive to the red/orange spectrum leading to avoidance of these rope colors during skim feeding in Cape Cod Bay (Kraus et al. 2014). The criteria that we provided to rope manufacturers can be found in Appendix A.

With these criteria in hand, we reached out to several rope manufacturers. T. Werner and A. Knowlton visited two manufacturers who supply ropes to both east and west coast fisheries in the U.S. and Canada – Everson Cordage Works in Everson, WA (November 2016) and Polysteel Atlantic in Edwardsville, Nova Scotia (December 2016). We provided the criteria and offered funding support to carry out R&D and manufacture of 1,700 lbf rope strength prototypes for eventual testing at sea. Both of these meetings were productive as we were given tours of each manufacturing facility so we could better understand the manufacturing process which differed greatly between the two companies. Everson Cordage Works uses a process whereby spools of extremely fine synthetic fibers of varying types are purchased from other companies and combined during the manufacturing process to create a 3-strand or braided rope which meets certain criteria as specified by the purchaser. Polysteel Atlantic uses a different approach whereby they melt plastic pellets of different types together, and extrude the melted plastic into flattened and elongated fibers that are then manufactured into 3-strand ropes. This co-extrusion process, which was developed in the mid 1990's, has resulted in significantly stronger ropes than those created using the process described for Everson Cordage.

Each company expressed interest in exploring the possibility of manufacturing ropes at the specifications we outlined. However, in the ensuing months we were notified by Everson Cordage that they would not be able to help with the project due to a serious illness of the main point person involved in the collaboration. Polysteel Atlantic, after reviewing their co-extrusion manufacturing formulas determined that it would be impossible to change the blend of plastic polymers in a way that would attain the 1,700 lbf breaking strength goal but they were willing to explore and test other options.

We continued to reach out to other rope manufacturers throughout the world by conducting online searches and contacting them to describe our request, provide the rope specifications sheet, and to offer funding support for R&D if they provided a suitable proposal. Despite reaching out to 20 rope manufacturing and supply companies, only one offered to help with this effort. Taian Cord Rope Co., based in Shandong, China, offered to try building a floating rope at the 1,700 lbf breaking strength and send a sample of the rope for further lab testing. Their first try was a ⅜-inch polypropylene float rope with a strength of 2,645 lbf which did not meet our required specifications. Their second attempt produced a sample with only slightly less strength of 2,425 lbf. The last attempt was a ⅜-inch polypropylene rope that has an estimated manufacturer (independent testing to be conducted) breaking strength of 1,984 lbf which is an encouraging trajectory towards meeting the 1,700 lbf breaking strength goal. Because of time constraints, we were not able to carry out laboratory or at-sea testing on this prototype but will aim to continue doing so under separate funding.

Figure 1. A piece of ⅜-inch Manho-Manline float rope (left) with the two samples created at Taian Cord Rope of 2,425 lbf (middle) and 1,984 lbf (right).

Interestingly, based on dialogs with several rope manufacturers, it appears that building ropes of ⅜-inch diameter and 1,700 lbf breaking strength runs counter to their business strategy which has focused on making ropes stronger and stronger and more degradation resistant. To gain more traction in building these whale release ropes, future efforts may need to focus on bringing this to the attention of academia to determine if any new research on polymers could aid in the development of formulas for rope manufacturers to build 1,700 lbf ropes that will have similar degradation resistance as the stronger ropes.

Other methods to reach 1,700 lbf breaking strength rope

Between 2006-2008, the Bycatch Consortium produced ropes of 5/16" and 3/8" diameter, with 600 and 1,200 lbf breaking strengths, respectively. The ropes were a mix of barium sulfate (60% by weight) and polypropylene (40% by weight). In many areas of inshore (shallow water) coastal Maine where fishermen deployed these ropes, they reported that the ropes fished satisfactorily. However, there were concerns—particularly in rockier bottoms—that the ropes were more prone to abrasion and severing. For this study, we chose not to include this prototype because of the relatively higher cost of producing them. Nevertheless, they provide an example of how the different use of materials can be used to manufacture ropes that meet the whale-release rope specifications.

Prior to the granting of this contract, we had been approached by the South Shore Lobster Fishermen's Association of Marshfield, MA with an idea they had developed of integrating hollow braided sleeves of <1,700 lbf breaking strength into their existing endlines every 40 feet. The premise of this sleeve was that it would act similarly to the Chinese finger toy and stay attached to the integrated ropes (with the help of tucks at either end) and break when rope tension reached 1,700 lbf or less. This group, after being closed out of lobster fishing grounds because of right whale presence in Cape Cod Bay for a 3-month period starting in Feb-Apr 2015 and every year since, was motivated to research the whale entanglement situation and came upon our paper recommending 1,700 lbf rope strength be used to mitigate entanglement risk. This prompted them to do some testing of weak links in the ropes and the sleeve approach was deemed to be the most practical for them. They worked directly with a rope manufacturer, Novatec Braids Ltd., to develop *Novabraid* brand sleeve prototypes for them to use in their fishery. Although a request to the Atlantic Large Whale Take Reduction Team (TRT) in April 2017 to allow sleeved rope fishing in a limited portion of the west side of Cape Cod Bay and Stellwagen Bank during the closed timeframe (with an extension to year-round use) was ultimately not approved by the TRT due to concerns of allowing rope into a closed area, the sleeves were the primary prototype that we have used in this study to test the efficacy of using 1,700 lbf ropes with a broader group of fishermen off of Massachusetts as well as one in New Hampshire (see at-sea testing section below).

Additionally, we aimed to identify and assess other options for reducing current ⅜-inch rope strengths to achieve a 1,700 lbf breaking strength. After conferring with rope engineer(s) John Flory at Tension Technology International Ltd., Jerry Richard at Holloway Houston Inc. and Sean Burke at Polysteel Atlantic Ltd. about our difficulties in getting fully formed 1,700 lbf ropes manufactured, they offered some additional ideas for development and testing. Below are summaries of the sleeved design as well as each additional design developed and tested throughout this research with rope engineers.

Testing strategy

For testing purposes and overall consistency, we first identified a commonly used and widely distributed 3-strand ⅜-inch sink and float buoy rope to serve as the base of each prototype design. This included ⅜-inch *Everson Pro* medium lay sink rope made of copolymer olefin fibers wrapped with industrial polyester and ⅜-inch *Manho Manline* medium lay float rope composed of polypropylene. Second, we tensile strength tested all of the rope used in this project (this includes all prototype designs and at-sea field testing samples) at the same testing facility, Holloway Houston Inc., Houston, TX. There, 11-ft rope samples were pulled until broken on a "20k Test Bed" (Figure 2) with load cell calibrated to ASTM E4 standards.

Figure 2. Rope testing machine at Holloway Houston Inc.

Rope samples were centered and wrapped around each capstan three times and then tied off. Testing summaries identified maximum load (lbf), maximum displacement (inches) and a brief description of where each sample broke. All tested samples were then returned to our facility for visual inspection. Initial break testing results of new *Everson Pro* and *Manho Manline* rope served as a baseline in this research (Table 1).

Novabraid sleeve design

The sleeve design can be applied to a variety of ⅜-inch 3-strand float or sink rope brands, which allows fisherman the ability to continue fishing with their desired rope brand. This approach incorporates a hollow 6-ft 12 strand *Novabraid* sleeve manufactured by Novatec Braid Ltd. A ⅜-inch sink or float rope is cut/melted and inserted halfway down the hollow sleeve meeting the two ends of cut rope together. The ends of the sleeves are then anchored to the rope in 3 tucks. For more in-depth instructions on the assembly of this design see methods section of at-sea field testing below.

Figure 3. *Novabraid* sleeve design integrated into: a.) *Everson Pro* sink rope, b.) *Manho Manline* float rope and c.) a combination of the two.

Our initial virgin break testing of this design contained three 11-ft samples of the 6-ft sleeve integrated into each type of rope, totaling 9 samples (3 *Everson Pro*, 3 *Manline* and 3 of the two ropes combined). Results provided by Holloway Houston Inc. identified the average tensile strength for the three trials of sleeve when inserted into *Everson Pro, Manho Manline* rope and a combination of the two to be 1,375 lbf (SD=51.5), 1,322 lbf (SD=111.72) and 1,284 lbf (SD=230.72), respectively. Though virgin breaking strengths were slightly lower than the desired 1,700 lb objective we moved forward with this design to be field tested due to other components of this design that seemed promising. This included: (i) the consistency among each sleeves maximum breaking strength, (ii) consistency in the location of each break - in the middle of the sleeve and (iii) the relatively low amount of time taken to assemble the design (~ 5 minutes per sleeve).

2.) Embedded 7/64-inch Samson strand

This approach utilized a 7/64-inch *Samson - Amsteel* rope strand that has a manufacturers average breaking strength of 1,600 lbf. To exploit this, a 20-inch piece of the strand was spliced into each end of a cut ⅜-inch *Everson Pro* rope. To maintain its structure, the sample was then submerged in a urethane Maxijacket™ (Yale Cordage) rope coating and wrapped in E-Z self-fusing silicone tape (The Original Super Glue®).

Figure 4. Embedded *Samson Amsteel* strand design.

Similarly, three 11-ft samples were sent to Holloway Houston Inc. for break testing. The three trials identified an average maximum tensile strength of 321 lbf (SD=118.66). In all cases, the very low breaking strength was a result of the Amsteel strand slipping out of the splice. Further trials were discontinued due to a lack of a timely and effective method of anchoring the strand.

3.) Spliced in ¼-inch Polysteel

This idea was to add a small section of 1,700 lbf rope into the ⅜ inch Everson Pro. For this an 18-inch piece of 3-strand ¼-inch *Polysteel* rope was spliced end-to-end into a cut piece of *Everson Pro*. The ¼-inch *Polysteel* rope has a manufacturer-specified breaking strength of 1,650 lbf.

Figure 5. Spliced in ¼-inch *Polysteel* design.

Discussions with fisherman about this design were overall positive, however the difference in rope diameters was of concern, that is, the thicker diameter formed by the spice versus the smaller ¼-inch rope could cause the rope to spit out of a pot hauler. Additionally, splice length was kept to a minimum of about 7 inches due to the consideration of assembly time for fisherman. The results of the three trials identified an average tensile strength of 2,009 lbf (SD=113.32). Though the breaking strength of the design proved favorable, the area of each break varied. Samples broke twice at the *Polysteel* link but one sample slipped out of splicing. Because of the added time of assembly and the variability in how the gear parted we did not move forward field testing this design.

4.) Cut strand of a 3-strand rope

The suggestion to manipulate a 3-strand rope by simply cutting one of the tree strands was brought forward during discussions with rope engineers. In theory, this quick and simple cut could be applied with ease and added to any section of a given rope to decrease its strength by 1/3 of its original breaking strength.

Figure 6. A 3-strand rope with a single strand cut before and after force was applied.

Initial strain testing demonstrated that the composition and structure of the rope would not be retained under force. Multiple attempts of incorporating additional materials to eliminate unraveling proved ineffective. This design was not sent for additional testing.

5.) Knot Strategy

In addition to the designs discussed with engineers, the idea of adding a knot in ⅜-inch rope as a strategy to reduce the breaking strength was put forward by fishermen during a TRT whale-release rope subgroup meeting.

Figure 7. Single and double overhand knot in ⅜-inch Everson Pro rope before and after testing.

Our knot testing was comprised of single and double overhand knots. Of the 6 trials (3 of each knot type) results identified a relatively consistent 47% reduction in breaking strength among all knot types used. This resulted in an originally manufactured ⅜ inch *Everson Pro* rope with an average virgin breaking strength of 3,975 lbf to be reduced to 2,108 lbf and 2,094 lbf when adding a single and double overhand knot, respectively (Table 1). The breaking point of the rope occurred within the knot itself, however in all cases portions of the knots still remained present. This suggests that after a complete rope break the ropes' diameter may still approach 1 inch where the knot was placed which, in turn, would prove difficult to pass through a whale's baleen plates.

In summary, our efforts to get fully formed 1,700 lbf rope prototypes did not yet succeed despite extensive outreach but after considerable evaluation and testing of other options, we decided to move forward with testing the *Novabraid* sleeve design. The sleeves are easily accessible through Novatec Braids, Ltd based in Yarmouth, Nova Scotia and are proving to be a viable option to achieving the 1,700 lbf rope strength goal.

Table 1. Summarized tensile strength testing for (a.) new, unaltered Everson Pro sink rope and Manho Manline float rope and for (b.) each prototype design. "lbf" represents pound-force, the rope name in parentheses indicate the type of ⅜- inch rope the design was assembled from, * indicates the sample did not break correctly

a.)

Rope Name	Size (Diameter)	Maximum Load (lbf)		
		Trial 1	Trial 2	Trial 3
Everson Pro	3/8"	3,975	3,988	3,925
Manho-Manline	3/8"	3,647	3,811	3,786

b.)

Design Name	Maximum Load (lbf)		
	Trial 1	Trial 2	Trial 3
Novabraid Sleeve			
(Everson Pro)	1,411	1,316	1,398
(Manline)	1,202	1,341	1,423
(Everson-Manline)	1,550	1,138	1,164
Embedded 7/64" Samson Strand			
(Everson Pro)	188*	416*	359*
Spliced in 1/4" Polysteel			
(Everson Pro)	2,069	1,879*	2,081
Knot Strategy			
Single overhand (Everson Pro)	2,170	2,132	2,024
Double overhand (Everson Pro)	2,195	1,936	2,151

SECTION 2: FIELD TESTING THE SLEEVED ROPE DESIGN

Field testing was developed with input from the Massachusetts Lobstermen's Association and the South Shore Lobster Fishermen's Association. Both organizations provided a list of fishermen potentially willing to participate. To gain further interest we provided fishermen the ⅜-inch rope in addition to the experimental 6-ft *Novabraid* sleeve with the option to keep any remaining rope and sleeves that were not compromised during analysis. The rope types provided were ⅜-inch Everson Prop medium lay sink rope and ⅜-inch *Manho Manline* medium lay float rope.

Assembling Sleeved Endlines

At the start of the season participants were given the option to assemble experimental lines themselves or to be given sleeved endlines in their requested length. Instructions for inserting the braided sleeve included: First, cut/melt a 1-inch slice at both ends of the orange sleeve about 4 inches from each end. Next, cut the 3-strand sink/float rope in the location you would like to add the sleeve. Insert each melted end into the slice in the sleeve. Slide the rope through the sleeve until it is half way down, about 3-ft.

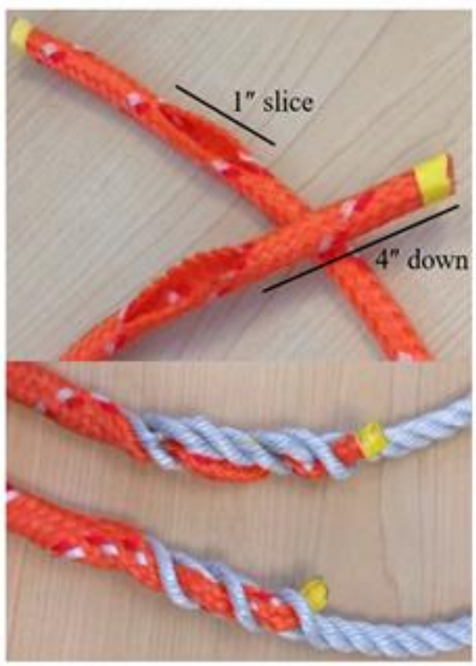

Figure 8. *Novabraid* sleeve assembly diagram

Similarly, take the other end of the rope and insert into the other side of the sleeve until both cut pieces of rope meet in the middle of the sleeve. Lastly, secure the end of the orange sleeve by splicing (or tucking) the exposed sleeve material under a single strand of the 3-strand rope at least 3 times. Make the ends as compact as possible against the 3-strand rope. When adding the *Novabraid* sleeve to the endline we asked participants to install a sleeve every 40-ft in both the sink and float portion of the endline. Once the technique of integrating a sleeve into the rope is learned, the time taken to add a sleeve should take no more than 5 minutes.

