Title: Evaluating the role of bycatch reduction device design and fish behavior on Pacific salmon (*Oncorhynchus* spp.) escapement rates from a pelagic trawl

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Abstract

Pacific salmon (*Oncorhynchus* spp.) bycatch is a significant driver in the management of walleye pollock (*Gadus chalcogrammus*) pelagic trawl fisheries in the North Pacific. Various bycatch reduction devices that permit salmon to escape from the trawl ('excluders') have been developed. High variability in escapement rates from the excluders underscores a lack of understanding regarding mechanisms that promote escapement. We developed an excluder that provided a 360˚ open area for escapement during towing, turns, and haulback. We used computational fluid dynamics simulations and flume tank testing to expedite development by producing quantitative flow and net mensuration data, which reasonably predicted performance at full scale under commercial conditions. During at-sea trials, salmon escapement rates were high (mean 0.58 ± 0.18); however, more comprehensive testing is needed among salmon species and over a breadth of fishing conditions. Video footage revealed that salmon disproportionately escaped by swimming forward from aft of the excluder during haulback and turns. This highlights the importance of providing an open path to the escapement area during these periods. Retention of any salmon despite the expansive, easily accessible open area reflects the important role played by perception of the open area and motivation of salmon to escape at that point in the fishing process.

Keywords

bycatch reduction device; salmon excluder; flume tank; computational fluid dynamics; fisheries selectivity

1. Introduction

Bycatch of Pacific salmon (*Oncorhynchus* spp.) is a significant driver in the management of the commercial walleye pollock (*Gadus chalcogrammus;* hereafter 'pollock') pelagic trawl fisheries in the North Pacific (Witherell *et al*., 2012; Ianelli *et al*., 2013; Madsen and Haflinger, 2014). Protections afforded to many Chinook salmon (*O. tshawytscha*) stocks under the U.S. Endangered Species Act, combined with a robust pollock fishery that harvests over 1 million metric tons (t) annually (Ianelli *et al*., 2013; Witherell and Armstrong, 2015), contributed to the setting of annual Prohibited Species Catch (PSC) limits for Chinook salmon by the North Pacific Fishery Management Council. Annual fishery closures are triggered if these limits are reached (Fissel *et al*., 2019). To meet performance standards and to avoid exceeding Chinook PSC allowances, fishermen target grounds when and where co-occurrence of Chinook salmon with pollock is comparatively infrequent (Gilman et al., 2006; Ianelli and Stram, 2015). Concern for chum salmon (*O. keta*) bycatch, while not PSC, also causes fishermen to adjust how they target pollock (Fissel *et* al., 2019). Spatiotemporal limitations can affect catch quality and lead to increased fuel usage and search time to harvest quota. Since 2002, members of the fishing and conservation engineering communities have worked to develop and improve upon bycatch reduction device (BRD) designs that permit salmon to escape from the trawl before they are landed on the vessel ('excluders'; Stram and Ianelli, 2015). Given high motivation to reduce salmon bycatch (e.g., low Chinook PSC allowances), fishermen and resource managers benefit from understanding the factors affecting escapement rates and from refining excluder designs based upon this knowledge to ensure reliable performance *in situ*.

Several salmon excluder designs have been tested in the pollock fishery over the past two decades; however, salmon escapement rates have been highly variable by species, fishery (Bering Sea vs. Gulf of Alaska), among designs, and, by design, among trips and tows (Gauvin and Paine, 2004; Gauvin and Gruver, 2008; Gauvin *et al*., 2011; Gauvin *et al*., 2013; Gauvin *et al*., 2015; Gauvin, 2016; Figure 1). The original excluder design to address salmon bycatch in this fishery included escape portals above a square-mesh tapered tunnel in the intermediate section of the trawl (between the net and codend), requiring salmon to access the escape portals by swimming forward, in the direction of tow, and up. Results from testing this design in the Bering Sea supported the hypothesis, posed by Rose (2004), that behavioral differences and the greater swimming ability of salmon (both Chinook and chum salmon) compared with pollock, despite some morphological similarities, were fundamental to the efficacy of the salmon excluder (Gauvin and Paine, 2004; Gauvin and Gruver, 2008). While improvements to excluder designs have been made, a mechanistic understanding of why escapement rates remain so variable is lacking.

Building on industry-driven research and innovation, we developed a new salmon excluder (called the 'Rope Tube & Funnel' [RT&F] excluder) to evaluate the potential to increase escapement rates above that of established designs and to evaluate important influences on escapement. We initiated and evaluated the design of the excluder based on the concept that salmon excluder efficacy previously relied on salmon to perceive and access an escapement area by swimming against the flow of water and in the direction of tow, and then to actively escape. To address the key processes of perception and access, the RT&F excluder was designed to significantly reduce water flow around the escapement area to make it more perceptible by salmon, inducing a rheotropic response (Winger *et al*. 2010). Manipulation of water flow in and around BRDs is an established practice for trying to increase escapement of non-target animals (Engås *et al*., 1999; Eayrs, 2007; Gauvin *et al*., 2008; Cha *et al*., 2011; Parsons *et al*., 2012; Prasetyo *et al*., 2017). It has potential for salmon given that they can react to changes in water velocity less than 3 cm/s and are attracted to or deterred from an area based on water velocity (Lyon, 1904; Arnold, 1974; Banks, 1969; Bell, 1991; Lindmark *et al*., 2008; Duarte *et al*., 2012; Lindberg 2016; Gisen *et al*., 2017). The RT&F design is also intended to break up the visual pattern of the net to disrupt the optomotor response, the tendency of fish to follow the real or apparent relative motion of their surroundings (Lyon, 1904). Finally, the RT&F excluder features a 360° open area for escape with nearly unobstructed access in the path toward the codend, addressing the question of whether salmon will use an excluder even if nearly all physical barriers to escaping are removed.

The RT&F design was based on the theory that the fast towing speeds used in the pollock fishery relative to salmon cruising speeds (approximately 1.2 m/s for larger salmon; Bell, 1991) are a limiting factor to increased escapement. This is evidenced by higher escapement rates on vessels towing at lower speeds. For example, salmon escapement for the same excluder design towed at speeds of 1.5 – 2.2 m/s in the Bering Sea ranged from 3-18% (mean of 11%; all tows combined by vessel-year-season combination), compared to trials in the Gulf of Alaska towing at slower speeds (1.3 – 1.5 m/s) in which escapement ranged from 34-54% (mean of 40%; Gauvin *et al*., 2015; Gauvin, 2016). For excluders to be effective without requiring a change in fishing practices (namely, tow speed), it is important that the excluder facilitate escapement despite the salmon's swift passage through the escapement area.

The RT&F excluder was developed using computational fluid dynamics simulations and flume tank testing of a scale model before trials at sea. This study evaluated the design process and how elements of the RT&F excluder affected salmon behavior and escapement rates during pollock fishing in the Bering Sea. The information is presented to help explain mechanisms influencing high variability in salmon excluder escapement rates. Further refinement of this, or other, excluder designs following the template provided here has the potential to save considerably on research and development costs and time frames, operationalizing effective conservation tools in a more expedient and less expensive manner.

2. Methods

2.1 Salmon Excluder Design Concept

The broad design concept for the RT&F excluder was to split the net at the last tapered section (at a break in the riblines) and attach a diamond mesh funnel encircled by a rope tube (Figure 2). At the start of the funnel, a straight section of diamond mesh would be attached to the outside, creating a 'sleeve'. The sleeve would terminate in jibs attached to the rope tube, which would extend over the length of the funnel and, after a given amount of open space, attach to another jib-terminated, straight diamond mesh section. This section would serve as a 'collector', which would reattach the excluder to the net. The concept was for fish to travel down a funnel that was no smaller in circumference than the codend and to emerge in a 360° open area surrounded by ropes. The aforementioned (Section 1), previously tested tunnel-style salmon excluder was hampered by accumulation of fish at the tunnel entrance (Gauvin and Paine, 2004; Gauvin and Gruver, 2008). To prevent this, we aimed to accelerate water flow through the funnel. At the collector, the pollock would flow (or tumble) back into the trawl. The funnel netting, inclined to the flow, would create reduced flow areas around the funnel and at the collector to promote salmon escapement by making the escapement area more perceptible.

