Observations of Fish and Shrimp Behavior in Ocean Shrimp (*Pandalus jordani*) Trawls

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Abstract

Underwater video observations of ocean shrimp (*Pandalus jordani*) and fish inside shrimp trawls and interacting with bycatch reduction devices (BRDs) were summarized. Ocean shrimp behavior inside trawl nets was passive and reactive in comparison to fish which generally exhibited the more typical optomotor responses. Mesh escapement for shrimp was mostly a two stage process in which shrimp entered an open mesh tail first. Escapement would occur a few seconds to many minutes later after a stimulus, such as motion of the catch or movement of the netting, initiated an escape response (tail flip) from the shrimp. Observations of rigid-grate BRDs showed that an accelerator funnel or panel was an important component of a successful BRD, keeping shrimp away from the escape hole and accelerating shrimp transport into the codend. Rigid-grate BRDs also provided a much more consistent net shape and grate angle with minimal water flow out the escape hole. Soft-panel BRDs were shown to deliver unpredictable angles in the deflector panel, due to an unpredictable net shape and diameter in the intermediate portion of shrimp nets, with associated water flow out the escape hole. Observations of the fisheye BRD showed it to be an ineffective BRD in ocean shrimp nets and very sensitive to placement.

Introduction

Bycatch reduction devices (BRDs) are now required fishing gear in many shrimp and prawn trawl fisheries throughout the world. A partial list includes the Gulf of Mexico and south Atlantic fisheries for penaeid shrimp, the Gulf of Maine fishery for northern pink shrimp (*Pandalus borealis*) and the U.S. and Canadian west coast trawl fisheries for ocean shrimp (*Pandalus jordani*). With the growing need to find effective BRDs in different types of fisheries with different styles of trawl nets, many comparative fishing experiments have been conducted to measure the relative performance of BRDs (e.g. Rogers et al. 1997, Brewer et al. 1998) and other net modifications that reduce bycatch, such as square-mesh panels (e.g. Broadhurst et al. 1996, Broadhurst and Kennelly 1996). These quantitative studies are probably the most useful approach to developing better BRDs, however they often don't yield direct information on the behavior of fish and shrimp inside trawls as they interact with BRDs and other components of the trawl net.

Understanding the behavior of fish and shrimp inside trawls and interacting with BRDs is an important component of the development of effective BRDs. It is also an important consideration when deciding about investing in research on BRDs as opposed to trawl designs that avoid or reduce entrainment of bycatch at the net mouth (e.g. Hannah and Jones 2003, Banta et al. in press). Observations of behavior can also shed light on the physical condition of fish and shrimp escaping through BRDs and codend meshes and potentially on their ultimate survival, which has been brought into question by studies of stress on fish escaping from codend meshes (e.g. Ryer 2002, Lehtonen et al. 1998).

The first underwater video observations of BRDs in the ocean shrimp trawl fishery were collected in 1994, shortly after fishermen began experimenting with soft-panel BRDs to reduce bycatch of Pacific hake (*Merluccius productus*)(Hannah et al. 1996, Hannah and

Jones 2000). These early observations were mostly collected to verify the proper configuration of BRDs to be tested in subsequent comparative fishing experiments. However, they led to many more opportunities to record underwater video observations inside ocean shrimp trawls between 1996 and 2000, as a part of cooperative efforts between the Oregon Department of Fish and Wildife and the Oregon shrimp industry to develop better BRDs for ocean shrimp trawls. These video observations were collected as part of a wide variety of brief studies with various objectives, ranging from BRD evaluation to simple observation of shrimp behavior inside trawls, as well as attempts to use video to better understand the catchability of shrimp trawls. This paper summarizes these observations of shrimp and fish behavior inside shrimp trawls generally, with a focus on findings that relate specifically to aspects of BRD design that effect performance.