At-Sea Procedure

Each participant used the experimental sleeved rope on five separate trawls, one at each buoyed end (ten total for multi-pot trawls). We asked that the location and configuration of each trawl not be changed from their normal fishing routine. Additionally, at the location of every experimental sleeved trawl we asked participants to deploy a "control" trawl (*Everson Pro* and *Manline* with no sleeves) in the same general area, making an experimental-control pair. Therefore, each fisherman represented 5 experimental and 5 control trawls (i.e a participant fishing with all multi-trap trawls, would have a total of 10 sleeved endlines and 10 control endlines.) Each endline was given a unique ID number. At-sea, participants were asked that all setting, hauling and other fishing procedures be carried out as normal. Data was recorded using field log sheets (see Appendix B). Participants were asked to record detailed information of each trawls' configuration including: weight of a single trap, number of traps, distance between traps and surface buoy type (i.e foam bullet buoys, polyball, high-flyers). When hauling, the date, endline ID, location, depth, and any additional information was recorded. A notes section was provided to include details of a broken sleeve or broken control line and other information that may be relevant on a day to day basis. This information included: lost gear, endline and/or sleeve condition, gear configuration changes - such as a change in the amount of traps, splices or knots added to an endline or groundline, sea state, etc. In the event of a break, black painted replacement sleeves were provided to indicate these replacement sleeves were not part of the experiment. At-sea instructions for participants are outlined in Appendix B.

Sample Collection

Endlines of all experimental and control trawls were retrieved from all participants at the end of the experimental time period. During collection rope was visually analyzed and given a score based on the severity of marine growth present on each endline. Rope was later cleaned to remove any remaining marine growth using warm water and a pressure washer. When dried, rope was then visually inspected to identify any abrasion and damage.

For each participant, endlines were grouped based on the following criteria: (i) endlines hauled most frequently, (ii) endlines hauled an average number of times and (iii) endlines hauled the lowest number of times, if at all (some fishermen haul from the same end of the trawl every time). Of each group, 3 sleeves were randomly selected and that rope with the integrated sleeve section was cut into 11-ft samples for further analysis to identify the maximum load, displacement and hold time until broken. This totaled 9 sleeve break tests per participant. Additional, sample collection and break testing was done to other areas of rope including sections of rope between sleeves and of controlled endlines. Each sample taken was given a unique ID to distinguish the area of rope at which it was cut from.

Field Testing Results

At-sea testing began in early summer of 2017 and concluded approximately one calendar year later. Experimental and control endlines were distributed to 7 participants in diverse fishing areas of Massachusetts and New Hampshire waters (Figure 9). Endlines were utilized primarily in the lobster fishery, however in some cases endlines were also configured to the whelk and black sea bass trap fisheries.

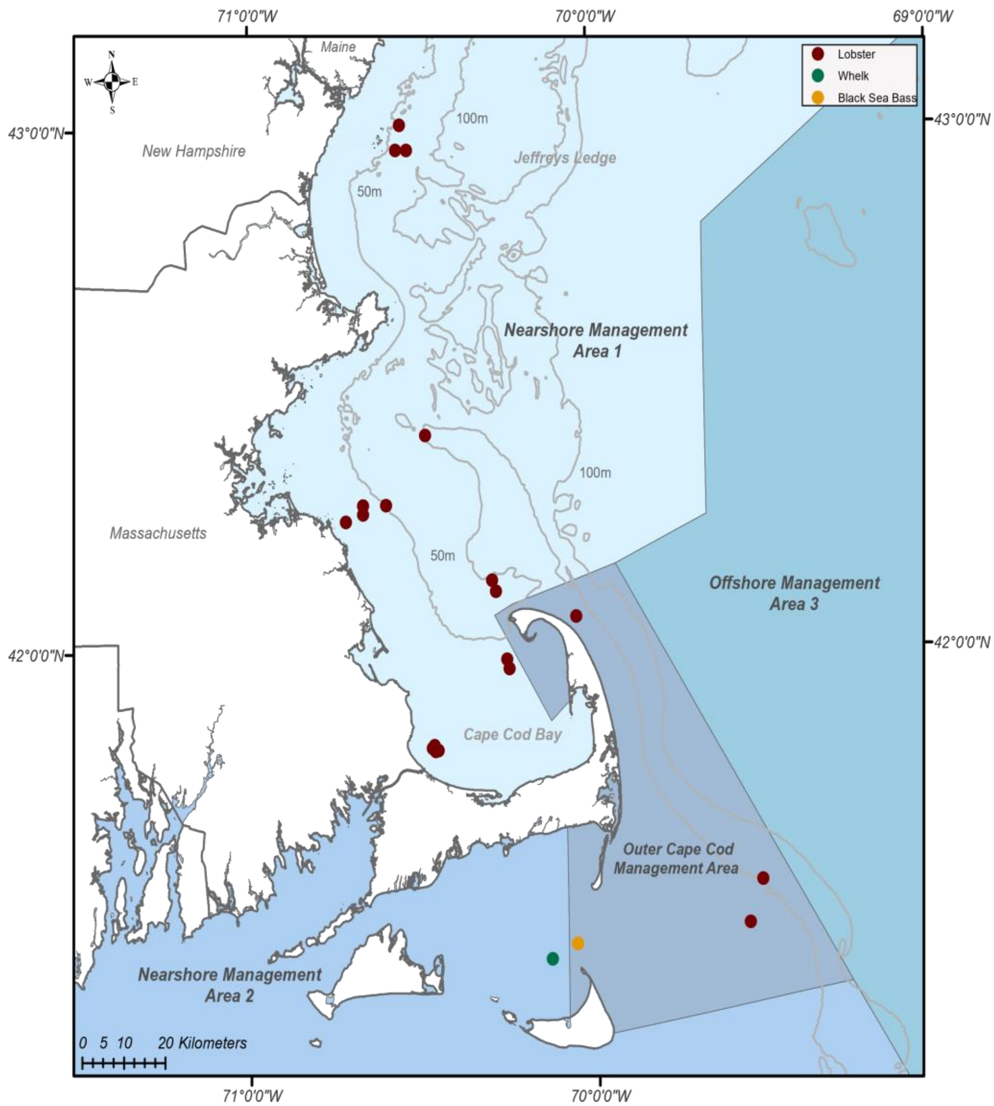

Figure 9. New England coast study area and general location of each participant's gear sets.

A total of 115 endlines were deployed with lobster, whelk and sea bass fishermen with varying gear configurations and weights and environmental conditions (Table 2.). 59.1% of these endlines were deployed with sleeves and 40.8% were control endlines. A complete 50/50 split was not obtained for experimental-control pairs as some participants used one control trawl to represent 2 nearby experimental trawls.

Table 2. Summary of field testing in the lobster, whelk and black sea bass fisheries.

	Lobster	Whelk	Black Sea Bass	Total
Endlines used:	105	7	3	115
Experimental	59	7	2	68
Control	46	0	1	47
Number of traps on a trawl	8-20	1	15	-
Weight of a single trap (lbs)	30-118	40	40	-
Maximum Depth (ft)	310	55	42	-
Dominant Substrate	Sand-Rock Mix	Sand	Sand-Rock Mix	-

Figure 10. Lobster (left), whelk (center) and black sea bass (right) traps used during field testing.

Throughout the duration of the project a total of 8 of the 68 (11.8%) experimental endlines and 4 of the 47 (8.5%) control endlines were reported broken (1 experimental endline was lost because the groundline parted and is not included in this tally). In 11 of the 12 endline events parting occurred while the trawl was soaking and 1 (Experimental Break #7) while in the process of hauling. All reported events were of participants fishing with lobster gear. The reported information of each specific case is outlined below.

<u>Experimental Break #1</u>: This 15 pot trawl was set in 125 ft of water containing a sand-rock mix. Each trap weighed 50 lbs with 100 ft of groundline between each trap. During the time of the break the trawl had been soaking for 3 months and the endline had been hauled 9 times. The endline broke at the top sleeve - log sheet notes suggest the break was due to heavy boat traffic. Foam buoys were used on this trawl.

<u>Experimental Break #2&3:</u> The two breaks occurred on the same endline of a 15 trap trawl set in 116 ft of water containing a sand-rock mixture. Each trap weighed 50 lbs with 100 ft of groundline between each. At the time of the first break the trawl had been in the water for 1 month and the endline had been hauled 5 times. The bottom sleeve broke and the participant replaced the endline completely, with new rope and sleeves.

Field notes mentioned the trawl was hung up for a period of time previous to the first break, however everything was hauled successfully. Additionally, notes mentioned high traffic during hauls after this break. The endline then broke a second time later in the same month after being hauled two more times. This break occurred at a sleeve 40 ft below the foam buoy. During the second break a note was made of heavy boat traffic.

<u>Experimental Break #4:</u> This break occurred on the same trawl described above but to the opposing endline. This endline break transpired 2 months (4 hauls) from the trawls initial setting. This sleeve broke at the bottom of the endline right before the trap. The participant replaced both rope, sleeve and foam buoy.

<u>Experimental Break #5:</u> The 8 trap trawl was set in 65 ft of water containing a sand-rock mix. Each trap weighed 30 lbs with 100 ft of groundline between each. At the time of the break the trawl had been in the water for 3 months and hauled 18 times. This break occurred at the only sleeve on the 80 ft endline, about half way down. Foam buoys were used.

<u>Experimental Break #6</u>: This event occurred on an 8 trap trawl and set in 70 ft of water containing a sand-rock mixture. Each trap weighed 30 lbs with 100 ft of groundline between each. At the time of the break the endline had been hauled 5 times. This endline was missing completely including the foam buoy, line and first trap. *This was included in this summary for information purposes as it technically is not a break at the endline but rather a trawl parting at the groundline.*

<u>Experimental Break #7&8:</u> The 15 trap trawl was set in 110 ft of water containing a gravel-cobble mix. Each trap weighed 118 lbs with 120 ft of groundline between each. At the time of the first break the trawl had been in the water for a week and had not yet been hauled. During the first haul the bottom sleeve parted (see Figure 11). The second break which was at the top sleeve of the opposing endline parted 3 months later. This sleeve had been hauled 9 times. This participant used a large go-deep and high-flyer.

<u>Experimental Break #9:</u> The break occurred on a 15 trap trawl set in 107 ft of water containing a sand-rock mix. Each trap weighed 118 lbs with 120 ft of groundline between each. At the time of the break the trawl had been in the water for 2 months and had been hauled 4 times. This sleeve was at the top of the endline and was replaced.

<u>Control Break #1</u>: The 15 trap trawl was set in 105 ft of water containing a sand-rock mix. Each trap weighed approximately 40 lbs with 100 ft of groundline between each. At the time of the break the trawl had been in the water for 2.5 months and the endline had

been hauled 7 times. This control endline broke at the very top, which required the participant to simply replace the foam buoy.

<u>*Control Break #2:*</u> *This break occurred on an 8 trap trawl set in 65 ft of water containing a sand-rock mixture. Each trap weighed 30 lbs with 100 ft of groundline between each. At the time of the break the trawl had been in the water for 3 months and the endline broken had been hauled 16 times. Foam buoys were used. This control endline broke at the top, and entire trawl was dragged. Notes suggested it was due to boat traffic.*

<u>*Control Breaks #3&4*</u>*: The 15 trap trawl was set in 107 ft of water containing a rock-sand mixture. Each trap weighed 118 lbs with approximately 120 ft of groundline between each. At the time of the breaks the trawl had been in the water for 2 months and the endlines broken had been hauled 6 and 4 times. Both control endlines were reported parted but traps remained and no additional information was given. This participant uses a large go-deep and high flyer.*

Post Fishing Tensile Strength Results

Throughout the season a total of 313 sleeves were actively fished by the 7 participating fisherman. Of this, a total of 72 (23.0%) Novabraid sleeves were break strength tested at the conclusion of the field trial. Variability in post fishing sleeve breaks was high as the minimum and maximum values of breaks were 467 lbf and 1,702 lbf. The average breaking strength of all sleeves fished was 1,213.11 lbf (SD 193.28). When comparing these results to our initial testing of new, unused sleeves, 1,327 lbf (SD 136.6), we see a 114 lbf reduction in average sleeve strength after fishing. For the results of pre and post fished control rope we identify an average 240 lbf reduction in *Everson Pro* and 427 lbf in *Manho Manline*. Results were analyzed further to identify any significant decline in breaking strength based on a number of parameters including: the number of hauls, area of rope the sleeve was located and maximum depth the sleeve was fished at, however no apparent trend was identified (Table 3).

Table 3. Summarized Holloway Houston Inc. break testing results of endlines used during field testing. n refers to the number of samples tested, lbf is pound-force and SD is the standard deviation.

		Maximum Load (lbf)			
	n	Min	Max	Average	SD
All Sleeves	72	467	1,702	1,213.11	193.28
Level of Hauling:					
High (14+)	18	872	1,436	1,202.9	233.12
Medium (7-14)	33	467	1,702	1,224.6	153.84
Low (0-6)	21	860	1,449	1,203.8	158.58
Sleeve position on Endline:					
Top	20	701	1,430	1,185.8	192.02
Middle	28	467	1,449	1,223.3	204.28
Bottom	24	746	1,702	1,224.0	187.01
Max Depth:					
0-100 ft	18	872	1,436	1,222.7	144.40
101-200 ft	39	467	1,449	1,210.0	221.00
201-300 ft	15	1,050	1,702	1,209.8	177.23
Control (Everson)	12	3,408	4,000	3,713.42	209.31
Control (Manline)	5	2,953	3,717	3,321.33	297.20

A Season of Use: Sleeve Abrasion

Throughout the field season, sleeve abrasion remained minimal with no recurring concern. However, in one particular case abrasion was very high as all components; *Everson*, *Manline* and the braided sleeve showed signs of extreme abrasion (Figure 11). This was seen on 4 total endlines (2-experimental and 2-control) of the same participant. These endlines were the source of the lowest sleeve breaks present in the study (sleeve breaks: 467, 701 and 746 lbf) and also made up 2 experimental and 1 control breaks in the field as outlined in the summary above. Cause of the excessive abrasion was believed to have been due to extreme twisting of the rope throughout the water column due to spinning of the go-deep and highflyer (even with a swivel present) during a stretch of storms.

Figure 11. A Novabraid sleeve, Everson Pro and Manline rope with heavy abrasion. The sleeve was broken while hauling in the field (experimental break #7).

The securing (or tucking) method of sleeves fastened to the rope did not pose an issue. Multiple sleeves began to show slight signs of wear and tear as endlines were collected at the end of testing. Mainly, this was shown at the middle of the sleeve which may be the result of the burnt, relatively sharp ends of rope poking through the braided sleeve. This is shown in an extreme case below. The presence of this type of wearing in our results did not show a lower breaking strength as sleeves with significant damage were noted and reviewed after break testing occurred, however this damage could reduce the lifespan of a functioning sleeve and eventually reduce the breaking strength.

Figure 12. Post season braided sleeve shown with a gap and damage around ends of Everson (white) rope.

SECTION 3: TENSION PLACED ON ROPES DURING HAULING

Background

For fishermen to effectively use whale release ropes to haul their gear, an understanding of the tensions placed on gear during normal fishing operations is needed. To carry this out, we pursued two avenues of research under a separate funding opportunity. First, we conducted a full day of at-sea load cell testing on a 42-foot lobster boat in Massachusetts Bay using a load cell device integrated between a davit and a pulley used to haul lobster gear. We conducted a series of tests to better understand the tensions placed on endlines while hauling and towing lobster gear.