2.2 Fluid Dynamics Modeling

A Reynolds Averaged Navier-Stokes (RANS) flow solver was applied to investigate the flow field in and around the initial excluder concept. We used a porous medium approach to simplify calculations given that hydrodynamic properties of the netting are determined by the netting porosity or solidity ratio (a function of the surface area and hang ratio, which we assumed to be 0.3 based on typical gear specifications in the pollock fishery; Riedel and DeAlteris, 1995; Breddermann and Paschen, 2011; Klebert et al., 2013; Breddermann, 2015; Breddermann, 2017). We investigated funnel netting types and configurations (stretched mesh size, twine size, and the resulting solidity ratio) to accelerate water flow through the funnel. We also assessed the shape of the collector section, including one with dimensions equal to the sleeve ('straight') or one with an enlarged opening that tapered down to the mesh length of the sleeve ('flared'). The fluid dynamics modeling methods are described in detail in Breddermann *et al*. (2019).

2.3 Flume Tank Testing

In March 2019, we tested the modeled excluder design at 1:2 scale in an 8-m wide × 4-m deep × 22.25 m long flume tank at the Fisheries and Marine Institute of Memorial University of Newfoundland (Canada; Winger *et al*., 2006) (Figure 3). The excluder was attached to a 4.4-m circumference ring (fixed opening), with fresh water flowing through at a rate of 0.91 m/s actual (1.3 m/s converted to full scale using Froude scaling). Several configurations were tested by adjusting the following variables: (*i*) the mesh depth of the sleeve; (*ii*) the shape of the collector section ('straight' or 'flared'); (*iii*) the spacing between the end of the funnel and the entrance to the collector section; (*iv*) the presence/absence of square mesh at the entrance of the collector section; and (*v*) the presence/absence of kites made of heavy vinyl to the square mesh, which incrementally increased (Figures 2 and 3). For each configuration, pictures and video were taken from a viewing gallery and from a camera inserted into the excluder, looking down its length. To quantify changes in water flow velocity, several vertical transects were taken over the extent of the excluder using a two-axis electromagnetic current meter (Valeport, Model 802, 3.2 cm discus) with a sampling rate of 96 Hz. Data were collected at the horizontal and vertical opening of the excluder at the leading edge of the funnel, in front of the sleeve jibs, at the funnel exit, and at the collector section at the leading edge of the kites. In addition, tension measurements were taken at the tow point (indicating total drag of the model) at 0.13 m/s intervals as flow increased to 0.91 m/s using an inline load cell (Honeywell Sensotec, Model 31) with a sampling rate of 50 Hz.

2.4 At-Sea Trials

In June 2019, during the 'B' season (summer/fall) Bering Sea pollock fishery, we tested a full-scale version of the RT&F excluder design (Figure 4) that resulted from the fluid dynamics simulations and flume tank testing. The F/V *Pacific Explorer*, a 47-m long, 1800-horsepower catcher vessel trawler, was chartered to test the RT&F excluder. The excluder was professionally made and installed (Swan Net, USA) in the standard pelagic trawl net used on that vessel (a Hampidjan 672 Helix Longwing) in the last tapered section (100-meshes forward of the first intermediate section). The headrope and footrope were 310 m long (wingtip to wingtip), with a mouth opening of approximately 22 m when fishing. The vessel used NET Systems series 2000, 8 m^2 high aspect ratio pelagic trawl doors; and two 100 mesh long (102 mm stretched mesh) intermediate sections between the net and the approximately 160 (t) codend. The excluder design was fixed with the exception of six attachment points where the sleeve of the excluder connected to the straight section behind the excluder funnel (Figure 4). The attachments allowed the excluder to be moved toward the mouth of the net in 0.91-m intervals, reducing the amount of open space between the end of the funnel and the collector section by the same amount. Kites made of heavy vinyl with a stainless steel spring inside the upper leading edge were attached to the square mesh section of the collector.

The excluder was evaluated with respect to shape, water flow differential, and salmon escapement. This was done under commercial fishing conditions with the exception of time of day and tow duration. Research operations did not go through the night, and, while commercial tows typically range from 20 min to 10 hours (Witherell and Armstrong, 2015), tow duration for this research was restricted to four hours due to run time of the camera batteries. In addition, the captain was asked to target areas with high incidence of salmon and pollock co-occurrence (under a Scientific Research Permit). Because the charter occurred in the summer, we anticipated that the primary Pacific salmon species bycatch would be chum salmon, based on predictable spatio-temporal movement patterns and historic catch (namely, chum are most prevalent during 'B' season, while Chinook are most prevalent during the winter, 'A', season; Witherell et al., 2002). Tows were completed with an open codend until camera positions and the start position for the placement of the sleeve were selected, after which point the codend was closed. At the completion of a tow, fish were released into a dry tank that fed a conveyor belt leading to the fish holds. Research and vessel crew monitored the catch, removing all salmon and taking a sub-sample of pollock (one full 0.5 m diameter top × 0.4 m high basket) at the start, middle, and end of the catch before going over the conveyor belt. These pollock and all salmon were measured (fork length, nearest cm). Salmon were identified to species and checked for the presence of an adipose fin and any external tags, and common bycatch of non-salmon species was recorded.

Pollock and salmon were observed using video from low-light cameras (Sexton, https://www.thesextonco.com/) placed strategically in the excluder, with the field of view illuminated by integrated LED lighting. We tested white and far red (peak at 730 nm) LED lights given that adult Chinook salmon in their marine residence cannot see the latter light frequency (Yochum *et al., in prep*). Video footage was recorded for each tow from the start to end of fishing, and, for most tows, until the trawl was on deck. Speed over ground and position were recorded from Globe software (http://www.electroniccharts.com/Globe.php). Wildlife Computers (https://wildlifecomputers.com/) data-archival tags with a mechanical flow meter were used to measure water velocity, temperature, depth, and light. The tags were each placed in a housing to secure the sensor to the trawl. Following the at-sea trials, water velocity sensors were tested at the flume tank in Newfoundland by securing the sensor, both with and without the housing used in the trawl, to a pole and submerging it in the flume tank. Flow was increased to and decreased from 0.8 m/s, stopping at 0.2 m/s intervals for 2 minutes.

2.5 Data Analysis

The salmon escapement rate for the *i*th tow (S_i) was calculated by

$$S_i = \frac{N_i - C_i}{N_i} \ , \qquad (1)$$

where N_i is the number of salmon during the *i*th tow that encountered the excluder, determined by counting the number of salmon (not identifiable to species) moving aft past a camera placed at the start of the funnel, viewing the full circumference of the funnel (video footage reviewed using VLC media player; Figure 5); and C_i is the number of salmon caught and retained (i.e., counted during catch sorting and verified from offload data). In calculating N_i, pollock and salmon were differentiated in the video using differences in morphology and behavior. Video reviewers underwent extensive identification training, and if a fish resembled a salmon, but the identification could not be made with certainty, it was not counted. Also, when a salmon swam forward past the camera, it was deducted from the total count to prevent double counting. When the camera was blocked for more than 5 minutes, footage from an alternate camera angle was reviewed during that time. For each tow, up to six cameras (mode of five) were placed in and around the excluder, balancing the need to observe the large area while reducing the amount of light that might affect fish behavior and camera exposure. Additional camera positions included: the end of the funnel looking aft, on the top and bottom panels of the collector looking over the escapement area, and on the bottom panel of the collector looking aft. All video footage was reviewed to evaluate excluder shape and to detect patterns in escapement and behavior (e.g., volitional or active swimming compared with passive escapement-tumbling out, location and timing of escapement).

3. Results

3.1 Fluid Dynamics Modeling and Flume Tank Testing

As a result of the computational fluid dynamics modeling, it was predicted that the conceptual excluder design would create the intended flow field in general: producing a wake region around the funnel and at the collector entrance, and increasing flow velocity at the funnel exit by 2-5%. Choosing funnel netting with a solidity of 0.3 prevented reduced water flow at the funnel entrance compared with a solidity of 0.5, which led, in simulations, to an undesirable decrease at the funnel entrance (for additional details, see Breddermann *et al*., 2019). In the flume tank, we verified the flow field predictions from the fluid dynamics modeling (Figure 6). While the wake region corresponded with the simulations, the flow velocity at the funnel exit matched tow speed rather than exceed it as was predicted.

The RT&F excluder design was further refined as a result of the flume tank testing. Kites were deemed necessary along the outer circumference of the entrance to the collector section to generate the desired spread, and square mesh at this location facilitated a fixed geometry for shape stability while towing. Of the two collector shapes tested, the straight design was selected. While the flared collector provided more opening between ropes and at the collector entrance, the amount of spread was limited by the length of the ropes. Also, the flared design generated 23% more tension at the maximum speed tested than the straight configuration. For the straight collector, optimal kite configuration was two per panel and one across each gore, all evenly spaced (12 kites total). Neither square mesh nor kites were needed for the sleeve to take the desired shape and, therefore, were eliminated at this location from the design for simplicity.