A general understanding of how different BRDs work and interact with net design is important basic information for developing effective BRDs in various fisheries. Ideally, BRD development for a fishery would begin with flume tank tests of various designs with various net styles, followed by extensive field tests that would refine a list of effective BRDs for a given fishery and bycatch problem, and perhaps provide guidance on BRD specifications to match individual net sizes and styles. In the real world, a mandate to develop BRDs for a fishery often arises from a conservation crisis, without adequate time or research funding for rational BRD design and testing. In these instances, BRD development is left to the fishing industry, with some guidance and testing supplied by the management agencies. Accordingly, the development of effective BRDs is sometimes a "trial and error" process, pitting what is known about BRDs in other fisheries against the local industry' s idea of what would make a workable BRD in their fishery. The history of BRD development for the ocean shrimp fishery fits this model. The process can be lengthy and can involve re-testing of BRD designs that have been tested and rejected in other fisheries. A second objective of this paper is to provide information on BRD designs that did not work reliably in the ocean shrimp fishery and hypotheses as to why they failed, the ultimate goal being to facilitate the more rapid development of successful BRDs in other fisheries.

Methods

The video observations described in this report were collected during commercial shrimping operations or research charter fishing on the commercial shrimp grounds between Newport and Astoria, Oregon (Figure 1). The depths fished ranged from about 120-200m. The nets used were all of standard 4-seam design, generally between 20 and 27m in footrope length. The vessels used were all of double-rigged design, and BRDs were generally employed in only one net at a time to allow a visual comparison of the catch. In some cases, a quantitative description of the catch in each net was compiled using the methods described in Hannah et al. (1996). In such cases, a specially modified divided hopper was used to keep the catches from the port and starboard nets separate.