The data collected during the at-sea testing was then used in the second avenue of research which involved consulting with a mechanical engineer, Dr. Jud DeCew, who is very familiar with a software called *OrcaFlex*. This software is used by the oil and gas industry and other marine operations to model the dynamic forces placed on cables and ropes used in these industries to hold platforms, moorings and towed seismic arrays to name a few uses. *OrcaFlex* has a broad variety of uses but Dr. DeCew was able to create a model using this software that would simulate the hauling of lobster gear under different weather conditions and current velocities and calculate the tensions placed on the endline. With this model, the influence of gear configuration, water depth, and hauler speed could also be evaluated. The Anderson Cabot Center now owns the software and has been trained on how to use it which will allow it to be utilized to investigate a broad variety of gear types and configurations in the future. A report provided to the Anderson Cabot Center by Dr. DeCew on his findings using both the at-sea testing results and *OrcaFlex* analyses are summarized below.

Main findings for at-sea testing

During the at-sea hauling which occurred off the coast of Massachusetts in May 2016, the team was able to measure tension on the endline while hauling a 5 pot lobster trawl in up to 200 feet of water depth. The gear was initially configured with 90 feet of groundline between each pot, each of which weighed 65 lbs. To evaluate the influence of weight in the water column on tension, a “groundline extension”, a lengthening of the groundline from 90 to 210 feet between the first and second pots was integrated. The team also towed up to four lobster pots behind the boat at increasing vessel speeds to calculate the influence of water velocity on tension.

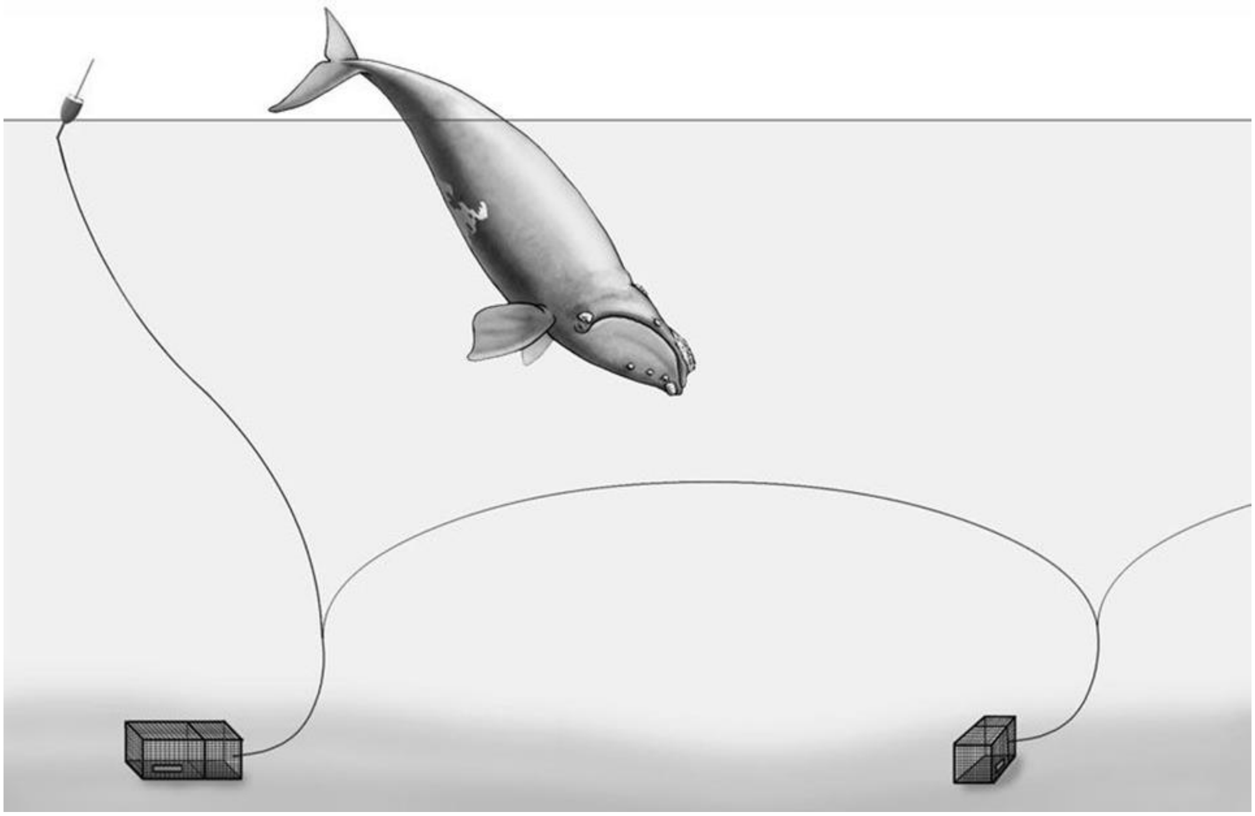

Figure 13. Illustration of lobster gear configuration showing endline from bottom gear to surface buoy and groundlines between the pots (note: illustration not to scale)

The tensions placed on endlines during the at-sea testing were most influenced by the weight of gear in the water column. When we added the groundline extension, the tension was reduced from a measured maximum of about 900 lbf to around 300-400 lbf, a dramatic reduction (Figure 14). And after applying a correction factor for the estimated 75% hauling angle around the pulley (see Figure 15), these tensions actually range from a maximum of approximately 570 lbf to around 190 lbf when a groundline extension was integrated.

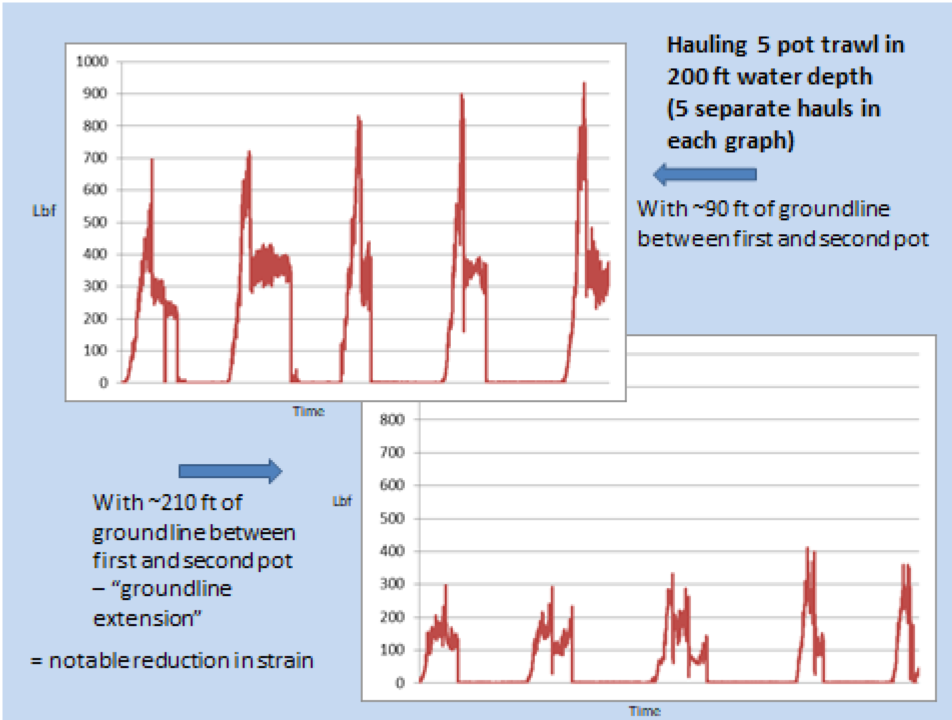

Figure 14. Difference in tension during regular hauling and after integration of a groundline extension. For each suite of tests, hauler speed was increased during the latter hauls. After adding the correction factor (see Figure 15), these tensions ranged from 570 to 190 lbf.

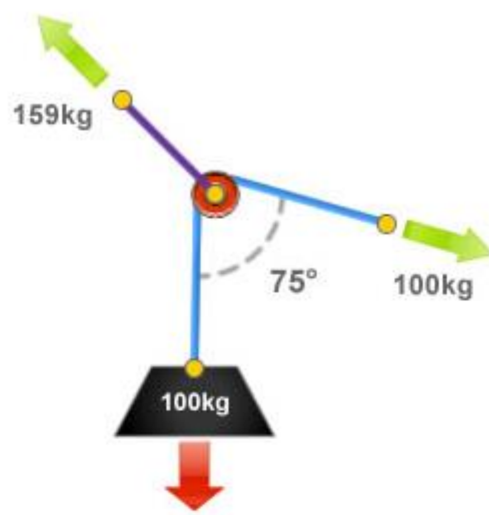

Figure 15. Correction factor employed to account for pulley system above which load cell was deployed (illustration from https://www.ropebook.com/information/angular-vector-forces/)

When towing four pots behind the boat, the maximum tension at 4 kts of speed was around 820 lbf (Figure 16). No correction factor needed to be applied in this test since the gear was not being actively hauled. The data collected during this towing of gear was used to inform the *OrcaFlex* model.

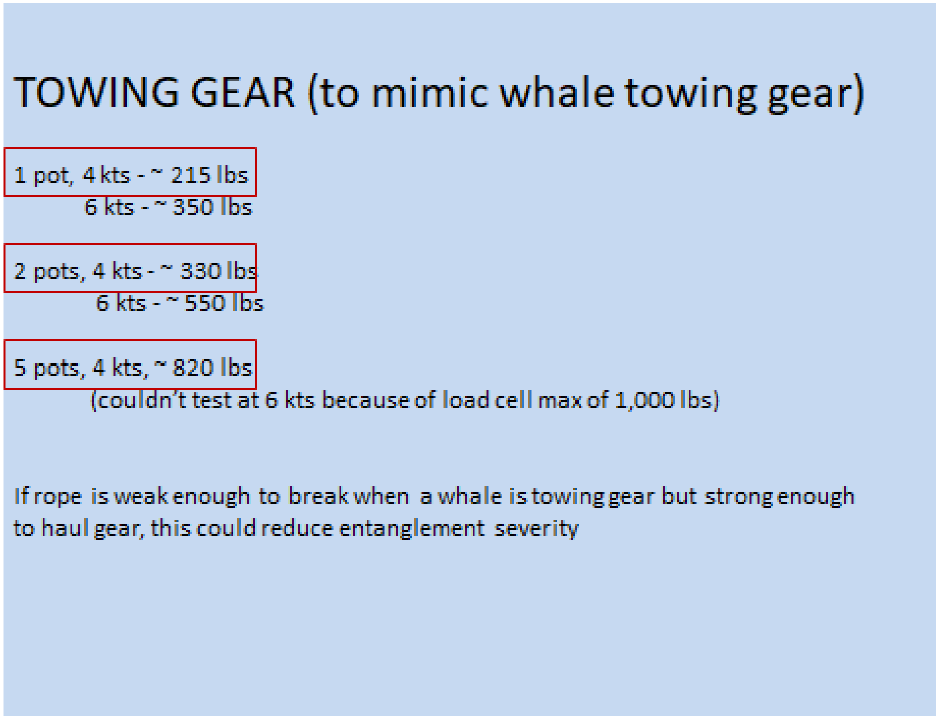

Figure 16. Tension placed on endline when towing pots at different vessel speeds.

Main findings from OrcaFlex model

The *OrcaFlex* software was adapted by Dr. Jud DeCew to test similar gear configurations used in the at-sea testing and to further evaluate the parameters that most influence the tension placed on endlines while fishing. Five different static parameters were tested in sensitivity analyses as follows:

Line diameter
Endline/groundline length (between pots)
Lobster trap mass
Lobster trap drag coefficient (Cd)
Number of lobster traps (1-5, 20)

Each parameter was compared to a baseline of 3 pots in the water column weighing 65 lbs each and measuring 48” x 22.5” x 15” using ⅜-inch diameter line and 90 feet of groundline between each pot. A water velocity of 0 to 6 kts was applied to evaluate sensitivity of each variable. The lobster trap drag coefficient (which is a measure of the hydrodynamic drag) and the number of lobster traps in the water column had the most influence on tension as water velocity increased (see Figure 17).

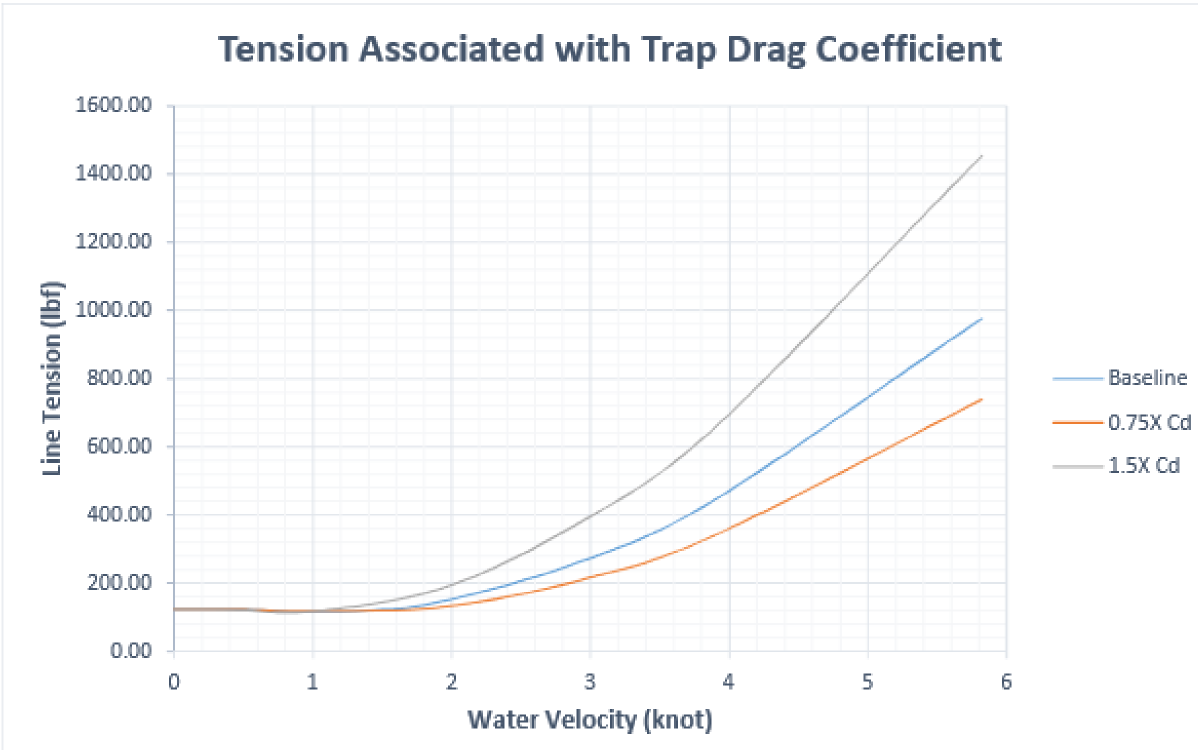

Figure 17. The results of the trap drag coefficient sensitivity analysis.