3.2 At-Sea Trials

In June 2019, 26 tows were completed in the Bering Sea between N 166° 00′ W 164° 30′ and N 55° 20′° W 54° 20′. For the first seven tows, we evaluated the excluder shape and sleeve position (related to the distance between the end of the funnel and collector section). Five of these seven pre-trial tows were completed at sleeve position-1 (the longest distance between the funnel end and collector; i.e., the most expansive escapement area), and two at position-3. These pre-trial tows were also used to finalize camera positioning (Figure 5) and lighting. Of the 19 trial tows that followed, three were completed with water flow sensors in absence of cameras to evaluate if the proximity to the cameras affected the ability to capture velocity measurements. Of the 16 remaining trial tows (Table 1; nine at sleeve position-3, seven at position-4), four were not included in the analysis because the codend was left partially open due to the vessel's limited remaining hold capacity (three tows) or video footage did not extend over the duration of the tow due to battery run time (one tow). This left 12 tows that generated usable data to quantify salmon escapement rates, though one of the 12 did not have video footage during the entirely of haulback (Tow 21).

The trial tows started between 0900 and 1800, lasting, on average, for 2.4 hours (start of fishing to the beginning of haulback), and occurred at an average depth of 118-m. Depth of the excluder was between 0- and 12-m above the seafloor. Mean speed over ground (speeds by tow were the average of recorded values at the beginning and end of each tow) was 1.9 m/s (range 1.4-2.2 m/s). Based on the captain's observations, mean wind speed was 6 m/s (range 0- 5 m/s) and mean swell height was 1 m (range 0-2 m). Mean temperature at the headrope was 5.4 °C (range 4.3-6.7 °C). The water velocity data collected during at-sea trials included many missing data points, suggestive of unreliable data, and zero values, indicating that the paddlewheel stopped moving. Moreover, results from testing the water velocity sensors in the flume tank revealed that the housing used to secure the sensor to the trawl low-biased the values, so data from these sensors were not analyzed further.

For the majority of the trial tows, several other fishing vessels were towing within eyesight. Fishing conditions and total catch for those vessels (based on real-time information reported by the captains) were similar to those for our research tows. At the time of the charter and for that fishing season, pollock catch rates were markedly low in the fishery compared to recent years (Ianelli et al., 2019). Typical pollock catch by tow for this fishery is between 50 and 200 t

(Witherell and Armstrong, 2015). However, we had an estimated 0-125 t per tow (33 t on average) and catch rates were between 0 and 36 t/hour (11 t/hour on average). The charter vessel holds were offloaded three times with a total of 505 t of pollock, and 13 Chinook, 1678 chum, and one pink salmon (*Oncorhynchus gorbuscha*) caught, none with clipped adipose fins or external tags. For all tows combined, 99% of the catch (by weight) was pollock, and the second highest catch was jellyfish (subphylum Medusozoa) (0.5%, 2.7 t), with all other catch combined less than 0.5%. Among other species, bycatch included roundfish (e.g., Pacific cod, *Gadus macrocephalus*; Pacific herring, *Clupea pallasii*; sablefish, *Anoplopoma fimbria*) and flatfish (e.g., flathead sole, *Hippoglossoides elassodon*; arrowtooth flounder, *Atheresthes stomias*). All pollock were 800 g and larger, but were smaller, on average (49 cm), than the retained salmon (59 cm; Figure 7).

3.2.1 Salmon Escapement

Data were not collected to measure salmon escapement rates for sleeve position-1 (maximum open space between the funnel exit and collector section) due to the apparent high pollock loss based on the review of video footage at-sea. This was likely due to the increased distance between the funnel end and collector and/or potentially reduced water flow in the open area. Positions-2, -5, and -6 were not attempted. Positions-5 and -6 would have created little to no open space and would have required the salmon to swim around the funnel to exit. Position-2, similar to postion-1, would likely have provided too much open space and, therefore, escapement of pollock. For trial tows at sleeve positions 3 and 4, a mean of 145 salmon entered the excluder per tow used in the analysis. Positive identification to species was not possible using the video images; therefore, escapement rates were calculated for all Pacific salmon combined. Given species composition of the retained salmon (of salmon, catch was 99% chum), we assume that the vast majority of salmon encountered in our at-sea trial were chum salmon. Salmon escapement rates ranged, by tow, from 0.23 to 0.83 (Figure 8), with a mean of 0.55 ± 0.19 (one standard deviation). The tow with the lowest escapement rate (Tow 21) did not have footage during haulback so the value is likely underestimated. Without that tow included, average escapement rates ranged from 0.38 to 0.83, and the overall average was 0.58 (± 0.18). We note that, while there was no significant difference in the mean escapement rate by sleeve position, the mean for tows with the sleeve at position-3 (0.58 ± 0.19, range 0.38-0.83) was higher compared to those at postion-4 (0.44 ± 0.18, range 0.23 to 0.60). For the latter, when Tow 21 was excluded, the mean was 0.54 ± 0.09 (range 0.47 to 0.60). The data that support the findings of this study are available from the corresponding author upon request.

Video footage revealed that the salmon and pollock actively swam or passively flowed/ tumbled down the funnel and either back into the net through the collector or escaped through the rope tube. Salmon regularly swam forward in the direction of tow, and frequently maintained the same position relative to the net for several minutes before going back again, and often repeated this behavior. There was substantial forward movement from aft of the excluder by individual and groups of salmon during haulback and turning. Many of these salmon escaped at the open area and some swam back up the funnel. There was also forward movement of pollock at these times, but proportionally fewer compared with salmon. Escapement rates could not be calculated separately for the different fishing events (i.e., tow, turn, haulback) due to lack of video coverage over the expansive open area. However, from the video footage looking over the escapement area from the end of the funnel and the collector section, escapement rates appeared to be higher during haulback and turning than towing. From this footage, we did not detect a preference for escape location (top, bottom, etc.).

4. Discussion

4.1 Fluid Dynamics Modeling and Flume Tank Testing

The computational fluid dynamics simulations and flume tank testing expedited the development of the RT&F excluder by reasonably predicting performance at full scale and under commercial fishing conditions, including different tow speeds. Given the dynamic and cumbersome testing environment at sea, employing multiple tools to design fishing gear before testing at-sea can greatly benefit development (Nguyen *et al*., 2005; Queirolo *et al*., 2009). Previous salmon excluder designs benefited from flume tank testing. Here, simulations combined with flume testing allowed for more quantitative flow and net mensuration data (Breddermann *et al*., 2019). Moreover, simulations and flume testing allowed for collection of both coarse and fine-scale data without constraints associated with at-sea trials, such as battery-limited sampling equipment and necessity to offload catch. For example, at the flume tank we were able to make a noticeable improvement by moving an attachment by one mesh. These fine-scale design modifications would be much harder to evaluate *in situ* on a full scale trawl. While these tools were beneficial in the design process, full at-sea trials under commercial conditions were necessary to evaluate design efficacy and fish behavior.

4.2 Excluder Design

It was not possible to determine whether the full-scale excluder design, at sea, generated areas of reduced water flow around the escapement area or accelerated water velocity through the funnel, given the lack of usable sensor data. The frequency of paddlewheel stoppage could be attributed to either highly abundant krill being lodged in the sensor, turbulence or velocity breaks in the trawl, or interference from fish. Post-charter results from testing the sensor in the flume tank revealed low-bias attributed to the housing design and error associated with high water flow rate. Collected water velocity data were further complicated by the interaction of high and low velocities at the netting, where the sensor is attached. However, pollock (and sometimes salmon) would often take up position on the bottom panel of the collector entrance and reduce tail beat frequency, suggesting reduced water flow at the collector entrance. Moreover, based on video footage, the excluder took the desired shape while under tow and during haulback, and the design did not constrict flow of fish at the funnel entrance (as was the concern based on Gauvin and Gruver, 2008), even during the highest catch rates encountered in our at-sea trials. During towing, the ropes remained taut and the funnel maintained shape. During haulback, the funnel was variably open. Despite the kites' increasingly flaccid appearance on deck with use, they took shape without issue under tow. The collector section opened reliably, and remained open during turns, haulback, and on one occasion when a rope was caught on a piece of scientific equipment.