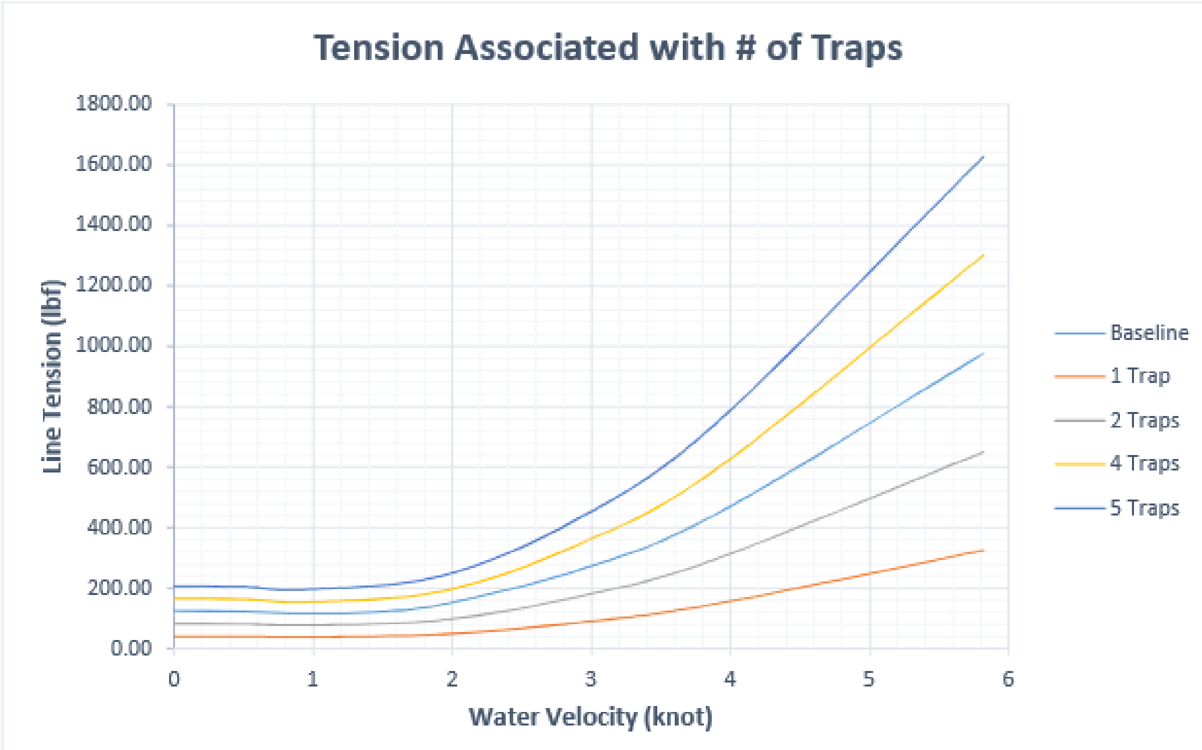

Figure 18. The results of the number of traps sensitivity analysis.

An additional analysis was carried out to compare how a 20 pot trawl with all pots in the water column would compare to a 3 pot trawl as water velocity was imposed. As seen in Figure 19, the tension reached the 1,700 lbf at just under 3 knots of water velocity. When actively hauling gear, it would be highly unlikely that all 20 traps of a trawl would be in the water column but if we consider how the gear might respond if a whale started towing the gear, this shows that if the trawl is longer and heavier, the whale would be able to part that 1,700 lbf endline by exerting a limited level of speed whereas it may not be able to part a 3-pot trawl unless it got hung up in other gear which based on the Knowlton et al. 2016 paper may happen fairly frequently as many of the retrieved gear cases involved 2 or more sets of gear.

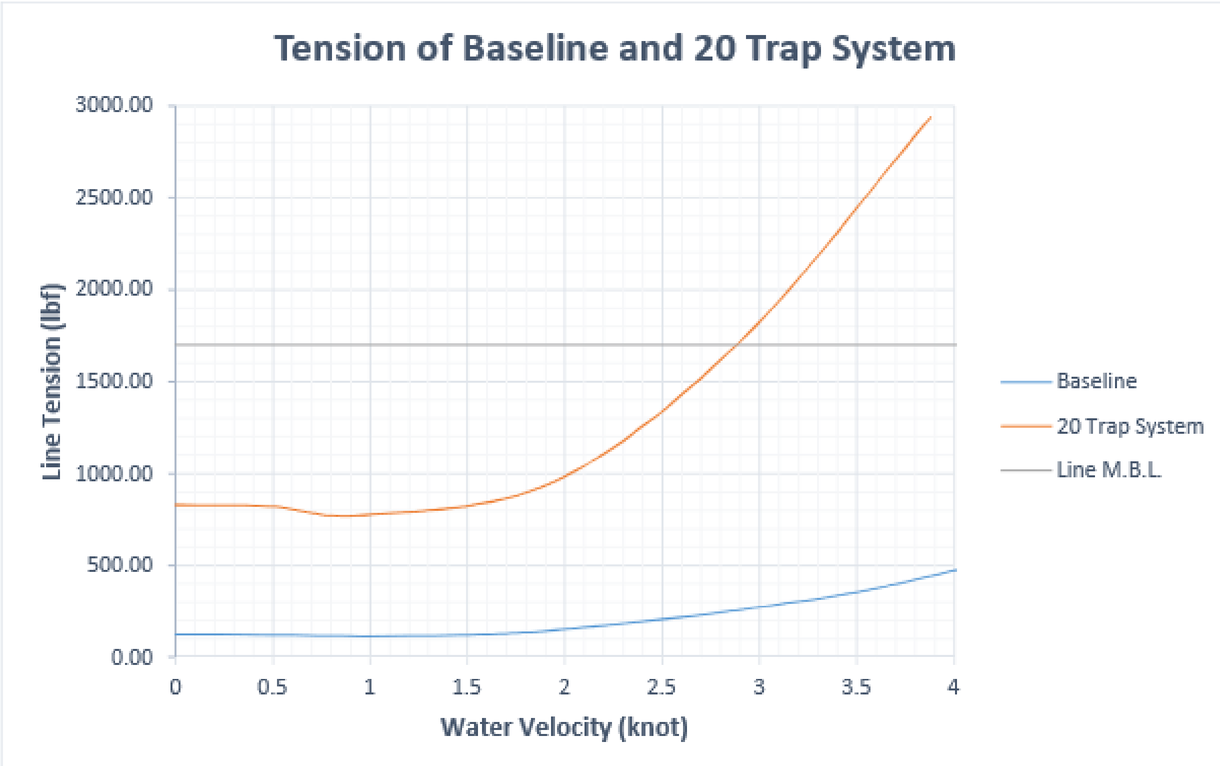

Figure 19. Tension on 3 pots vs 20 pots in the water column when water velocity increased

To help elucidate this further, a formulaic approach based on at-sea testing was used by Dr. DeCew to estimate the effect of water velocity on a variety of trawl lengths (Figure 20) although it was noted that further simulations need to be done to confirm the accuracy of the curves estimated for the longer trawls.

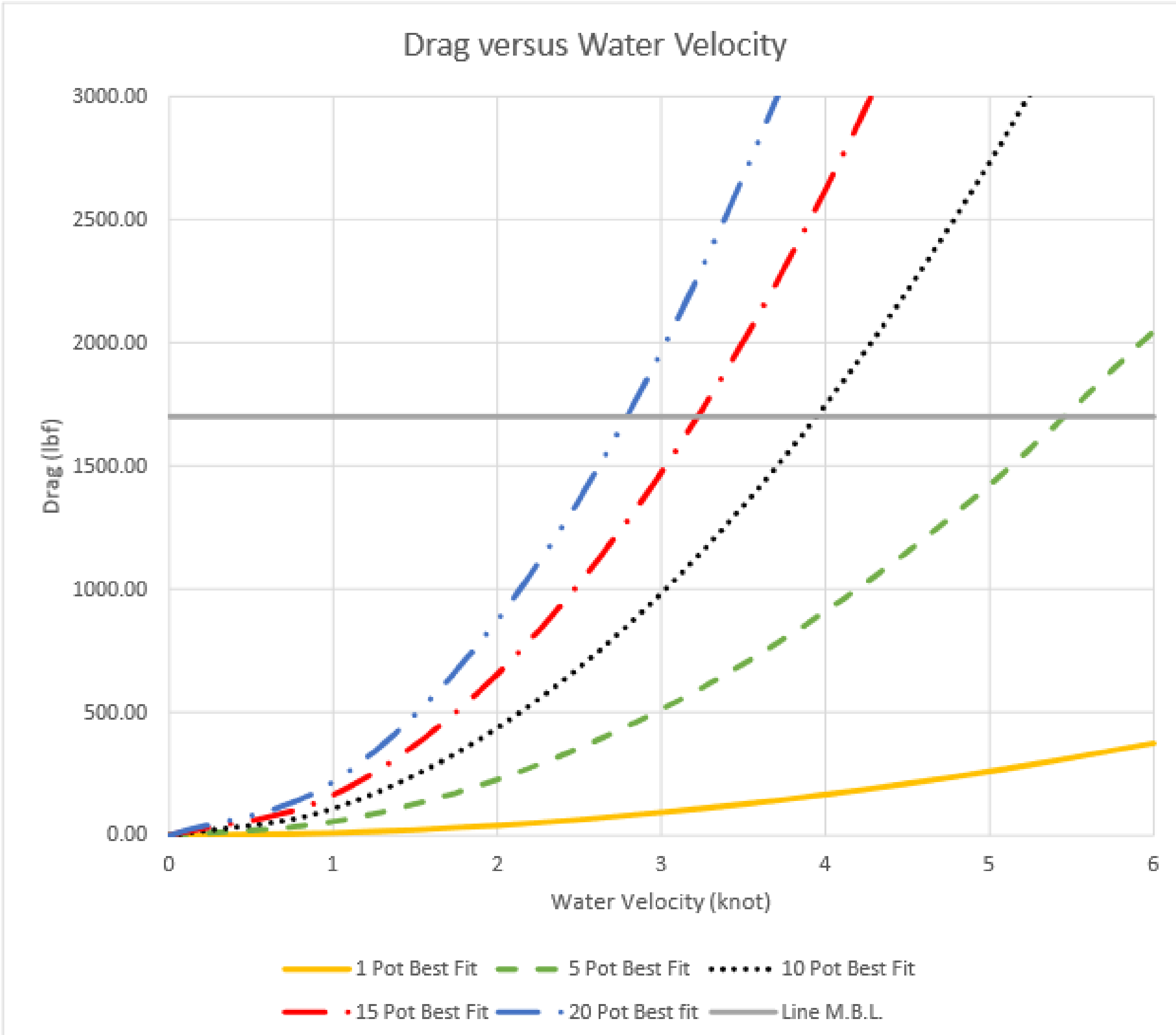

Figure 20. The velocity square best fit curves for a variety of lobster pot systems based on field data for a 1, 2 and 5 trap system and extended to longer trawls.

DeCew also tested a variety of dynamic parameters including:

Hauler speed (slow and fast)
Seafloor drag
Surface elevation (waves)
Combination of surface elevation & hauling speed
Combination of hauling and seafloor drag
Line stiffness

Although each of these dynamic parameters influenced line tension in various ways, the analysis that was most informative for this study was the comparison of surface elevation (wave height) and hauling speed. Using the baseline of three pots in the water column, two hauling speeds were calculated from the at-sea testing of 3.2 and 4.8 ft/s and used to compare the effects of different regular wave periods for a 3.28 ft (1 meter) wave height. Shorter wave periods will amplify the line tensions during hauling with slow hauler speeds resulting in maximum tensions of just over 600 lbf and high hauler speeds resulting in tensions of over 1,000 lbf (Figures 21 and 22).

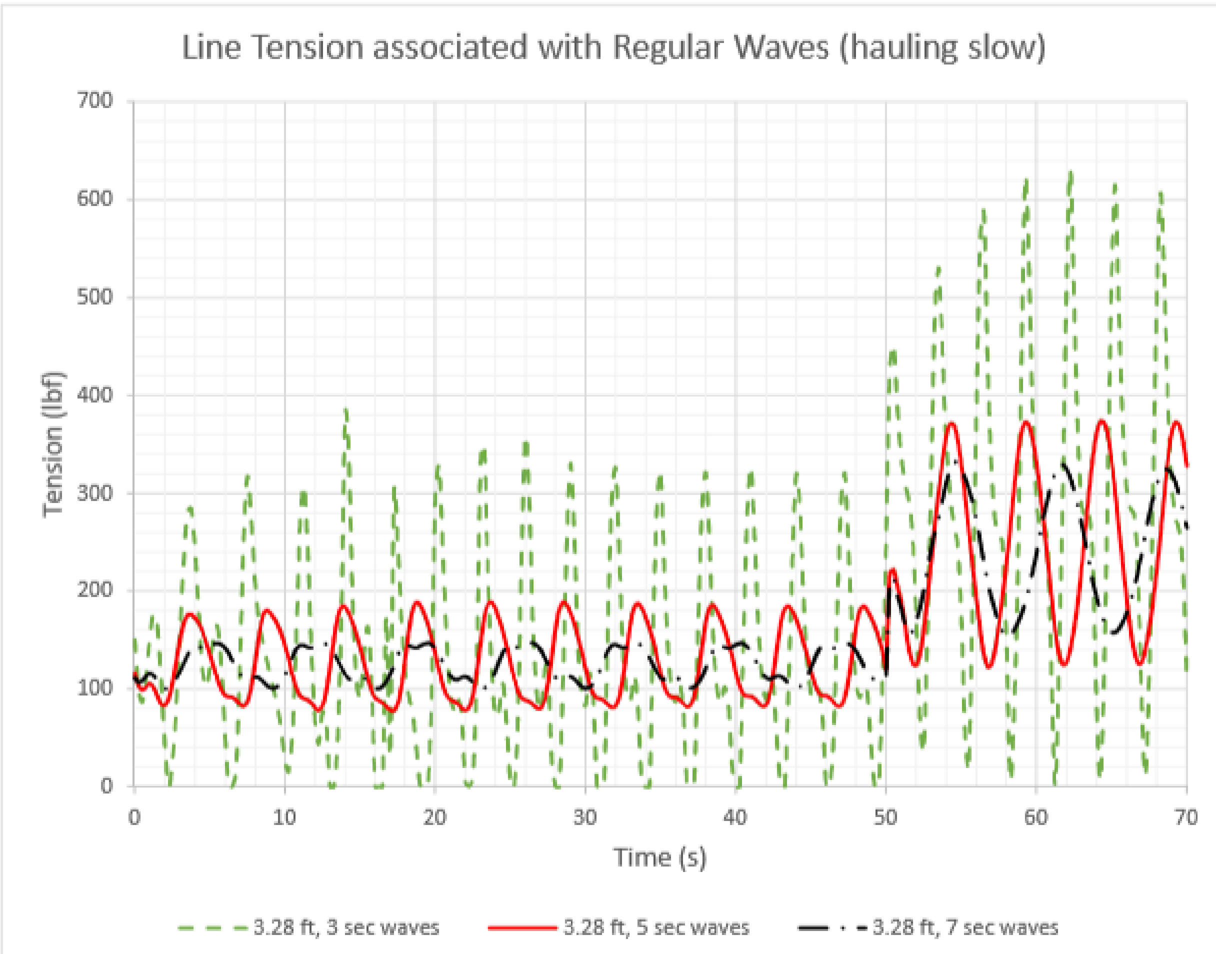

Figure 21. The line tension of the baseline system in regular waves of different periods, with slow (3.2 ft/s) line hauling beginning at the 50 second mark.