Despite uncertainty around our ability to manipulate water flow at sea, the design exceeded the highest reported escapement rate for salmon excluders by trip for previous designs (in both the

Bering Sea and Gulf of Alaska; Gauvin and Paine, 2004; Gauvin and Gruver, 2008; Gauvin *et al*., 2011; Gauvin *et al*., 2013; Gauvin *et al*., 2015; Gauvin, 2016; Figure 1). Further, we think that the salmon escapement rates in our study were likely underestimated, given the methods used to count salmon going down the funnel (N_i in Eqn. 1). While we are confident of the census of salmon retained in the catch, we can identify a number of measurement difficulties that would act to underestimate the number of salmon entering the excluder (and therefore the calculated escapement rate). First, limitations of the camera footage likely meant that some salmon entered the excluder and were not counted. For example, often the camera view and/or light source was blocked by fish (both due to large quantities and to those stuck in the camera housing), jellyfish, large amounts of krill, or other organisms. At those times we could detect salmon actively swimming forward (unless the camera was obscured for long periods), but it was more difficult to identify salmon moving aft. When the camera was blocked for more than five minutes, footage from an alternate camera angle was reviewed during that time period. However, there was not always additional usable footage. Some video footage had better quality than others: cameras illuminated with red light and those recording in black and white generated footage that made it more difficult to identify salmon, and if illumination was not sufficient it was difficult to detect salmon against the bottom panel. Secondly, our criteria for counting salmon erred on the side of undercounting salmon encountering the excluder. For example, when a salmon swam forward past the camera, it was deducted from the total count (N_i). The salmon that swam forward nearly always fell back, so this subtraction prevented double counting. However, if a salmon swam or passively moved back when the camera was blocked, or there was missing video footage, it contributed to underestimation of escapement. An example of this is tow 21 (Table 1), during which the captain made a turn. During the course of the turn, many salmon swam forward and back into the funnel. These salmon likely fell back during the tow or haulback; however, there was no footage for the haulback. This meant the salmon that swam forward were deducted from the total count, but were not re-counted as they would have been with full video coverage. This is likely why the escapement rate from tow 21 is so anomalous (Figure 8), and why data are reported with and without this outlier. An alternative hypothesis is that during the turn, similar to the haulback, the salmon swam forward and up the funnel, but got stuck. We think this is unlikely because a large number of salmon would have been found in the net, which was not the case.

4.3 Excluder Assessment and Future Research

During at-sea trials, salmon escapement rates (0.58 ± 0.19, range 0.38-0.83) were higher than reported escapement rates for previous designs (Figure 1). The sample size was not sufficient to evaluate the influence of fishing variables (e.g., tow duration, tow speed over ground, fishing depth, time of day) on salmon escapement rates, and the tows did not represent the breadth of conditions experienced in this fishery (e.g., vessel horsepower, fishing season; Witherell and Armstrong, 2015). In particular, while the catch rates experienced during the charter were similar to nearby vessels fishing at that time, pollock catch was in the lower range of typical values for this fishery. Pollock and Chinook salmon catch rates are nearly always higher in A season and toward the end of B season (Stram and Ianelli, 2015). Before there can be confidence in performance reliability, additional research is needed to evaluate this design under a breadth of conditions, including fishing in denser schools of pollock. Future testing should also better establish efficacy for Chinook salmon, the species of highest management concern for this fishery.

While the RT&F excluder design showed promise and catch was similar to vessels fishing nearby, there was no quantification of target species (i.e., pollock) loss, an important metric for measuring excluder 'success' and encouraging industry use. For previous excluder designs, pollock escapement, by weight, was less than 2% on average, 1%-9.8% by study and 0%-18% by tow (Gauvin and Paine, 2004; Gauvin and Gruver, 2008; Gauvin et al., 2011; Gauvin et al., 2013; Gavin et al., 2015; Gauvin, 2016). In an evaluation of the earliest salmon excluder design that resulted in 12-20% salmon escapement, 2-3% of pollock loss was considered a justifiable tradeoff to queried pollock captains (Rose, 2004). Our initial trial of the RT&F excluder resulted in higher salmon escapement than that design; however, given the easily accessed 360˚ open area, pollock loss for the RT&F is likely higher than previous averages, but within the range of values experienced with other excluders. A systematic assessment of catch loss is needed, under conditions of higher pollock catch rates and including the role of pollock size given differential swimming abilities and lateral line sensitivity (Castro-Santos and Cotel, 2009), to allow for an assessment of the trade-offs between target and salmon catch reductions.

While escapement rates during this study were relatively high, retention of any salmon despite the expansive, easily accessible open area reflects the important role played by variables ancillary to excluder design. This includes perception of the open area (which is influenced by tow speed) and motivation of salmon to escape at that point in the fishing process. Given this, behavioral aspects of the capture and escapement process need to be better understood. For example, if salmon definitively have higher escapement during haulback and turns, as suggested in this and previous excluder trials (Gauvin *et al*., 2015), more research is needed to determine what is driving this phenomenon. It is not clear whether increased escapement during haulback and turns is motivated by crowding avoidance, sea state, or pulsing of the codend (as observed in Madsen *et al*. 2008; and Pol, 2017), increased ambient light as the trawl is brought to the surface, or reduced tow speed in relation to speeds maintained by salmon in the codend. For example, when the trawl speed is reduced during haulback, water that was previously pulled forward during the tow continues to move forward, resulting in flow opposite from the original towing direction (Engås *et al*., 1999). Increased understanding of forward movement and increased escapement during particular fishing events could lead to improvements in future designs related to both escapement rates and reducing the amount of time salmon spend in the trawl before escape to reduce stress and trauma (e.g., exhaustion, injury, lactic acid build up) (Bell, 1991; Madsen *et al*., 2008; Roscoe *et al*., 2011).

Additional research is also needed on how to increase perceptibility of the escapement area. The impact of the change in water flow and visual pattern disruption on escapement from this study is unknown. However, visual stimuli can affect behavior and motivation to go to certain areas (Lyon, 1094; Glass *et al*., 1995; Glass and Wardle, 1995; Olla *et al*., 2000; Parsons *et al.*, 2012; Lomeli and Wakefield, 2019), and the use of artificial lights to increase salmon escapement has been effective in a very similar fishery (Lomeli and Wakefield, 2019). Salmon could be swimming to match the tow speed to maintain their visual field. Animals tend to follow the relative movement of their surroundings (either real or apparent), adjusting their swimming with changes in the surrounding current (Lyon, 1904). Water velocity could also be triggering behavior. For example, Johansson et al. (2014) found that increased water velocity caused Atlantic salmon (*Salmo salar*) to maintain station at fixed positions. This aligns with behavior observed during this study.

As we continue to refine the RT&F excluder, and as others are developed, we highlight the importance of considering these behavioral and biological components. Along these lines, the excluder needs to be tested in the future without camera lights that are perceptible to salmon and pollock given the potential effects of light on behavior (e.g., Olla *et al*., 2000). The red lights tested here would be effective for evaluating behavior but were limited in their ability to quantify salmon in our application.

Acknowledgements: We thank the captain (Lorin Perry) and crew (Mario Torgerson, Janek Szymul, Mike Urbanczyk, Lauti Tuipala, Ron Ferro, and Tor Storkersen) of the F/V *Pacific Explorer*. We also acknowledge Harold DeLouche, Craig Hollett, George Legge, and Mark Santos for assistance at the flume tank; Katherine Hellen Schneider for assistance in the field and with video review; Seamus Melly and Chris Brewer (Swan Nets) for feedback on excluder design; John Gruver for feedback on this project; Paul Winger and Dayv Lowry for thoughtful comments on the manuscript; and Dave Colpo (PSMFC) for helping to facilitate the research charter. This work was supported by the National Cooperative Research Program (FY2019). The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect those of NOAA or the US Department of Commerce.

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List of Figures

Figure 1 Results from industry-led Exempted Fishing Permit (EFP) testing of previous salmon excluder designs by trial (with one to five fishing trips per trial) in the Bering Sea (light grey) and Gulf of Alaska (dark grey) (Gauvin and Paine, 2004; Gauvin and Gruver, 2008; Gauvin et al., 2011; Gauvin et al., 2013; Gavin et al., 2015; Gauvin, 2016) indicating escapement rates, by number, of Chinook salmon (*Oncorhynchus tshawytscha*) and chum salmon (*O. keta*) from a pelagic trawl used to harvest walleye pollock (*Gadus chalcogrammus*) in the North Pacific in both seasons ('A': winter/spring and 'B': summer/fall, when Chinook and chum are most prevalent, respectively). Values listed by species were estimated using a recapture net, whereas 'all salmon' values were estimated using video footage where species identification was not always possible. For each excluder style ('Funnel', 'Flapper', and 'Over-and-Under'; note there are variations among the configurations for the different trials) and body of water, values are listed from oldest to most recent study (left to right). Pollock escapement, by weight, for these studies was less than 2% on average, 1%-9.8% by study and 0%-18% by tow.