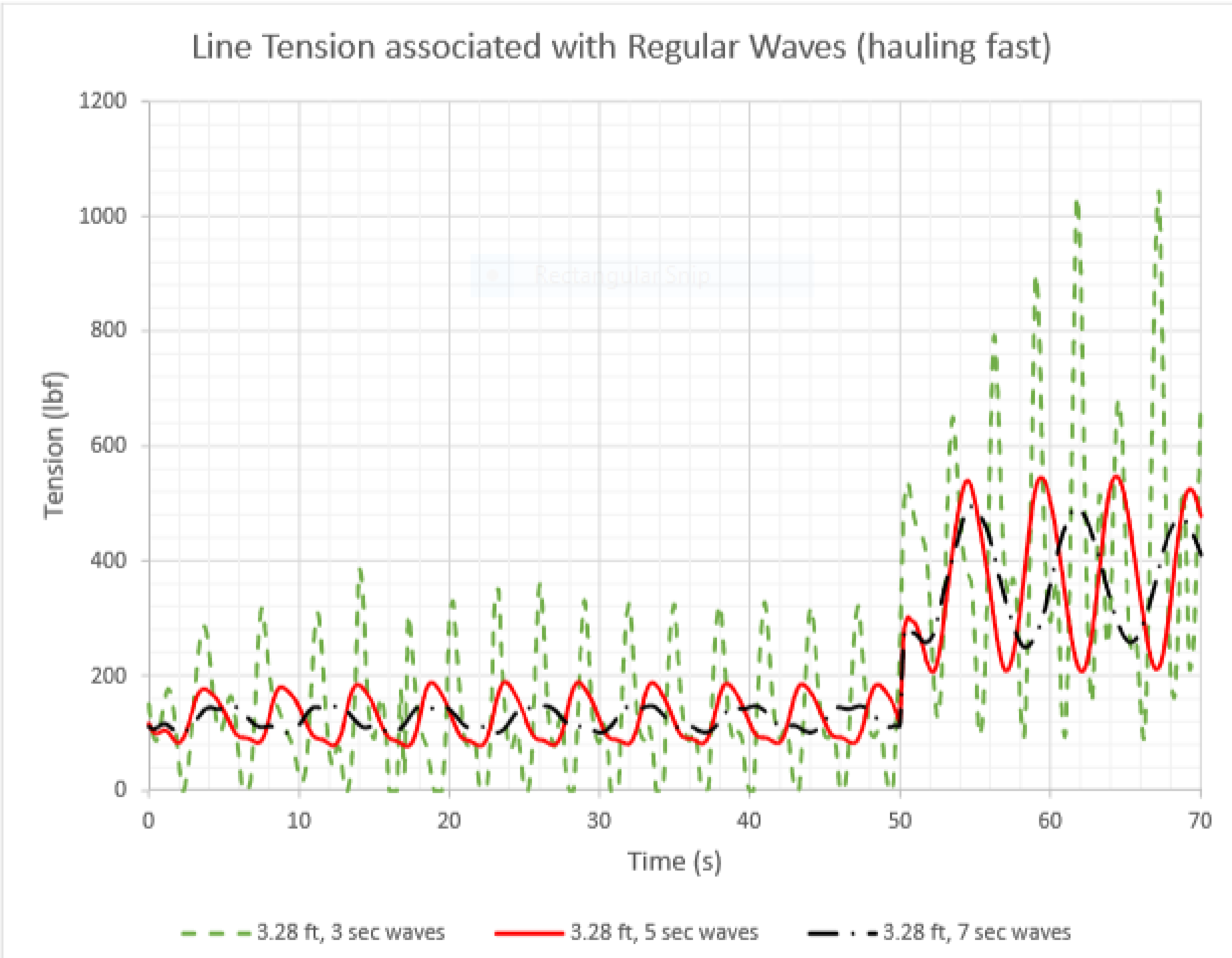

Figure 22. The line tension of the baseline system in regular waves of different periods, with fast (4.8 ft/s) line hauling beginning at the 50 second mark.

When slow hauling was simulated in irregular wave heights reaching 6.52 feet (2 meters), tension exceeded 1,700 lbs (Figure 23) indicating the rope would part in these high seas scenarios. Fast hauling was not simulated as fishermen told us that they reduce hauler speed in high seas.

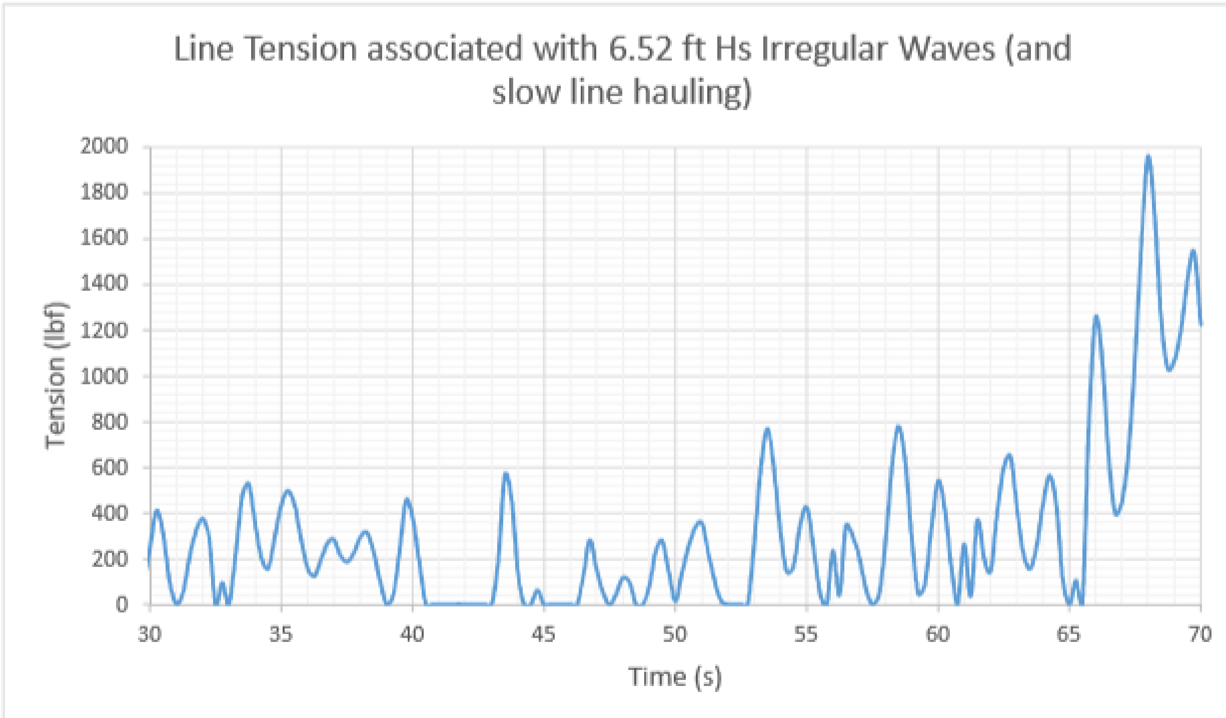

Figure 23. The line tensions as a function of time for the 6.52 ft irregular wave profiles with line hauling.

In summary, the analyses conducted by Dr. Jud DeCew show that there are many different variables that can influence the tension placed on endlines. Some of these scenarios simulated would lead to tensions that exceed the typical working loads which are recommended as 20% (340 lbf) of the mean breaking load of 1,700 lbf. However, the addition of a groundline extension to reduce the number of pots hanging in the water column and a reduction in hauling speed, especially in higher sea states, and efforts to keep the vessel over the top of the gear when hauling are all operational measures that could be used to reduce tension to be below the 20% working load. And if a whale did start towing gear (increasing water velocity on the gear is considered as a proxy), in many of the scenarios simulated, the 1,700 lbf load would be reached allowing the whale to break free from the gear.

SECTION 4: APPLYING COMPUTER SIMULATED ENCOUNTERS BETWEEN THE NARW AND POT FISHING GEAR

Background

Under the auspices of the Atlantic Large Whale Take Reduction Team (ALWTRT), NMFS has implemented several changes within Category I and II gillnet and pot fisheries targeting crustaceans, fish, and other invertebrates. These have included prohibiting the use of floating line at the ocean surface, time-area closures, mandating the use of "weak links" in buoy lines and net panels, requiring that lines tying strings of fishing pots together along the sea floor (groundlines) be negatively buoyant, and reducing the ratio of vertical lines to lobster pots ("trawling up") (*see* https://www.greateratlantic.fisheries.noaa.gov/protected/whaletrp/plan/index.html for a full list of regulatory requirements). Despite these mandated changes, the negative trends for the populations persist and these measures do not appear to have reduced the rate of serious injury to large whales (Pace et al. 2015). Some geographic areas are exempt from some or all of these measures. In particular, Maine's near shore lobster pot fishery is exempted from the sinking groundline requirement.

One challenge that members of the ALWTRT have faced in deciding on changes to fishing practices is the absence of controlled experiments showing whether or not proposed modifications to gear produce lower entanglement rates compared to traditional gear. Testing gear modifications directly with NARWs has not been possible for several reasons. Entanglements, while posing a serious threat to the persistence of the NARW, are relatively rare events, and observed infrequently. The species' low abundance prevents achieving a statistically valid sample size within a manageable timeframe. Furthermore, purposely subjecting a critically endangered population to potential risk of entanglement using experimental gear is inadvisable, and unlikely to receive an experimental permit from governmental agencies to carry out the trial. In the absence of structured experiments to test the efficacy of fishing gear modifications, deciding which of these to implement has instead been based on intuition or common sense using whatever information at hand. For example, the ALWTRT concluded that groundlines resting on the sea floor would be less prone to entangling large baleen whales swimming through the water column. Yet baleen whales, the NARW included, do come into contact with the seafloor as evidenced by mud on the upper surface of their rostra (Figure 24). This could indicate that sinking ropes fastened in-between multiple pots on the seabed do not eliminate entanglement risk by keeping them from floating up into the water column. The group also came to consensus on calling for the use of breakaway (weak) links tied onto the vertical buoy line, just below the buoy's lower end. These links, designed to break at a force that is dependent on the fishery and ranging from 500–2,000 lbf (NOAA 2010), were designed with the understanding that a rope entangling a whale would slide along its body until contact with the buoy was made, at which point the link would break and release the whale. After many years of incorporation into fishing gear off the eastern US, there is still no evidence that they work as envisioned, nor that they have contributed to reducing entanglement rates or severity. Although without these regulated changes to fishing gear even more entanglements may have resulted, no evidence exists to justify these changes that were formulated only from informed conjecture.

Figure 24. A NARW with mud on its rostrum. (Photo: NEAq).

If we want to break the cycle of advocating for changes to fishing practices that have consequences to the industry yet have as much chance of benefiting whales than random changes alone, clearly a different strategy is needed. Recognizing this need, the New England Aquarium-based Consortium for Wildlife Bycatch Reduction carried out a study that combined analyses of ropes retrieved from entangled whales off the eastern US and Canada with life history information on the whales involved, and including additional information on entanglement complexity with the outcome of the encounter. The study represented an alternative approach to field testing gear modifications as a way to identify any trends that might suggest scientifically-informed gear modifications. The resulting publication revealed that ropes with a breaking strength higher than 1,700 lbf were more likely to lead to life-threatening entanglements of large whales (Knowlton et al. 2016).

In parallel, scientists at the NEAq initiated a collaboration with an engineer at Duke University and BelleQuant Engineering, LLC, to develop a computer model capable of simulating encounters between a NARW and fishing gear and using it as a platform to study the dynamics of whale entanglements and test entanglement scenarios involving ropes with different tensions as well as other gear modifications (Howle et al. *in press*). In this study, we used the Virtual Whale Entanglement Scenario (VWES) program to compare line tensions recorded from different entanglement scenarios. The purpose of this study was to see if the data provide supporting evidence for using buoy lines of reduced breaking strength to facilitate whales breaking free of entangling ropes.

Materials and Methods

The programming code for the VWES model was written by Laurens Howle of BelleQuant Engineering with grant support from NMFS to the Bycatch Consortium and BelleQuant Engineering, and private donations to the NEAq. T. Werner of the NEAq conceived of the project and provided advice and guidance into that capabilities required, including information on fishing gear characteristics and configurations. S. Kraus (NEAq) and D. Nowacek (Duke University) contributed input into swimming behaviors and other biological information used to develop the whale model.

The programmable interface for the model (API – Application Programming Interface) selected was the XNA 4.0 Game Studio Programming package, which is capable of incorporating the different graphics and physics program applications with the unique code written by L. Howle in C#. Additional advantages include its ability to incorporate MS Windows operating instructions with manipulation using an XBOX controller. The whale was developed initially as a 10m-long wire mesh model using Lightwave software system (LightWave 3D), drawing from the basic body plan for a baleen whale. This model was then refined and scaled from necropsy and photogrammetry measurements of NARWs (Nousek-McGregor 2010) using Blender software. To animate the whale, a skeletal rig was produced again using Blender software, and skin mesh vertices were assigned to move with appropriate mathematical weights in reference to up to four of the skeletal bones. These skin meshes change form based on swimming behavior made either in response to manual control using a XBOX Game Controller (wired version) or from programmed swimming behaviors. Howle programmed in a constraint to the whale’s tail-beat frequency, amplitude, and swimming speed based on a well-established relationship between these variables under propulsion in a marine medium defined as the Strouhal number, defined as:

$$St = \frac{fA}{U}$$

where f is the tail-beat frequency, A is the peak-to-peak tail motion amplitude (the peak-to-trough vertical excursion of the tail trailing edge), and U relative speed between the animal and the fluid.

Based on peak efficiency values from the literature for swimming animals, this value was held constant at 0.3. In addition, pectoral flippers become arranged in the proper position relative to the whale body/skeletal rig based on the swimming direction input by the user. For example, a rolling motion causes the flippers to pitch in opposite directions. The types of swimming behavior and whale articulation was programmed based on input from whale scientists (S. Kraus and D. Nowacek), with the range of movements summarized in Table 4.

Table 4. Current NARW movements recreated in the VWES model. An "X" denotes where the model can presently recreate the associated movement.

Movement	Manual control	Programmable for automated model runs
Forward movement	X	X
Tail fluke swimming motion (vertical)	X	X
Pectoral fins: forward-back sweep	X	X
Pectoral fins: tilt angle	X	
Full body roll	X	X (default away from rope)
Ascend / Descend	X	
Turn left/right	X	

The fishing gear incorporated into the model is based on lobster pot gear commonly used off the northeastern US (McCarron and Tetreault 2012). The configuration has a vertical buoy line extending down to one or more weighted traps (Figure 25). In the fishery, these may be anchored or attached to an adjacent trap by a rope known as a groundline. Lobster fishermen may fish with one pot ("singles"), two pots ("doubles"), three pots ("triples"), or many additional pots, such as in deeper offshore environments where 30 or more pots in a single string may be fished. Three or more traps connected by groundline is referred to as a "lobster trap trawl" (Figure 25), which may use one or two buoy lines depending on the number of connected traps. In much of the eastern US, the upper one-third of the vertical line consists of sink rope, whereas the lower two-thirds is float rope.

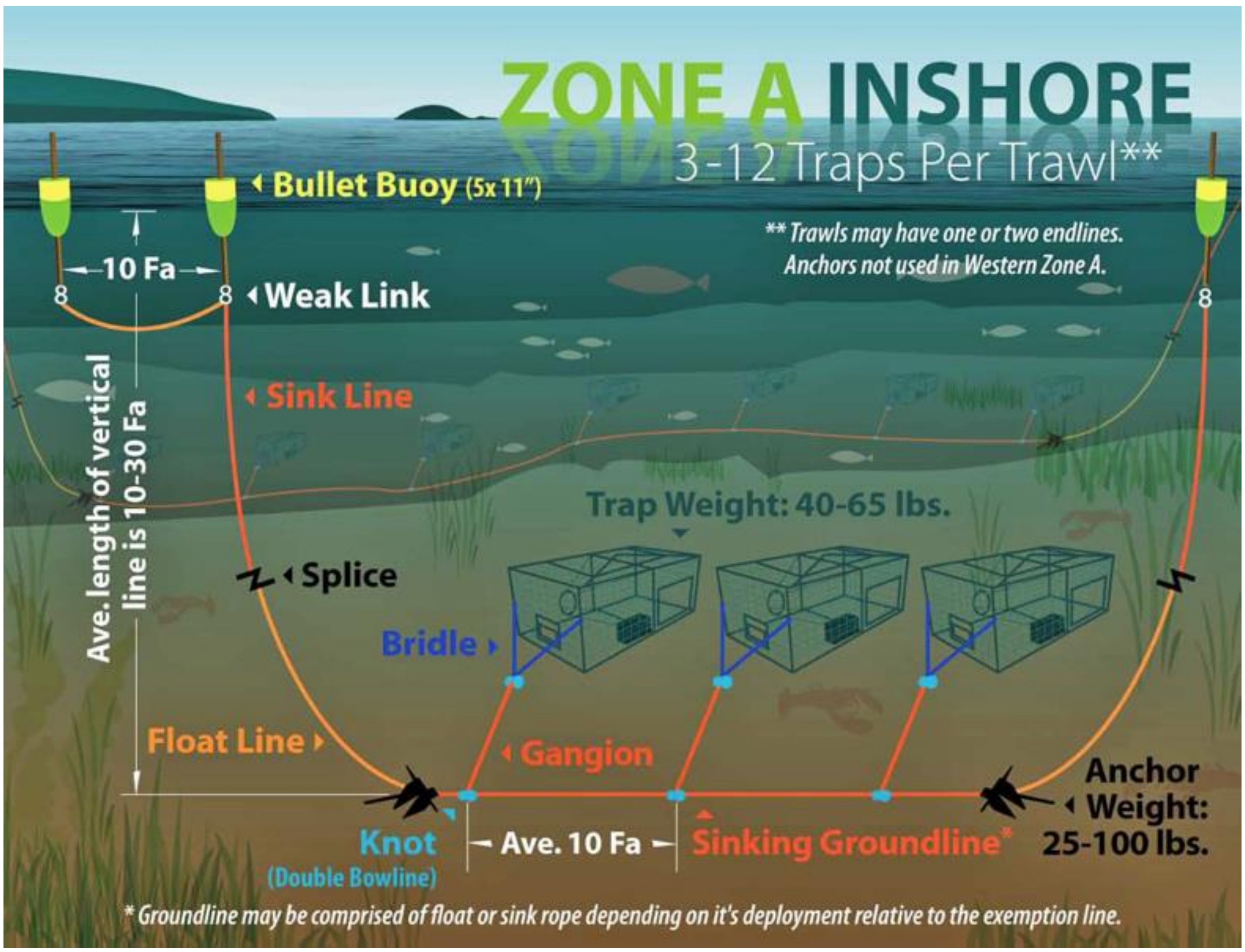

Figure 25. An illustration of a lobster gear configuration in the Gulf of Maine (Zone A Fishing Zone). There may be more than one endline (buoy line) on a lobster trawl, typically when the number of pots reaches five or more, but sometimes fewer. Fa = fathoms. (Illustration from McCarron an Tetreault, 2012).

The main source of entanglement in crustacean and fish pot fisheries in the northwest Atlantic is the rope, and because regulators in the US now require much of the northeast coast fishery to use sinking groundline that rests on the seafloor, the focus here is on evaluating entanglements involving the vertical buoy lines. The rope model used in the VWES is a chain of rigid bodies (Servin et al. 2011), in which the continuous rope consists of capsule shapes connected to one another by virtual springs. In this rope model, forces can be transmitted across each link which facilitates collision detection calculations. One limitation of this model, however, is that as these forces become too large, the dynamic rope response became unstable. As a result, under certain conditions the rope can "tunnel" its way through the body of the whale, rendering subsequent calculations inaccurate and impossible to record. This can be controlled under the current version of the simulator by not imposing large loads on the rope, which is influenced primarily by swimming speed and the number of pots selected, that equate to the drag force of the pots being pulled by the whale.

The rope diameter in the simulator is 1/2 inch. Although this is a slightly larger diameter than that used by most pot and gillnet fishermen off the eastern US, it does not affect scenario outcomes nor the measurements of rope tension. The forces exerted on the rope are the same regardless of diameter. However, larger diameter ropes of the same material, construction, and condition as those with smaller diameters would require higher loads to part them.

In the VWES model, the vertical rope is partitioned into two separate pieces. The upper 1/3 is sink rope, and has a specific gravity of 0.9, and the lower 2/3 of the rope is positively buoyant, with a specific gravity of 1.1. These portions of the rope can be visually distinguished in the simulator graphics, with the sink rope colored red and the float rope yellow (Figure 26). A rope bridle attaches from the trap to the vertical line.

The rope profile is not perpendicular to either the plane of the seafloor nor the surface of the water. It was intentionally modeled to remove any slack in the line, based on observations that northeast lobster fishermen reported to two authors of the Howle et al. (*in press*) paper (Howle and Werner). During the design phase of the model, a slight current was introduced with a heading into the swimming trajectory of the whale, to prevent slackness in the line. These settings were then used to "freeze" the rope configuration at this setting for the starting point of any simulation. This produces a slight curvature in the rope such that the lowest floating rope portion of the buoy line extends away from the vertical axis of the buoy. Essentially, the rope forms a right triangle with the 90-degree angle occurring between the horizontal plane of the seafloor and an axis running vertically up to the whale, and the rope forming the hypotenuse but in a catenary formation. Running simulations without using this preset initial starting configuration would require approximately two minutes of run time for the rope to form this pattern at the outset of each simulated run. Once contact is made between the whale and the rope, this pre-set condition is relaxed so that it does not affect model outputs.

The simulator uses scaled models of 40 lb rectangular lobster traps (pots) measuring 36 ´ 24 ´ 14 inches, with a 1/2-inch diameter becket connecting to the 1/2-inch diameter floating buoy line. The surface buoy consists of a 6-inch diameter poly ball. The length of groundline between pots is 5 m.

For the focus of this study, the most critical measure is how hydrodynamic drag translates to rope tension. Hydrodynamic drag on a length of rope is a function of its length, diameter, fluid viscosity, the direction of flow with respect to the longitudinal axis of the rope, which are proportional to the square of the flow speed. The VWES model used the following equation to calculate an angle-dependent drag coefficient:

$$C_D(\alpha) = 0.688 + 0.544\cos(2\alpha + \pi)$$

where $\alpha = 0$ in the case of no flow and $\alpha = \pi / 2$ is for the area calculated as the product of the rope segment length L and diameter D (based on Fridman, 2008). VWES simulations use this equation for calculating drag on each rope segment. Howle et al. (*in press*) provides more detail on the development and details of the VWES model.

Tunneling

Examples of thresholds at which tunneling occurred include using the parameters in Table 5 each based on 10 scenario runs. The results suggest that maximum swimming speed and number of traps can be selected in simulation runs without incurring tunneling, provided a minimum column height of 25% is used. To avoid tunneling, the simulation run with a two-pot configuration used a maximum velocity of 1.6 kts.

Table 5. Summary of model parameters that in multiple runs (>3) determine whether or not tunneling occurs. (1N = 0.224809 lbf; 1 knot = 0.514444 meters/second).

Number of traps	Swimming speed (knots)	Column height (%)	Result
2	1	10	Tunneling in all interactions
1	1	10	Tunneling in interactions when trap suspends in water below whale body
1	1	20	Tunneling in some interactions
1	1	30	No tunneling
1	1	25	No tunneling
1	2	25	No tunneling
2	1	25	No tunneling
2	2	25	No tunneling

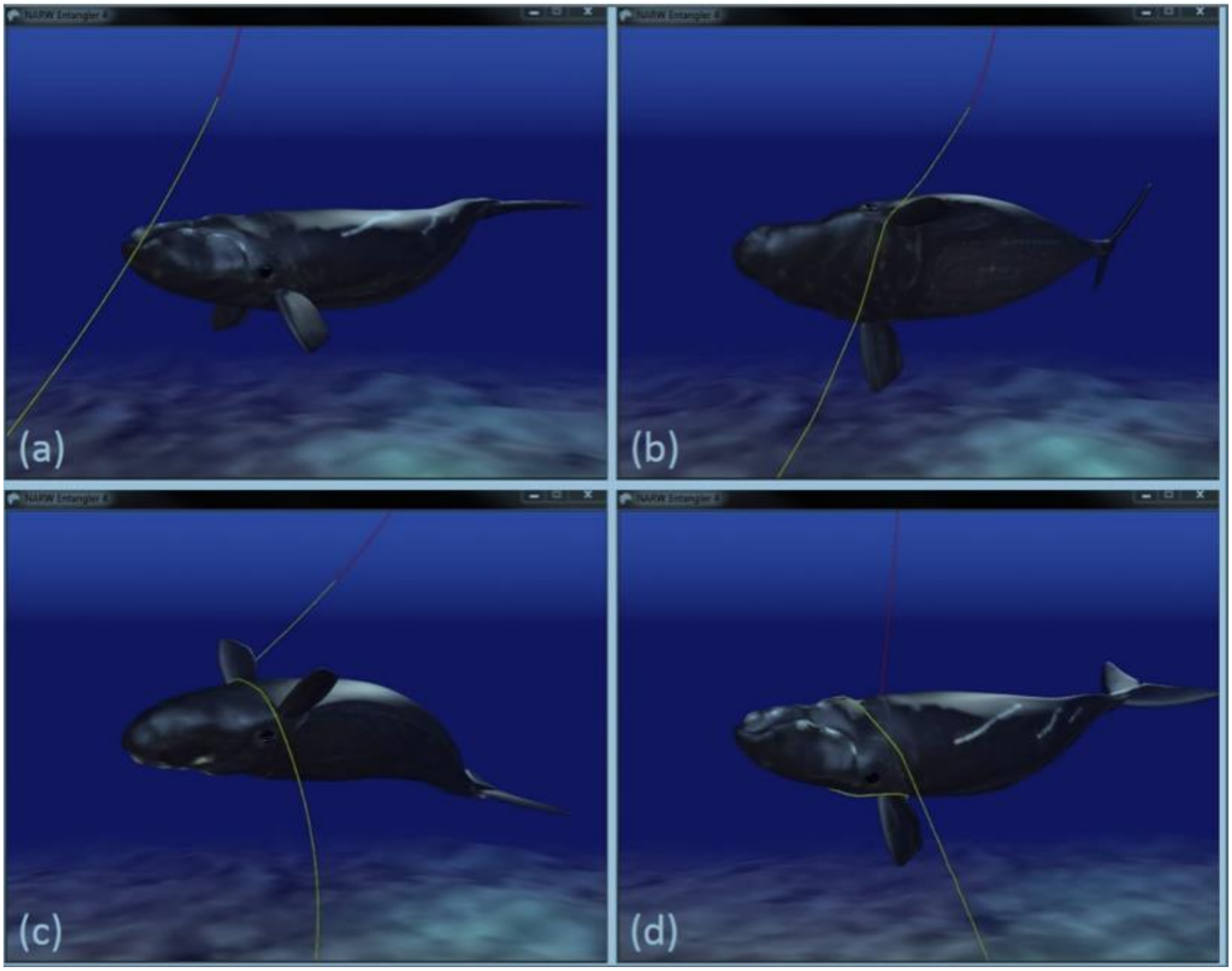

Figure 26. An example of the graphics depicted during a whale entanglement using the VWES model, and demonstrating the rolling behavior. The red portion of the rope is the upper sink rope. In (a) the whale approaches the rope and will initiate rolling behavior upon contact; (b) the whale begins to roll away from the rope that is becoming lodged in the attachment point of the left flipper and main body; (c) the whale continues to roll with its dorsal side facing downward; (d) the whale resumes swimming in an upright position with the rope attached. (Images from Howle et al., in press).

Additional settings used in the model are described in the appendix.

Analysis

Multiple Monte-Carlo runs were carried out on three different scenarios involving different combinations of swim speed and trap number (Table 6). The simulator can model encounters using a maximum of five pots and two knots, as well as at different water column height, but a series of trial simulations showed that altering column height or increasing either the velocity or trap number in Scenario 3 led to tunneling. Tunneling produces false reading, rendering the outputs not subject to analysis of rope tension.

Table 6. The scenario settings used in this study. All other values were as reported in the text or from default settings.

Scenario	Swim speed (kts)	Number of traps
1	2	1
2	1	2
3	1.6	2

Increasing the number of traps and velocity both cause higher rope tension and drag (see *Discussion*). By altering these inputs, we can examine how the levels of tension relate to the ability of a rope to generate the force needed to part the rope at a particular threshold of rope breaking strength, and how these compare with configuration of pot gear used where NARWs occur.

The three scenarios selected had the whale contact the rope on the side of the head in front of the flipper and approximately at the halfway point between the tip of the head and the flipper. This was created by setting the lateral offset to 0.2 m and the trigger distance to 1.4m. Having the head as the initial contact point with the rope is based upon a suspicion among several experts in NARW entanglement events that many entanglements of long duration are initiated as contact with the head region. The behavior upon contact used for these scenarios was rolling away from the rope. Observations involving right whale-rope encounters have not been recorded, but one involving a humpback whale did show that the animal rolled in a direction away from the rope (Weinrich, 1999). Frequent anecdotal reports from the west coast of the US also report similar behavior between humpback whales and kelp stems. Furthermore, previous simulated encounters using the VWES were able to recreate the types of entanglement gear configurations observed on right whales as documented by disentanglement responders when this rolling behavior was used (Howle et al. *in press*), so there is strong evidence to indicate that it is among the behaviors that individuals of this species use upon sensing the presence of a rope on their bodies. For the purposes of this study, the more critical factor is that this behavior causes the rope to become lodged on the body so that measurement of rope tension from a whale towing gear can be calculated.

VWES outputs the data into .txt files that were converted into Excel for analysis, with values rounded to the nearest one. A Kruskal-Wallis test (McDonald 2009) was performed on the first 35 runs of each scenario using MS Excel (Version 15.25.1 for Mac 2016). In the model, rope tensions are recorded every 0.01667 seconds and the total time for each run of between 55 and 110 seconds, depending on the velocity, meaning that calculations were compiled from a maximum of over 9000 readings per run. Values recorded in the thousands (Newtons) were removed from the data set if they occurred at only one timestamp, likely indicating that they were produced owing to model instability than an actual value. It was far more credible when these peak values occurred in association with higher values than as quick spikes within a series of lower ones.

Results were compared with observations in a study by DeCew (2017) that measured rope tensions in lobster gear using *OrcaFlex* software.

Detection of Tunneling in the Data Output

The simulation run timer allows the user to observe the time at which tunneling occurs by looking at the data at the time in the run when tunneling is observed in the graphic display. In a tunneling event, the data output file shows that data stops recording even though the simulation run continues in the graphics window. This is visible as two blank rows in the Excel spreadsheet after the tunneling event occurred before the run was completed, followed by the data for the second simulation run. In contrast, examination of the data table for a partial gear shed, such as when the rope slipped over the top of the head but remained attached to the flippers and main body, only registers as significant reduction in the number of rope contact points. Output data files were examined to identify any tunneling events that may have occurred.

Results

The results showed a highly significantly difference between the average loads produced under each scenario ($p<.00001$) (Table 7).

Table 7. Results of Kruskal-Wallis Test on three scenarios. N = number of data points.

SCENARIO	N	Mean Rank
1	115728	19753425801.5
2	227121	57248718332.5
3	147249	43063118793.5
TOTAL	490098	

H = 48251.24

Df = 2

The VWES model correctly showed increasing loads under scenarios that had comparatively greater bottom weight (2 traps versus 1) and higher swim speeds. Although at first glance the lower mean rank of Scenario 3 over that of Scenario 2 may not seem consistent with this trend, the higher number of data may explain this higher than expected average, seeing as the Kruskal-Wallis test appears to give higher rankings with more data present.