Figure 2 The approximate location (not to scale) of the RT&F salmon excluder in the pelagic trawl (in the last tapered section of the net, in front of the intermediate sections and codend) and components of the general excluder design concept, including the sleeve, funnel, rope tube, and collector.

Figure 3 Photograph of one candidate RT&F salmon excluder configuration from the flume tank viewing gallery, highlighting the main sections: sleeve, funnel, rope tube, and collector (the straight configuration is shown here with square mesh and kites).

Figure 4 Net plan for the RT&F salmon excluder developed based on results from the fluid dynamics modeling and flume tank study, and trialed at full scale under commercial fishing conditions during the research charter.

Figure 5 A diagram of the RT&F salmon excluder (not to scale) indicating the approximate locations of three of the video camera attachment points (numbered boxes, 1-3) and fields of view (dashed lines). Camera 1 is the vantage point used to count the number of salmon that encounter the excluder. Cameras 2 and 3 were used to evaluate fish behavior and shape of the excluder (another common camera location was immediately below camera-3, but on the bottom panel; looking forward and/or aft). Images taken from video footage at these three vantage points are listed by camera position: (1) salmon (*Oncorhynchus* spp.) and pollock (*Gadus chalcogrammus*) moving aft down the excluder funnel; (2) during haulback, salmon escaping out the top ropes and fish swimming forward from the direction of the codend; and (3) the three different sleeve positions (1, 3, and 4) evaluated, which correspond to the widest (1) to narrowest (4) escape space between the end of the funnel and collector section.

Figure 6 Water velocity data from the flume tank (converted to full scale using Froude scaling) comparing a straight collector with a long sleeve (top), straight collector with a short sleeve (middle), and flared collector with a long sleeve (bottom).

Figure 7 Fork lengths (cm) of sub-sampled pollock (*Gadus chalcogrammus;* top) and censused chum salmon (*Oncorhynchus keta*; bottom, left axis) caught during tows when the trawl codend was closed, shown in grey as cumulative frequencies by tow (stacked-chart) as they occurred in time. The innermost line represents the first tow and the outermost line represents all tows combined. Chinook salmon (*O. tshawytscha*; eleven of the thirteen captured in the codend) length frequencies are shown as black bars (bottom, right axis).

Figure 8 Mean salmon escapement rates (error bars indicate $\pm$ one standard deviation) for all analyzed tows and by sleeve position indicating shorter (position-4) and longer (position-3) distance between the end of the funnel and collector section of the excluder. Mean values are reported on the plot, while minimum, maximum, and number of samples are reported below. Values are also listed with and without the inclusion of Tow 21, which did not have complete video footage during haulback and likely underestimated the salmon escapement rate.

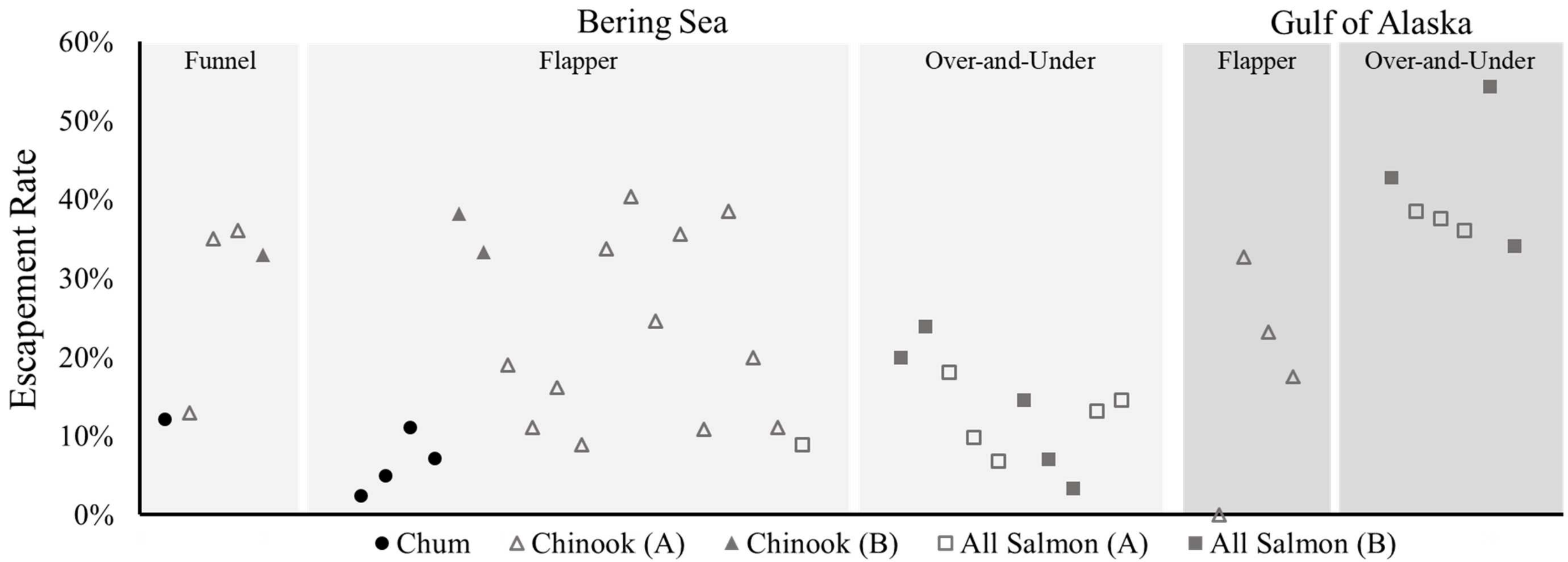

Bering Sea
Gulf of Alaska
Funnel
Flapper
Over-and-Under
Flapper
Over-and-Under
Escapement Rate
60%
50%
40%
30%
20%
10%
0%
Chum
Chinook (A)
Chinook (B)
All Salmon (A)
All Salmon (B)

Figure 1

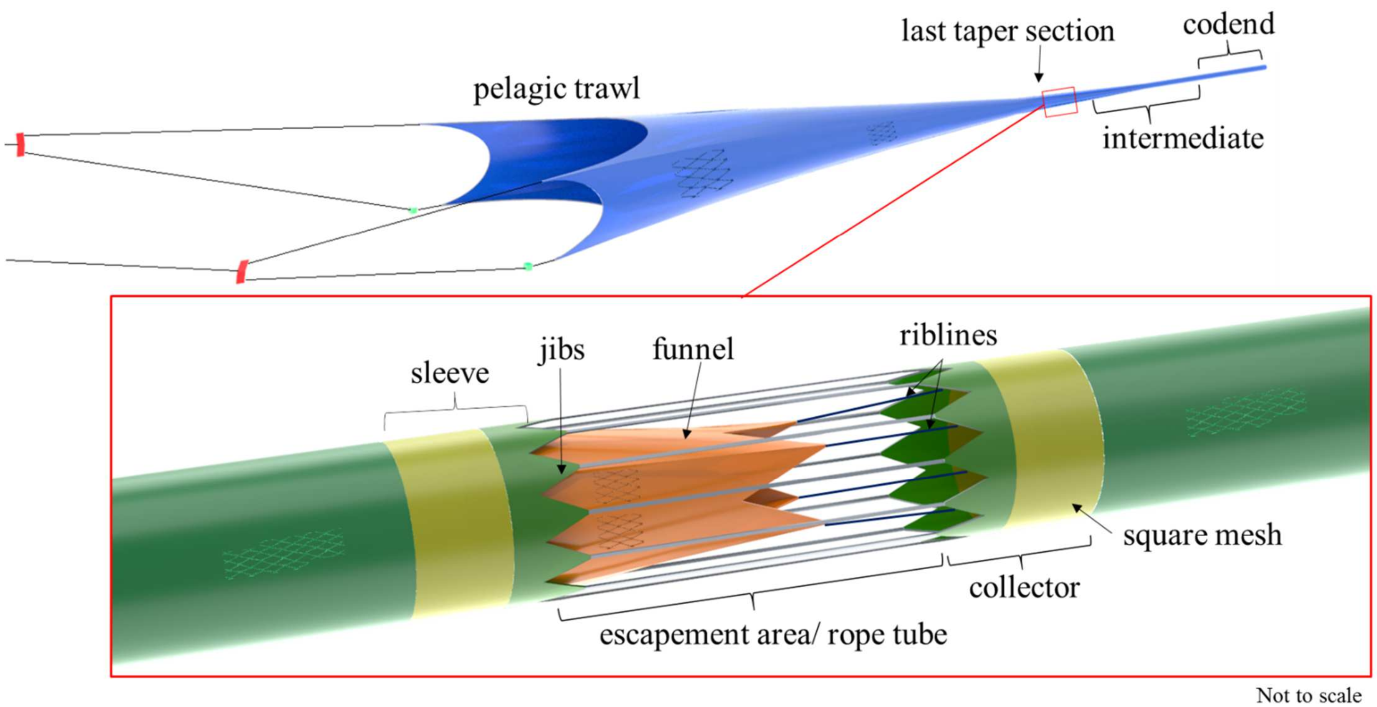

last taper section
codend
pelagic trawl
intermediate
riblines
jibs
funnel
sleeve
square mesh
collector
escapement area/ rope tube
Not to scale