A previous analysis of the same data set by Werner (2018) examined the average of the highest loads recorded for each of 65 runs under the three scenarios. In that data set, any reading of 50,000 N was excluded from the data used in statistical comparisons. For Scenario 1 there was one single reading of 50,000 N deleted from the data. With Scenarios 2 and 3, there were 49 and 98 records of 50,000 N, respectively. Excluded from these totals are the several continuous readings of 50,000 N for one of the runs in Scenario 2, which caused that run to end prematurely before initiating the next run. Except for this instance, all were single measurements at one-time stamp; values preceding and following this value—except in the instance in which it was repeated for multiple timestamps and did not return to normal recording mode—were two orders of magnitude lower, and showed no wild fluctuations in value thus showing that the model returned to a steady state.

Table 8 lists the maximum values recorded during the first 65 runs for each scenario. The two scenarios with two pots had higher maxima than the first scenario with only one pot, even though the latter was run with a swimming velocity of 2 knots.

Table 8. Maximum values in ascending order recorded for 65 runs of each entanglement scenario, in Newtons (N). The threshold breaking strength for new 1,700 lbf rope is 7562 N. Maxima greater than 7562 are in bold font.

Scenario 1 – One pot, 2kts		Scenario 2 – Two pots, 1kt		Scenario 3 – Two pots, 1.6 kts	
34.40	101.90	141.11	578.85	144.85	1372.34
83.44	102.88	149.38	587.49	164.59	1449.17
84.62	109.20	151.80	595.77	190.49	1520.99
86.19	115.87	153.57	643.80	201.35	1570.28
86.20	119.88	154.52	675.28	251.86	1570.28
86.54	134.84	162.42	678.66	274.09	1836.38
86.66	138.57	170.23	785.11	279.59	1981.09
87.21	143.94	171.46	795.69	311.02	2081.08
87.38	146.50	173.17	827.65	314.69	2177.34
87.50	150.33	208.67	865.37	350.77	2458.55
87.74	154.07	217.25	886.50	404.55	2630.98
87.79	155.22	224.81	908.29	423.83	2639.43
88.28	160.28	232.09	910.37	434.85	2787.16
88.38	172.67	241.84	997.98	446.74	2807.01
88.81	180.83	252.97	1142.67	450.50	3025.90
88.82	193.76	253.04	1229.96	453.45	4979.96
89.20	199.84	268.31	1287.52	468.22	6369.40
89.28	230.36	271.24	1477.32	487.42	**7743.97**
90.07	255.09	307.00	1668.88	518.29	**7884.01**
91.99	306.07	321.23	1710.28	548.02	**8103.15**
93.19	390.12	323.86	1854.81	589.77	**9158.71**
94.10	427.26	355.50	2,102.14	593.11	**10,102.18**
94.41	460.76	415.37	2,181.54	598.25	**10,326.96**
94.48	480.45	421.56	2,806.58	639.47	**11,239.58**
94.56	538.30	424.94	3,124.77	646.77	**22,577.13**
95.34	807.45	442.62	3,350.16	652.56	**24,641.69**
96.59	956.19	473.10	4,130.33	656.54	**31,339.46**
96.90	3,164.64	494.20	4,649.23	688.74	**31,575.80**
97.00	4,906.82	494.58	5,037.25	692.49	**34,515.76**
97.29	7,293.48	509.92	**7,684.79**	922.60	**34,705.62**
99.00	**18,564.32**	544.11	**7,684.79**	935.53	**39,007.35**
99.20	**22,894.77**	548.64	**41,891.44**	1137.28	**42,040.54**
99.49		570.19		1257.89	

For these data, a one-way ANOVA and a Tukey-Kramer post-hoc pairwise mean comparisons resulted in significant statistical differences between mean maxima. The spread of data showed that most of the higher loads were recorded in Scenario 3, and the least in Scenario 1.

In combination, the results from this study and the previous study indicate that higher tensions are produced by increasing the number of pots in the water column, and by increasing whale speed when the weight of the bottom gear is the same.

Visual observation of the data showed no instances of tunneling, nor any evidence in which the gear was shed from the whale. Close to the end of some runs during Scenario 3, however, the buoy would often descend below the virtual surface of the water, and the line would slide slightly under the whale's ventral side. For the cases in which this was observed, the progress of the slide was exceedingly slow such that no gear was ever shed by the end of any run. If the run were to continue for longer, the gear eventually might have been shed by the whale.

Discussion

Two conditions need to be met if ropes of reduced breaking strength are to become a viable option in some US fisheries. First, they need to result in a sufficient number of whales breaking free from entangling gear before serious injury occurs (i.e., a degree of injury that leads to death or has sub-lethal effects that affect survivability in the long term or fitness). Second, they need to be practical for fishing, meaning that bottom set gear can be set reliably and not lost more frequently than it is presently as a consequence of extreme weather or oceanographic events, or from conflicts with other fishermen or vessel traffic; that it can be retrieved reliably without more frequent rope partings; and ropes need not be replaced more often than ones currently used.

Drag forces on hauled lobster pots of approximately the same size and weight as the ones in the VWES model were calculated by DeCew (2017), based on a drag coefficient from Baldwin and Pickett (2009) and factoring in actual load cell readings of hauled lobster pot gear (NEAq, *unpublished data*). The equations he determined for calculating line tensions were:

$$T = 10.42 \times U^2 \text{ (for one lobster pot)}$$

$$T = 21.8 \times U^2 \text{ (for two lobster pots)}$$

where T is the line tension in lbf, 10.42 and 21.8 are constants, and U is the water speed in knots. Water velocity can be measured either as the flow of water into a static trap and line in the water, or, in this case, the velocity of the trap and line moving through water as it is being hauled. Although the DeCew (2017) study evaluated the potential of other factors such as trap friction along the sea floor surface, these were found to be negligible in terms of their numeric influence over drag forces. The calculation for drag force is similar to that used by VWES, where

$$T = 9.24 \times U^2 \text{ (for one lobster pot)}$$

so the results from the simulator can be used to compare outputs from DeCew (2017) modeling of rope tensions.

Figure 18 shows that rope tensions for the “lighter” gear conditions used as part of these scenarios will tend to be low as with the low averages recorded during the runs in this study. One difference however is that in the VWES the hauling force is not exerted from a fixed point at the ocean surface as it is in the DeCew model, but instead produces drag from bottom gear and the surface buoy. The physical loads on the ropes in the VWES model incorporate drag from the surface buoy, which would tend to make tension readings higher than what we might expect using *OrcaFlex* calculations. Furthermore, the hauling force in the *OrcaFlex* model is far less dynamic than a moving object with variable motions in the water column, especially when it is as large and powerful as a whale, and the next phase of this study will involve a way to more conclusively distinguish high loads recorded as a result of model instability, and those that may be recording values that could eventuate from a whale exerting force on a rope under even lighter gear conditions. Conceivably, whale swimming patterns would not only produce different degrees of pull on dragged gear, but also might be recorded as sudden high or low values depending on how well these movements were in synchronicity with slack or tautness in the line.

While the focus of the VWES is on understanding dynamic forces associated with whale entanglements and the *OrcaFlex* study on static rope tensions while hauling lobster gear, the two can be considered together to address the question of whether ropes of reduced breaking strength can be weak enough to facilitate whales breaking free from them while being strong enough for fishing. First, the model performed predictably well by producing consistently higher loads with increasing weight of bottom gear and swimming velocity. Second, the previous study looking at the maximum load values recorded suggested that whales can frequently produce the kind of forces that exceed the 1,258 lbf (76% of 1,700 lbf) breaking strength target, although subsequent analysis needs to confirm whether these values were measured within the normal constraints of the model or if they resulted from model instability. Values in excess of the 1,258 lbf threshold were generated with relatively high frequency, particularly when the weight of gear and velocity increased, which is what would be expected based on the physics of hydrodynamic drag. This occurred even with a speed of 1kt, which does not account for any thrust or thrashing force that the whale might exert once entangled, but only by forward motion. By contrast, Figure 19 shows that even a 20-trap trawl in two knots of current would not attain the breaking strength threshold for “whale-release” rope. Two knots of current may be high for fishing gear, but probably not excessive for whale swimming speed or the short bursts of thrashing that probably occur when a whale becomes entangled. Although there are no precise measurements of the velocities produced by NARWs including from short bursts of energy, even whale cruising speeds can exceed this velocity. NEAq scientist P. Hamilton observed a single NARW that went from Cape Cod Bay to Georgia in as little as 11 days, which would give its average speed as 4kt, and another NEAq scientist D. Pendleton reported a whale traveling horizontally for a short distance in the Bay of Fundy at 8 kts. In fact, for a 20-pot trawl, the water velocity would have to approximately 2.2kts before the threshold for whale-release rope would be met.

The results from these models considered together suggest that under typical hauling conditions, a rope of reduced breaking strength should hold up well to fishing except perhaps for extremely heavy gear of 30+ pots or more, whereas in the event of an entanglement these preliminary analyses suggest the forces generated should be higher than typical hauling conditions.

There are several caveats that need to be pointed out. The obvious one is that any model cannot account for all the variables that go into approximating real-life situations. Equally important, the lack of observations about how whales become entangled means our understanding about the dynamics of entanglement events are still lacking. Nevertheless, gear is observed to become secured to whales, and in those instances the VWES model should provide a reasonable approximation of the forces generated.

One characteristic of whale entanglements that cannot be treated by the VWES model, at least as it is currently coded, is the cutting effect of ropes into the body tissue. Lacerations are frequently observed in entangled whales from ropes cutting into them. For the purposes of this study, the focus was on evaluating whether or not the forces generated during an entanglement might be high enough to part the rope, with an assumption that entanglements of shorter duration will not produce the severe injuries that they often cause. Woodward et al. (2006) constructed an apparatus that created an oscillatory motion of ropes along the leading edge of a right whale fluke submerged in seawater. They ran 3/8” ropes consisting of polypropylene (float) and polypro/polyester (sink) over a preserved right whale fluke and showed that increased tension from a 9kg weight suspended by the rope versus one of 4.5 kg, produced furrows 0.40cm–0.27cm deep, respectively. However, these furrows did not extend beyond the epidermal layer. A later experiment using the same apparatus but modified to create a continuous loop for the rope to abrade body tissue from a humpback whale fluke and a right whale flipper, showed that thinner diameter ropes led to more severe abrasions (Winn et al. 2009). In this latter study, the authors mentioned that less whale oil on the skin's surface might increase friction and be a factor that influences the severity of lacerations. During the VWES Scenario 3 runs, the upper portion of the rope (the buoy end) was observed to slide along the ventral portion of the whale, which might cause the types of injuries reported in the lab experiments, but this would depend on the drag force of the gear and friction along the body's surface.

Considerable refinements to the VWES model should improve its utility to understanding the dynamics of entanglement events and in evaluating gear modifications. At the moment, it does not have an open mouth capability, yet many entanglements are recorded as ropes lodged in the baleen either alone or in tandem with other body wraps. Once the "startle response" is enabled, the model can test the response time of whales to earlier detection of ropes in more visible color spectra based on work carried out by Kraus et al (2014). Another study might look at the probability of different outcomes based on where the whales encounter the gear (i.e., at the surface or deeper in the water column). This is especially relevant seeing as NARWs are frequently entangled whereas the rates for Southern Atlantic right whales (*Eubalaena australis*) are virtually non-existent off the coast of Australia, which may have something to do with that region not being a feeding area (Groom and Coughran, 2012).

Further development of this modeling tool is one way to help eliminate the enduring challenge of coming up with gear modifications that are based on better scientific justification, and therefore have a higher probability than chance alone of meeting their intended benefits. The urgency comes at a time when the NARW is on the brink of extinction, and alternative measures may either never achieve the political support required to become implemented, fail to produce their intended outcome, or be so draconian that they threaten the continued livelihoods of lobster and gillnet fishermen in the eastern US, Canada, and in other parts of the world.

SECTION 5: CONCLUSIONS AND NEXT STEPS

The funding provided by the Office of Energy and Environmental Affairs to the Anderson Cabot Center at the New England Aquarium has allowed for an extensive assessment of the development and use of 1,700 lbf rope strength to lower the risk of lethal entanglements of right whales. It supported investigation of a concept for using a 1,700 lbf rope from manufacturing and computer modeling of fishing and whale interactions, to evaluation in the field with fishermen.

The most challenging aspect of this study was identifying manufacturers committed to producing prototypes according to specifications. Several ideas for prototype development were tried but the only successful option deemed to be suitable for testing at sea was the hollow braided *Novabraid* sleeve developed between several members of the South Shore Lobster Fishermen's Association and rope manufacturer Novatec Braid Ltd.

During at-sea testing of the braided sleeve rope there did not appear to be an increased rate of breakage in endlines where sleeves were integrated as compared to the control endlines. In addition, at-sea use showed minimal loss of breaking strength and the potential for most sleeves to be used for multiple seasons. Some participating fishermen expressed concern about the time involved in integrating sleeves into the endlines, although with a small degree of practice it takes typically less than 5 minutes per sleeve. Some fishermen have questioned whether it would be possible to integrate the sleeves during the rope manufacturing process, a suggestion worth exploring with manufacturers.

Encouragingly, the results of our study did not indicate that use of these ropes would lead to more gear loss. Gear loss is a common occurrence for the commercial lobster fishery and many often report it as a result of vessel traffic in the area or during hauling when gear gets hung down by rocks or being set over by other fishermen's gear.

The modeling of tensions placed on gear during hauling showed that the tension placed on these endlines will be most affected by the amount of weight (# of pots) in the water column at a given time which is a variable that can be controlled by fishermen if they were to consider modifying their trawls and adding a groundline extension between the first and the second pot. In most areas of the Gulf of Maine, regulations require fishermen to use sinking groundline for minimizing large whale entanglement risk. These ropes typically have an equal or higher breaking strength than endlines currently used. By using a 1,700 lbf endline to get their first pot on board, this groundline extension could help reduce the tension on the endline dramatically, especially as water depth increases. Sea states, hauler speed, and water velocity also greatly influence these tensions, but these loads can also be minimized by adopting practices that include slowing down hauler speed in high seas, and keeping the vessel over the top of the gear as much as possible during hauling.

Although gear may part more on those rare occasions that gear is hung down when caught on rocks or laid over by someone else's gear, two fishermen from the SSLFA noted that they prefer their rope to part in these scenarios rather than potentially damaging their hauling system by putting too much force on it. There may be other benefits to fishermen when using 1,700 lbf endlines that we could not assess with this study. One benefit might be that if a whale gets entangled in an endline, if they cannot break free quickly, it can often get wrapped up in the entire gear set and carry a portion of the bottom gear with it as it struggles to get free. This would result in a fisherman losing some or all of their bottom trawl especially if the whole gear set is dragged some distance. If the endline parts quickly, it would greatly reduce the chance of this gear being lost.

Sleeves appear to be a viable, relatively low cost option that could be implemented without requiring the replacement of all ropes as was required when lobster fishermen converted to the use of sinking groundlines. Sleeves could also serve another purpose if they could be used as a gear mark (NOAA Fisheries requires gear to be marked 3 times within an endline with a color specific to fishery type and region). The sleeves were developed with fishermen and so far appear to be the most cost-effective and practical option for a reduced breaking strength rope.

Preliminary analyses of whale-rope entanglement scenarios using the VWES model demonstrate its utility to measuring variable gear loads by modifying the weight of bottom gear, rope diameter, specific gravity, and other variables.

Simulated encounters using the VWES model produce increasing load readings when either or both bottom weight and swim speeds are increased, consistent with theoretical and actual readings obtained from fishing gear.

Based on the simulated encounters analyzed so far, it appears likely that whales entangled in fishing ropes produce much higher loads than those typically experienced under pot fishing, a finding that is encouraging for using whale-release ropes that are durable enough for fishing but that have a higher probability of facilitating a whale’s release if entangled.