Figure 2

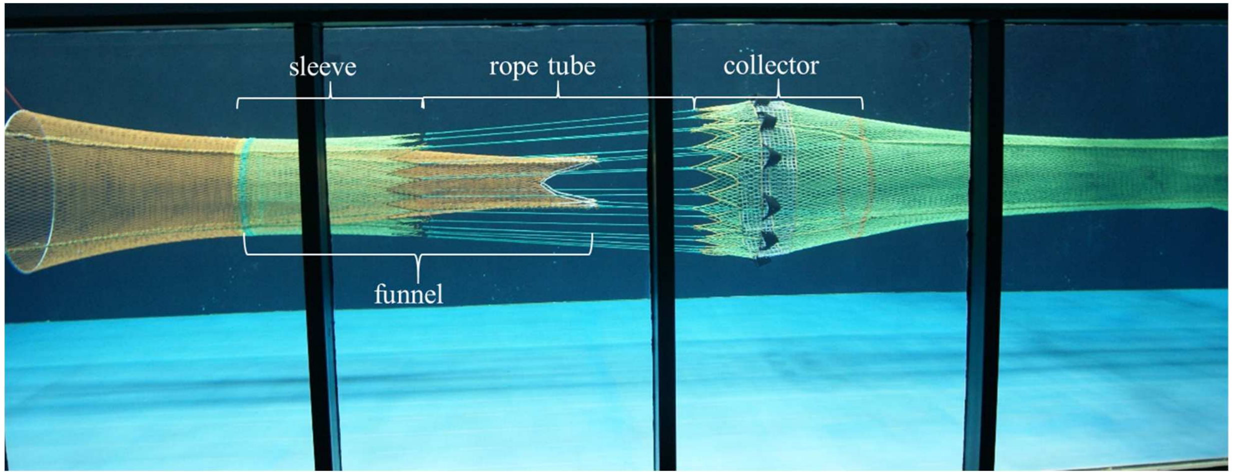


Figure 3

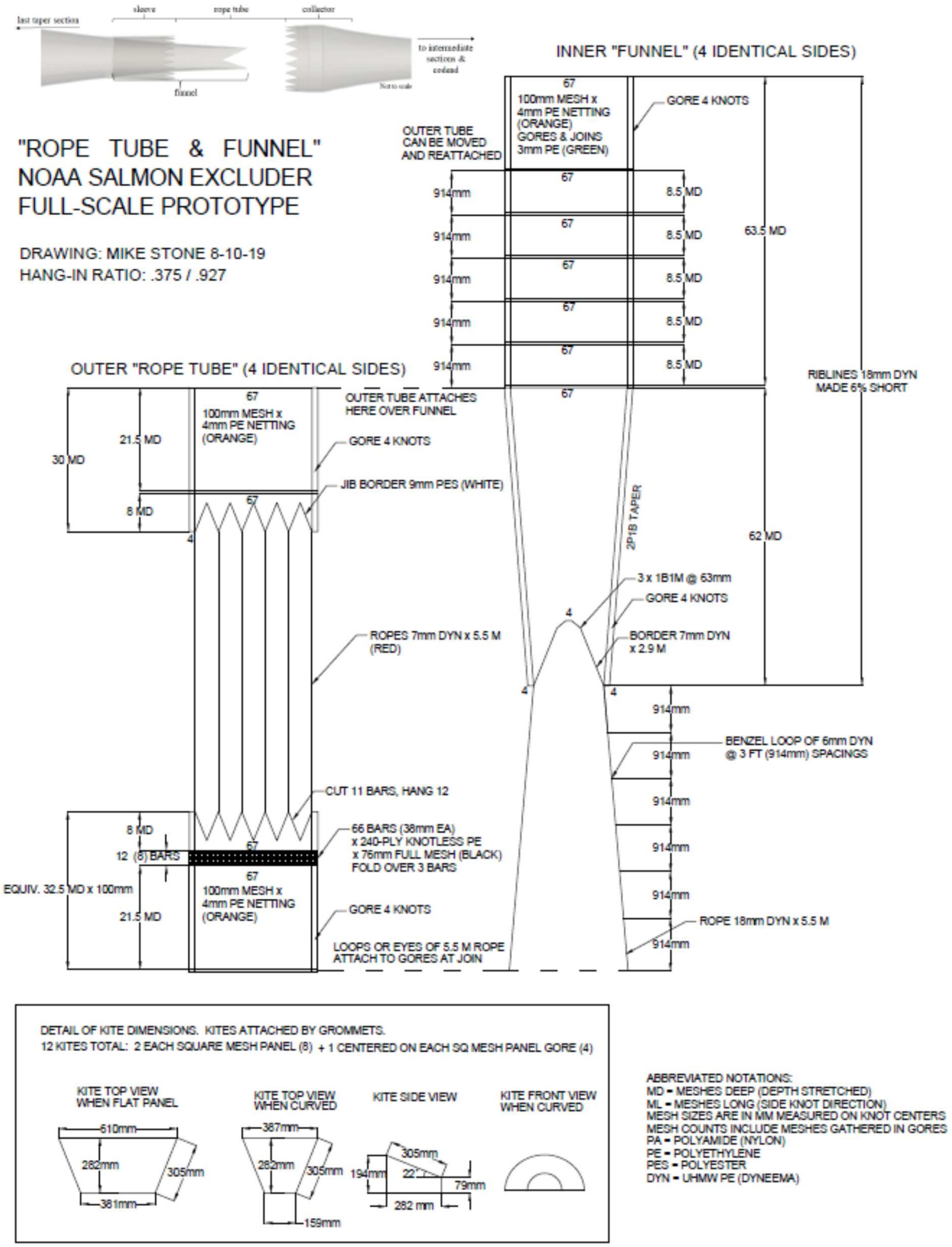

last taper section
sleeve
rope tube
collector
funnel
to intermediate sections & codend
Not to scale
"ROPE TUBE & FUNNEL"
NOAA SALMON EXCLUDER
FULL-SCALE PROTOTYPE
DRAWING: MIKE STONE 8-10-19
HANG-IN RATIO: .375 / .927
INNER "FUNNEL" (4 IDENTICAL SIDES)
100mm MESH x 4mm PE NETTING (ORANGE) GORES & JOINS 3mm PE (GREEN)
GORE 4 KNOTS
OUTER TUBE CAN BE MOVED AND REATTACHED
914mm
8.5 MD
63.5 MD
RIBLINES 18mm DYN MADE 6% SHORT
OUTER "ROPE TUBE" (4 IDENTICAL SIDES)
OUTER TUBE ATTACHES HERE OVER FUNNEL
100mm MESH x 4mm PE NETTING (ORANGE)
21.5 MD
30 MD
8 MD
JIB BORDER 9mm PES (WHITE)
2P1B TAPER
62 MD
3 x 1B1M @ 63mm
BORDER 7mm DYN x 2.9 M
ROPES 7mm DYN x 5.5 M (RED)
BENZEL LOOP OF 6mm DYN @ 3 FT (914mm) SPACINGS
CUT 11 BARS, HANG 12
66 BARS (38mm EA) x 240-PLY KNOTLESS PE x 76mm FULL MESH (BLACK) FOLD OVER 3 BARS
12 (8) BARS
EQUIV. 32.5 MD x 100mm
ROPE 18mm DYN x 5.5 M
LOOPS OR EYES OF 5.5 M ROPE ATTACH TO GORES AT JOIN
DETAIL OF KITE DIMENSIONS. KITES ATTACHED BY GROMMETS.
12 KITES TOTAL: 2 EACH SQUARE MESH PANEL (8) + 1 CENTERED ON EACH SQ MESH PANEL GORE (4)
KITE TOP VIEW WHEN FLAT PANEL
KITE TOP VIEW WHEN CURVED
KITE SIDE VIEW
KITE FRONT VIEW WHEN CURVED
610mm
282mm
305mm
381mm
387mm
159mm
194mm
22°
79mm
282 mm
ABBREVIATED NOTATIONS:
MD = MESHES DEEP (DEPTH STRETCHED)
ML = MESHES LONG (SIDE KNOT DIRECTION)
MESH SIZES ARE IN MM MEASURED ON KNOT CENTERS
MESH COUNTS INCLUDE MESHES GATHERED IN GORES
PA = POLYAMIDE (NYLON)
PE = POLYETHYLENE
PES = POLYESTER
DYN = UHMW PE (DYNEEMA)

Figure 4

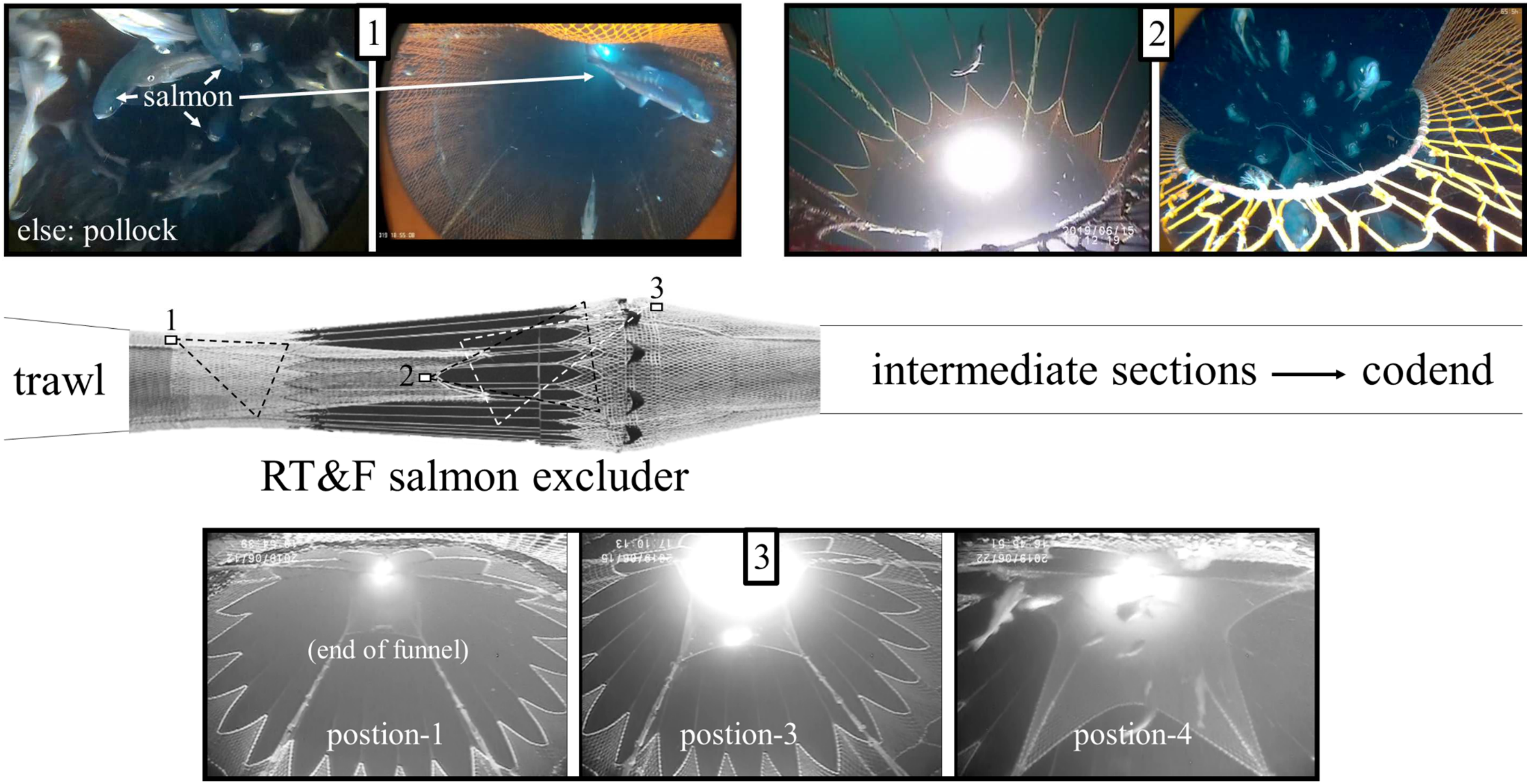

1
salmon
else: pollock
2
3
trawl
intermediate sections
codend
RT&F salmon excluder
(end of funnel)
postion-1
postion-3
postion-4