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APPENDICES

Appendix A – Optimal Specifications for building an innovative "whale-release" endline

Consortium for Wildlife Bycatch Reduction

Anderson Cabot Center for Ocean Life at the New England Aquarium

Building an innovative "whale-release" endline for whales and fishermen

Expression of Interest
We are seeking proposals to develop a 3/8" diameter endline with 1700lb virgin breaking strength that is comparable to those currently used in northwest Atlantic lobster pot fisheries. The concept is to use a rope that is practical for many pot fisheries while facilitating escape should whales come into contact with them.

Innovative "whale-release" ropes should be developed according to the specifications provided below. We offer facilitation to test these ropes with fishermen in the northeastern US using a rigorous protocol developed between our scientists and lobster fishermen. We also have small seed grants available should they be necessary to support the research and development of prototypes, and support for relatively small production runs to produce sufficient coils for preliminary testing with fishermen. We are not interested in being part of any patent on whale-release rope ideas submitted, but are only committed to facilitating their evaluation and eventual adoption if they are shown to achieve the objectives laid out herein. ***Expressions of interest will be accepted at any time, however concepts submitted by June 1, 2018 stand a better chance of receiving support*** owing to the urgency for solutions to the current crisis facing North Atlantic right whales (NARWs).

The Need
Ropes extending vertically from the seafloor to surface buoys (endlines) are one of the principal sources of fatal entanglements to endangered NARWs and other large whales. Several years ago, the Consortium for Wildlife Bycatch Reduction, which includes both lobster fishermen and wildlife scientists, experimented with weaker endlines. The rationale for using ropes of reduced breaking strength was that they might be fished practically while increasing the probability that whales entangled in them might break free more quickly. A recent study (Knowlton et al, 2016) bears this out, and indicates that ropes of this breaking strength may be one of the simplest modifications to fishing gear to reduce deadly whale entanglements. Reducing the breaking strength of ropes from ≥3000lbs to 1700lbs (all else being

equal, including the same rope diameter), should increase the probability that all but the smallest individual whales can exert sufficient force to break them, thereby releasing the whale before a complex entanglement occurs.

NARWs are dying at an accelerated rate from entanglement, leading to a population decline since 2010 (Pace et al, 2017). This has prompted U.S. and Canadian regulators to identify 1700lb ropes as a priority bycatch mitigation technique. Among the rope prototypes we have tested to date, including ropes with "weak links" produced by splicing in braided sleeves, we are seeking to evaluate prototypes that are 1700lb breaking strength along their entire length.

Optimal Rope Specifications

A three-strand twisted polypropylene or another poly blend rope with a diameter of 3/8" and virgin breaking strength of around 1700 lbs. Two versions of the same rope are needed, one that is positively and one negatively buoyant in seawater. Innovative designs and ideas are encouraged provided they will not eventually be overly cost-prohibitive at a commercial scale. Ropes should be relatively easy to splice, and able to run through pot haulers.

Additional Preferred Property – Color/Luminosity

Research by the New England Aquarium and collaborating scientists has demonstrated that NARWs show an aversion response sooner when presented with ropes colored orange-red than with other hues (green, black, white, etc.), during daylight hours in shallow waters where there is sufficient light penetration. Optimal rope designs would incorporate red-orange coloring in at least two strands ($580 \leq n \leq 620$nm), while the third strand could have a phosphorescent substance coating or impregnating the rope so that it has a UV-charged blue-green glow at ~494nm. This should improve the visual perception of ropes to whales in well-lit surface waters, and also at night and in deeper waters.

Why not fish with ropes of lesser diameter?

We are frequently asked why we just don't use ropes of lower diameter to achieve the target breaking strength. This is because research that we and others have undertaken show that thinner lines have a tendency to produce more severe lacerations to whales that become entangled in them.

How much in seed funding is available?

We anticipate providing up to three grants of $5000/ea, but this will depend on our internal evaluation of the concepts received. Estimates for producing experimental ropes for testing (cost/coil) should also be provided but will be considered separate from seed funds.

What is the next step if I am interested in collaborating?

Whether or not seed funding is requested, any rope designer or manufacturer should describe the prototype to be produced, its material, construction, dimensions, properties, estimated price/coil, when a prototype can be available, and any other information necessary for evaluating the concept. All those requesting seed funds should provide us with what they require to develop a prototype.

Contact: Richard Malloy, Bycatch Consortium/ACCOL, rmalloy@neaq.org, 617-226- 2217.

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Appendix B – Participant Field Instructions & Log Sheet

Whale-Release Ropes Project: Instructions for Participants

The purpose of this document is to provide written instructions for fishermen participating in the evaluation of whale-release ropes. Below is information for preparing experimental ropes and at- sea procedures when setting and hauling. These instructions accompany a Field Data Log Sheet in which the results will be recorded. Developed with input from the Massachusetts Lobsterman's Association and the South Shore Lobsterman's Association.

Preparing the Experimental Braided Sleeve Rope

When using the experimental **braided sleeve rope** please:

- Add a sleeve for every 40 ft. of three-strand rope. If the rope is less than 40 ft., place the sleeve somewhere in the middle of the rope. This procedure should be followed for both the sink and float pieces of the endline. We will provide all sleeves and three-strand rope for the experiment.
- Position the sleeve at any desired section of the rope without exceeding a 40 ft. space between sleeves.

Example 1: A 70 ft. endline = only need 1 sleeve but position the sleeve toward the middle of the endline so the rope is about 35 ft. on each side.

Example 2: A 85 ft. endline = add two sleeves, while taking into account 40 ft. rule when positioning.

- To assemble the braided sleeve rope, first cut/melt a 1″ slice into both ends of the orange sleeve about 4″ from each end (Figure 1a). Next, cut and melt the three-strand sink/float rope where you would like to add the sleeve. Insert each melted end into the cut in the sleeve. Slide the rope through the sleeve until it is half way down (about 3ft.). Similarly, take the other end of the rope and insert into the other side of the sleeve until both cut pieces of rope meet in the middle of the sleeve. Lastly, secure the end of the orange sleeve by splicing the exposed sleeve material under the three-strand rope at least 3 times. Make the ends as compact as possible against the three- strand rope (Figure 1b).

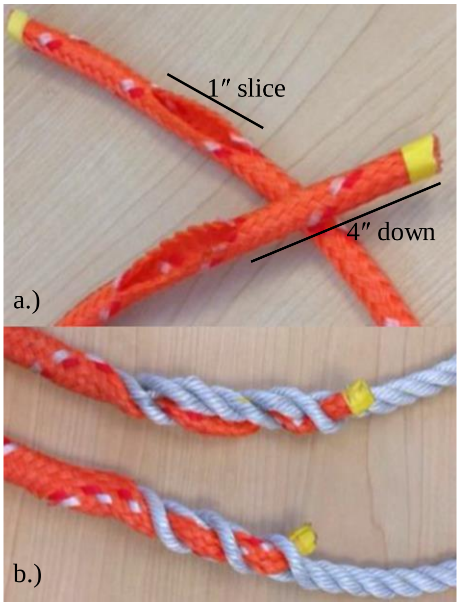

Figure 1.

At-Sea

- Each participant will use the experimental sleeved rope on five separate pot strings, one at each buoyed end (ten total for multi-string trawls). In addition, any set made with sleeved rope should be deployed in the same area as a string with an identical number of pots and groundline length using only the 3/8″ three-strand rope that the project will furnish for all participating fishermen. These sets will serve as experimental controls.

- All setting, hauling and other fishing procedures should be carried out as normal, however we ask that you please provide as much detail on the log sheet as possible mentioning any changes in gear or procedure throughout the season (ex. change in hauling speed, gear configuration etc.).

Setting:

- As indicated, when setting a string with experimental ropes always set a control string close by.
- When moving offshore and adding length to endlines, please continue to maintain the 40 ft. rule and make note of the added line in the log sheet (note whether splice or knotted into existing endline) Extra 40 ft. rope pieces and sleeves will be provided (Note: NMFS discourages knotting and for this trial we prefer ropes be splices whenever possible.)

Hauling:

- The field log sheet provided corresponds to an experimental trawl/control trawl pair and should be filled out every time one or both trawls is hauled.
- Rope Labels: Each rope will be labeled with a unique individual ID number. When filling out the log sheet use number for trawl # and letter to identify endline. Endlines that have experimental ropes will be marked either with an "A" or "B" for the different ends, and "C" or "D" for the control endlines. If only one endline is being used, then only an "A" and a "C" will be used.

For example, **5B** refers to trawl #5 and endline "B"

- A notes/gear changes section has been provided for any additional information of use for the project. This section is pertinent to help fully understand how the rope will perform under a number of fishing conditions. More descriptive information and comments will provide a more diverse understanding of whether the rope will be successful if applied to the lobster fishery.

The type of information that should be entered is, where relevant:

- Gear configuration changes (such as type of buoy, splices or knots added or a change in the number of pots in the string) during the season
- Lost gear (describe how much of the endline remains and where it parted, i.e. at a sleeve or weak point in the line).
- If parted during hauling, describe what may have contributed (sea state, rock down, weight of traps in water column, etc.). Describe if the gear is retrieved, such as by grappling.
- The sea state during the period between the last haul and when the gear was discovered lost. If possible, note the wave height, wind speed and direction provided by NOAA
  Marine Weather during that timeframe.
- Any additional pictures or information you may think is important.

- We will periodically check in and get updates on the log sheets every few weeks. However, we encourage a more frequent update by sending a picture of the log sheet via text or email to Richard Malloy.

<u>Duration and Collection</u>

- If a sleeve or elsewhere has broken, please document its loss in the log sheet per guidance above. If it is broken at a sleeve please add the replacement sleeve provided.
- We plan to have the experimental and control endlines in the water for as long as possible

- (likely until the end of the season), please continue to use the endlines until notified.
- To avoid disrupting fishing operations we will collect endlines while considering the most suitable time for participants.
- After completion, all experimental and control endlines will be collected. Although, after lab testing is complete, remaining rope will be returned if desired.

Confidentiality

Although each data log sheet requires the name of participating captains and vessels, we have no need of sharing this information publicly. This information will be kept confidential by the project; however we are happy to acknowledge the names of participating fishermen if desired.

Any questions please contact: Richard Malloy - Office: 617.226.2217, Cell: 508.308.8534 Email: rmalloy@neaq.org

Consortium for Wildlife Bycatch Reduction

Whale-Release Ropes Project - Field Log Sheet

Anderson Cabot Center for Ocean Life at the New England Aquarium

Contact Name:______________ Phone:______________ Vessel:______________

Experimental Trawl #:__________ **Control Trawl #:**__________

Initial Trawl Configuration:

Endline length (ft.): __________ Number of pots on trawl: __________ Date first set:__________

Distance between pots (ft.): ______ Weight of a single pot (lbs.): __________ Buoy #/type (polyball?, foam?): ______

*NOTES/GEAR CHANGES SECTION: AS APPROPRIATE, PLEASE REPORT ANY ROPE BREAKS, GEAR LOSSES, LIKELY EXPLANATION FOR GEAR LOSS, GRAPPLING TO RETRIEVE LOST GEAR AND OUTCOME (SUCCESSFUL? REPLACE SLEEVE?), AND CHANGES MADE TO TRAWLS (# OF POTS, SPLICES ADDED, ETC.) - SEE INSTRUCTIONS

Date Hauled	Location (latitude/longitude)	Depth (ft.)	Endline Hauled	Sediment Type Rock, Sand, Mixed	Control Endline Hauled	Notes/Gear Changes
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	
			A B	R S M	C D	

Any questions please contact: Richard Malloy - Office: 617-226-2217, Cell: 508-308-8534, Email: rmalloy@neaq.org

Appendix C - Default and Selectable Settings in the Virtual Whale Entanglement Scenario Model

<u>Scenario Settings Window</u>

Scenarios. Multiple runs using different whale behavioral scenarios are selectable in the settings window. At present, only the first two ("Roll away from rope" and "Maintain apace") are programmed; however, the settings window shows future selections that include veering away. When "roll away" is selected, the whale will always roll away from the rope from either side of where the rope is positioned relative to the rostrum (Figure 26).

Water Column Height. Determines where in the vertical column the whale encounters the vertical line. At a 0% setting, it is at the bottom (which goes directly to the minimum value which is 10%). At 100%, it is near the surface (90%). The model uses a set depth of 10fm.

Lateral Offset. The distance from the central long axis (bi-lateral line) of the whale body to the rope. A simulation using the default setting has a straight heading so that the whale's long axis is approximately perpendicular to the vertical line upon contact. At certain maximum and minimum distances between this line and the rope, the whale will not come into contact with the line. The distance is always measured from the rope and the left side of the whale (with its ventral side oriented to the sea floor), so that a negative value shifts the rope to the right side of the whale. In other words, changes to this setting shifts the position of the whale rather than the rope.

Initial Gear Distance. The average and standard deviation distance is set from the center of mass of the whale (i.e., average location of an object's weight)—essentially at a point slightly behind the flippers in the middle of the body—to the rope. An average is used so that each new scenario run begins in a different phase of the fluke's stroke, and therefore there are variable outcomes when running different scenarios.

Scenario Trigger Distance. The distance from the rope at which the whale initiates the behavior selected. The distance is measured from any portion of the rope to the closest eye. In other words, it will be triggered once that distance to either eye and the gear is achieved.

Rolls per Body Length Traveled. Controls the speed of the roll. [Only used when "Roll away from rope" is selected]

Number of Rolls. Controls the number of rolls. [Only used when "Roll away from rope" is selected.]

Swim Speed. The maximum is currently 2 kts.

Current Speed. The current speed is functional, however the higher the speed the greater probability that the model can become unstable and the line passes through the body of the whale ("tunneling").

Current Heading Angle. The direction of the current is determined relative to the rope so that a 90-degree angle has a current running perpendicularly away from the right side of the rope as it is being approached; a 180-degree angle runs counter to the trajectory of the swimming whale, and 0-degree angle causes the current to run in the same direction as the whale's swimming trajectory.

Turn Angle. [Not yet functional]

Simulation Timeout. The time after which a run during a simulation will quit if contact with the rope is not made.

Travel Distance After Contact. This setting defines the end of the active run in a simulation.

Flipper Sweep Angle. The angle determines how near to the body the trailing edge of the flipper is. At 0 degrees, the leading edge of the flipper is approximately perpendicular to the elongate axis of the whale body; at 30 degrees (maximum setting) the trailing edge is most tucked into the body. At –10 degrees, it is slightly forward.

Rope Breaking Strength (N). Sets the rope breaking strength in Newtons. (1 N is equivalent to 0.0224809 pound-force). Only if "Enable breaking rope" is selected will the program check the value input into "Rope breaking strength". Otherwise, it will continue to record the actual line tension.

Traps. The number of traps tied onto the rope. Only one or two traps can be selected in the current version of the model. Traps will not appear graphically until the scenario is run. To display traps for manual runs, activate the scenario after selecting the number of traps and then move to manual mode.

Number of Monte Carlo simulations. Determines how many iterations of a simulation are run.

<u>Graphic Window Information Display</u>

In the upper left corner of the graphic display, the information that is being recorded during simulation runs are shown. These are:

- Left/Right eye distance to gear
- *Contacts* – number of points at which the rope and whale surface come into contact

· *Distance since first contact* – distance moved following initial contact between whale and rope.

· *Scenario game time* – total time recorded for all runs of a given scenario.

· *Scenario trigger time* – the time at which contact is made between the whale and rope for each scenario run, so multiple timestamps will be recorded with multiple runs.

· *Scenario simulation start time* – the start time for a selected scenario.

· *Scenario simulation run time* – the total run time for a selected simulation.