Figure 5

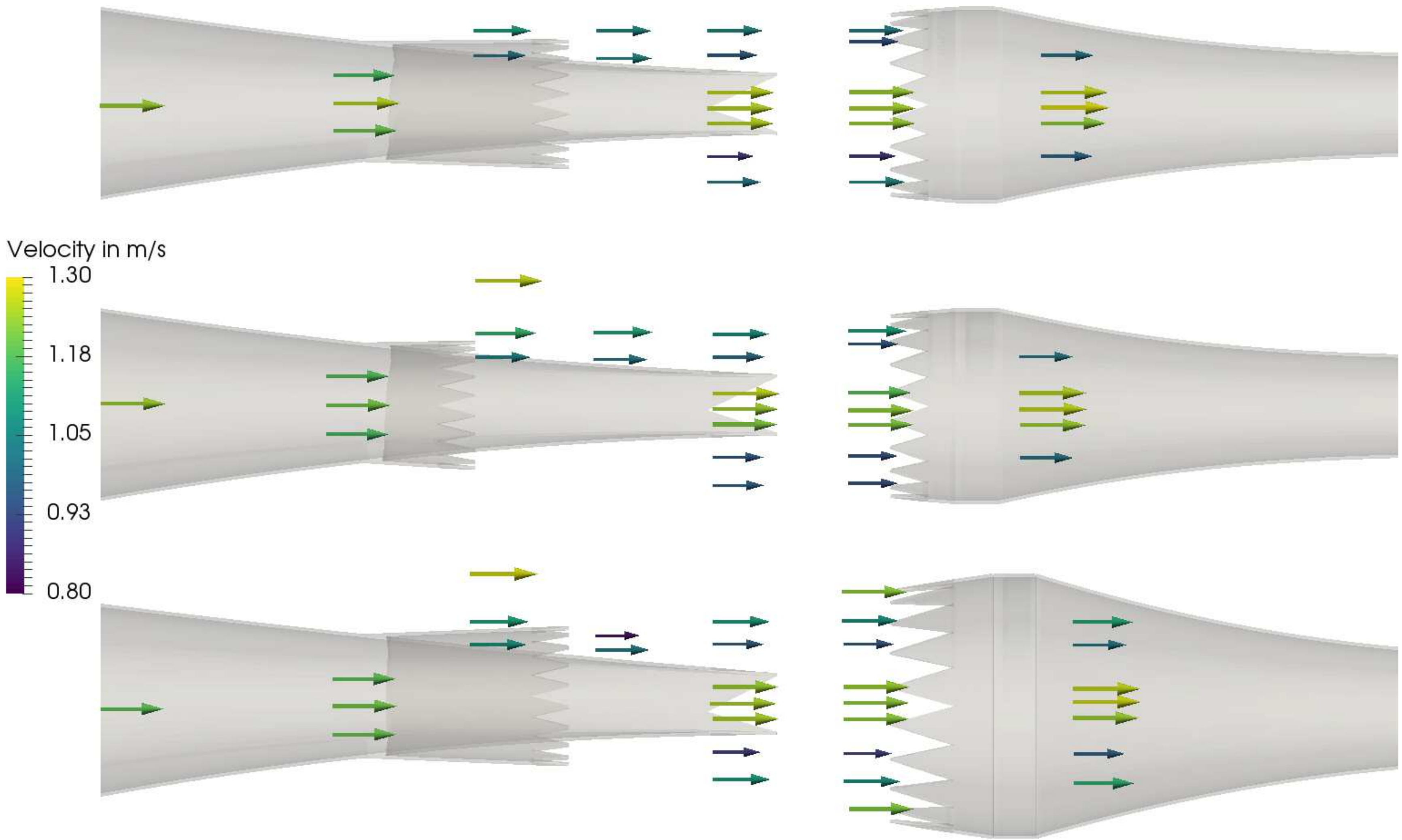


Figure 6

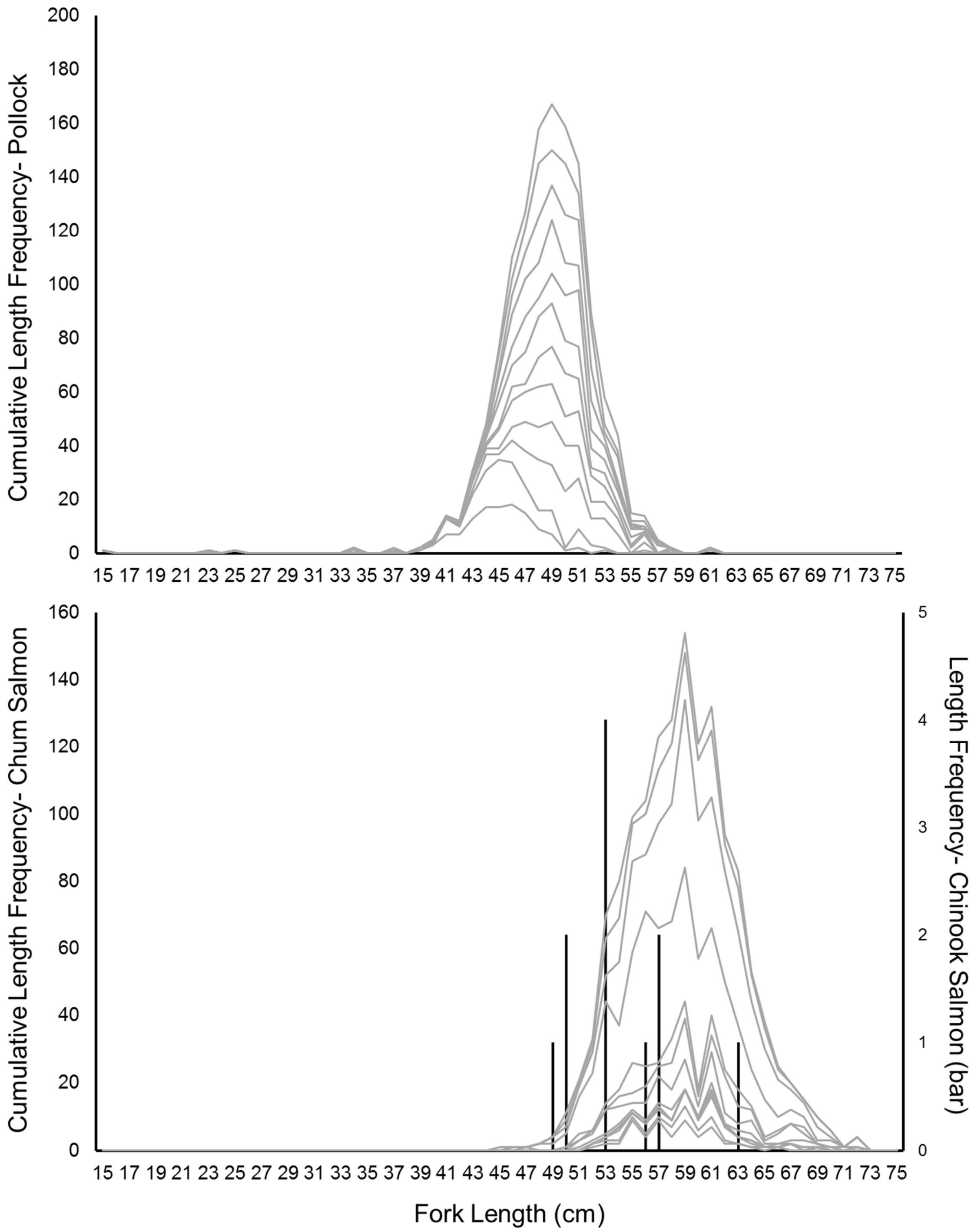
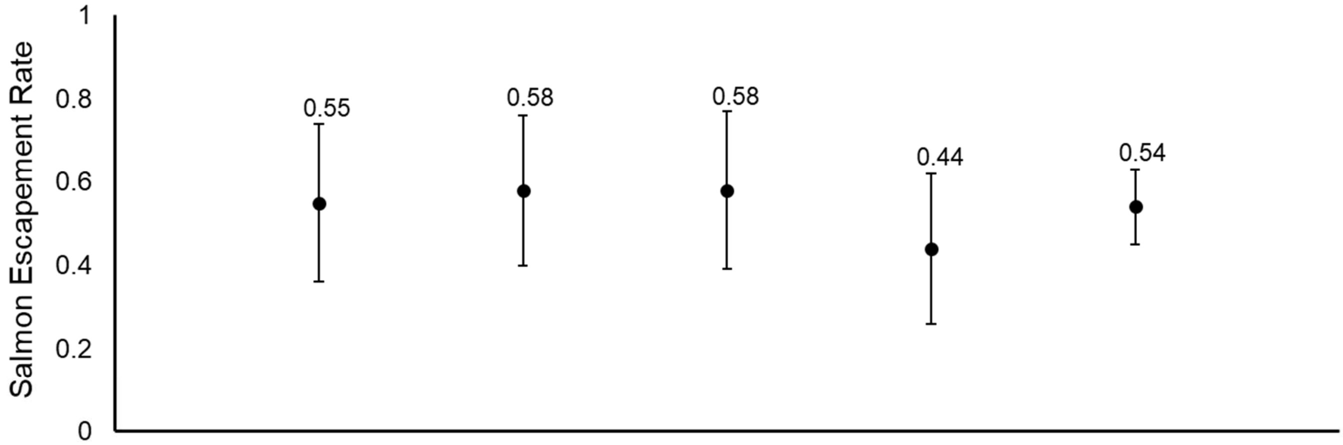

Cumulative Length Frequency- Pollock
200
180
160
140
120
100
80
60
40
20
0
15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59 61 63 65 67 69 71 73 75
Cumulative Length Frequency- Chum Salmon
160
140
120
100
80
60
40
20
0
Length Frequency- Chinook Salmon (bar)
5
4
3
2
1
0
15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59 61 63 65 67 69 71 73 75
Fork Length (cm)

Figure 7



Tows	All	All ≠ 21	Sleeve-3	Sleeve-4	Sleeve-4 ≠ 21
N	12	11	9	3	2
Min	0.23	0.38	0.38	0.23	0.47
Max	0.83	0.83	0.83	0.60	0.60

Figure 8

Table 1 Information about the 16 trial tows during which video footage was collected, including: time of day the tow began (light grey: 0900 to 1200; medium grey: 1201 to 1500; dark grey: 1501-1830); the position of the sleeve (1-6, indicating attachment closer (1) or further forward (6) from the start of the funnel taper); salmon escapement rate; total number of salmon observed going down the funnel; estimated pollock caught; tow duration from when the gear began fishing to the beginning of haulback; average of the speed over ground ('SOG') at the start of fishing and at the beginning of the haulback as determined by Globe software; average depth of the tow at the excluder from archival tags; amount of wire out to the trawl doors; estimated wind speed and swell height from the captain; and average temperature ('Temp.') over tow duration based on sensor data placed at the headrope. Note that some fields were not included when the codend was partially open (Pollock= 'X') or if video footage was lacking to quantify salmon (Salmon= 'X').

Tow No.	Time of Day	Sleeve Position	Salmon Escapement	Salmon (N)	Pollock (t)	Duration (h)	Catch rate (t/h)	SOG (m/s)	Depth (m)	Wire Out (m)	Wind Speed (m/s)	Swell Height (m)	Temp. (°C)
8		3	0.43	101	18	3.2	6	1.4	118	448	10	2	4.6
9		3	0.70	70	30	3.3	9	2.1	111	311	8	2	4.7
10		3	0.40	10	0	1.0	0	1.7	114	539	8	1	4.7
11		3	0.41	59	50	2.8	18	1.9	106	421	8	0	5.2
12		3	0.79	24	18	1.2	15	1.5	104	450	8	1	5.2
13		3	0.83	12	10	1.2	8	1.6	208	750	8	1	4.3
15		3	0.79	87	2	3.2	1	2.0	165	439	8	2	4.9
16		3	0.53	158	15	2.5	6	2.0	119	402	5	1	4.8
17		3	0.38	121	22	3.6	6	1.9	94	466	5	1	6.7
18		4	0.47	108	3	2.1	1	2.2	121	479	5	1	4.7
20		4		X	125	4.5	28	1.9	100	388	8	1	6.3

21		4	0.23*	537	105	2.9	36	2.2	92	316	1	1	6.1
22		4	0.60	458	35	3.1	11	1.9	94	380	0	0	6.2
23		4			X	0.9		1.8	101	402	5	0	6.7
24		4			X	1.3		2.2	97	439	0	0	6.3
26		4			X	1.6		1.5	159	585	8	1	4.6

* Tow 21 did not have video footage during haulback, which likely resulted in an underestimation of escapement.