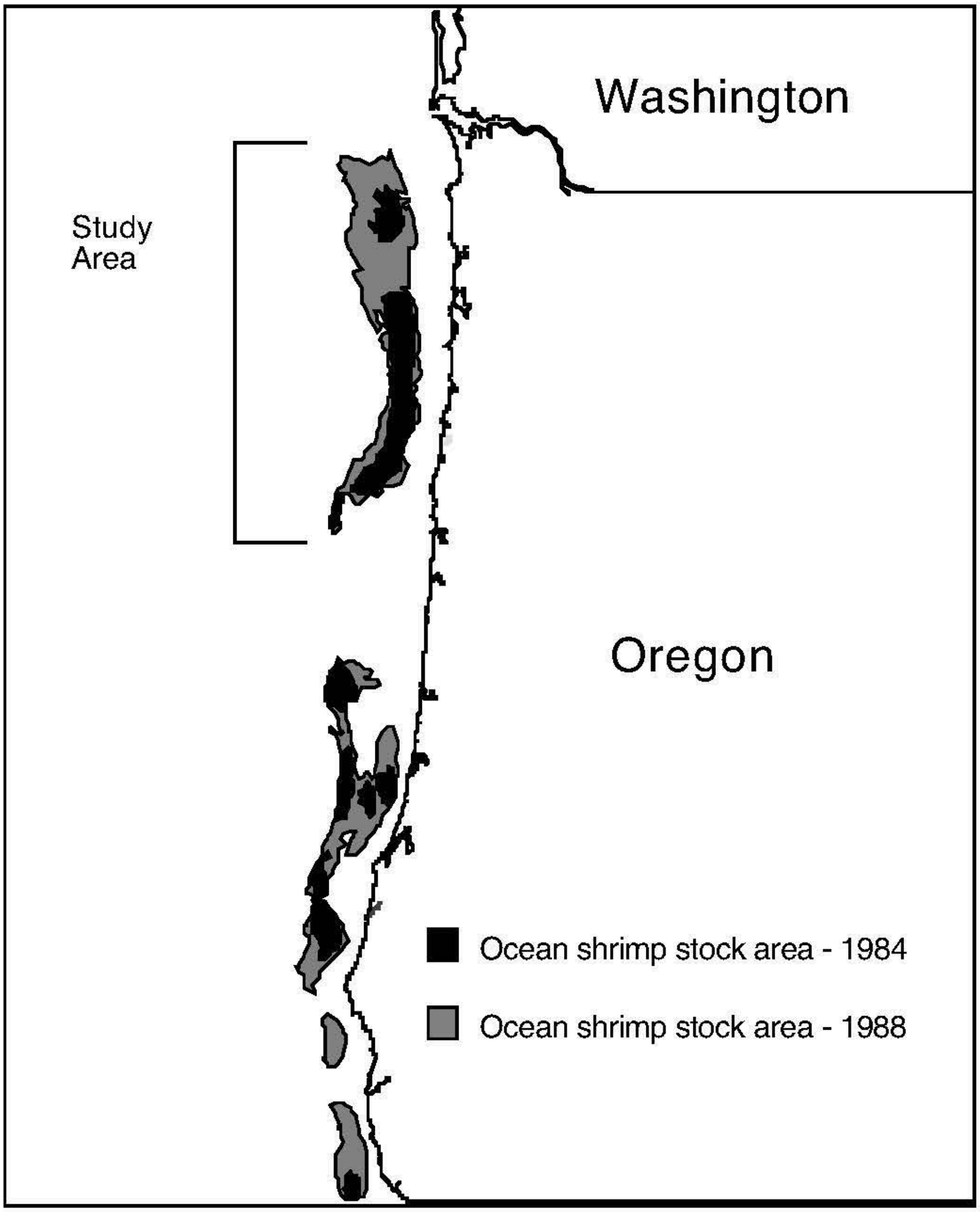

Figure 1. Study area and locations of commercial concentrations of ocean shrimp (*Pandalus jordani*) off coastal Oregon. Dark areas show the approximate minimum areal extent of the shrimp grounds (1984) and the lighter shaded areas show the largest areal extent observed from 1980-96 (1988).

The underwater video system we used consisted of a small black and white underwater camera and one or two lights, connected by cables to a pressure housing holding an 8mm video camcorder and a series of 12 volt gel-cell batteries (Figure 2). The camera and lights were mounted on 3/4 inch thick high density polyethylene (HDPE) plates with aluminum brackets to allow adjustment of camera and light angles. The HDPE plates were constructed with numerous large holes to lighten them and facilitate fastening of the plates to the trawl netting.

Our camera system was designed to operate remotely, with no cables to the vessel on the surface. To use the system, the camera and lights were first attached to the net in the area to be observed. Next, the camcorder was started and the underwater housing was sealed and attached to the net. The housing was then connected to the camera and lights and the trawl was deployed, with the camera system running. After the trawl was retrieved, the housing was removed and opened and the videotape was reviewed, at which point any adjustments to camera or lighting angles or viewing location were made and the trawl re-deployed. With this system, obtaining good footage was a "trial and error" process and somewhat time consuming and highly dependent on water clarity.

The video observations described in this report were collected from a wide variety of shrimp trawls and BRDs. Camera positions varied from study to study, including camera positions both inside and outside of the trawl nets. For almost all of the observations, the available natural light was insufficient for filming and artificial lighting had to be used. The wattage of bulbs used ranged from 20 to 100 watts. It has been shown that the presence or absence of light can alter the behavior of fish reacting to trawls (Glass and Wardle 1989). The synthesis of behavioral observations presented here for fish and shrimp assumes that the presence of artificial light did not significantly alter the observed behavior. This is probably a reasonable assumption for the ocean shrimp grounds because low levels of natural light are most likely available during daylight hours when these observations were obtained. Shrimp have been shown to migrate vertically in response to reduced light levels at the surface (Pearcy 1970, Beardsley 1973).

For observations of the behavior of shrimp escaping from codend meshes, the camera and lights were attached on the outside of the codend, on the top looking aft and down, towards the pursing rings. For these observations, a 35mm (stretched measure) diamond mesh codend was used. This is slightly larger than the average codend mesh used by most Oregon shrimp vessels (about 29mm) and very close in size to the mesh used in the body portion of Oregon shrimp trawls, as well as the minimum codend mesh size required in California waters (Jones et al. 1996). The larger codend mesh size was used to be certain that many mesh escapements would be observed.

For observations at the net mouth, the camera and lights were attached to the fishing line looking sideways. For observations of shrimp and fish passing under the fishing line of the trawl, the camera and lights were attached on the underside of the netting in the trawl belly, just behind the fishing line, looking down at the substrate and slightly forward. Ocean shrimp trawls are semi-pelagic trawls that are rigged to maintain a constant height above bottom, ranging from about 35-70 cm depending on how the footrope is rigged

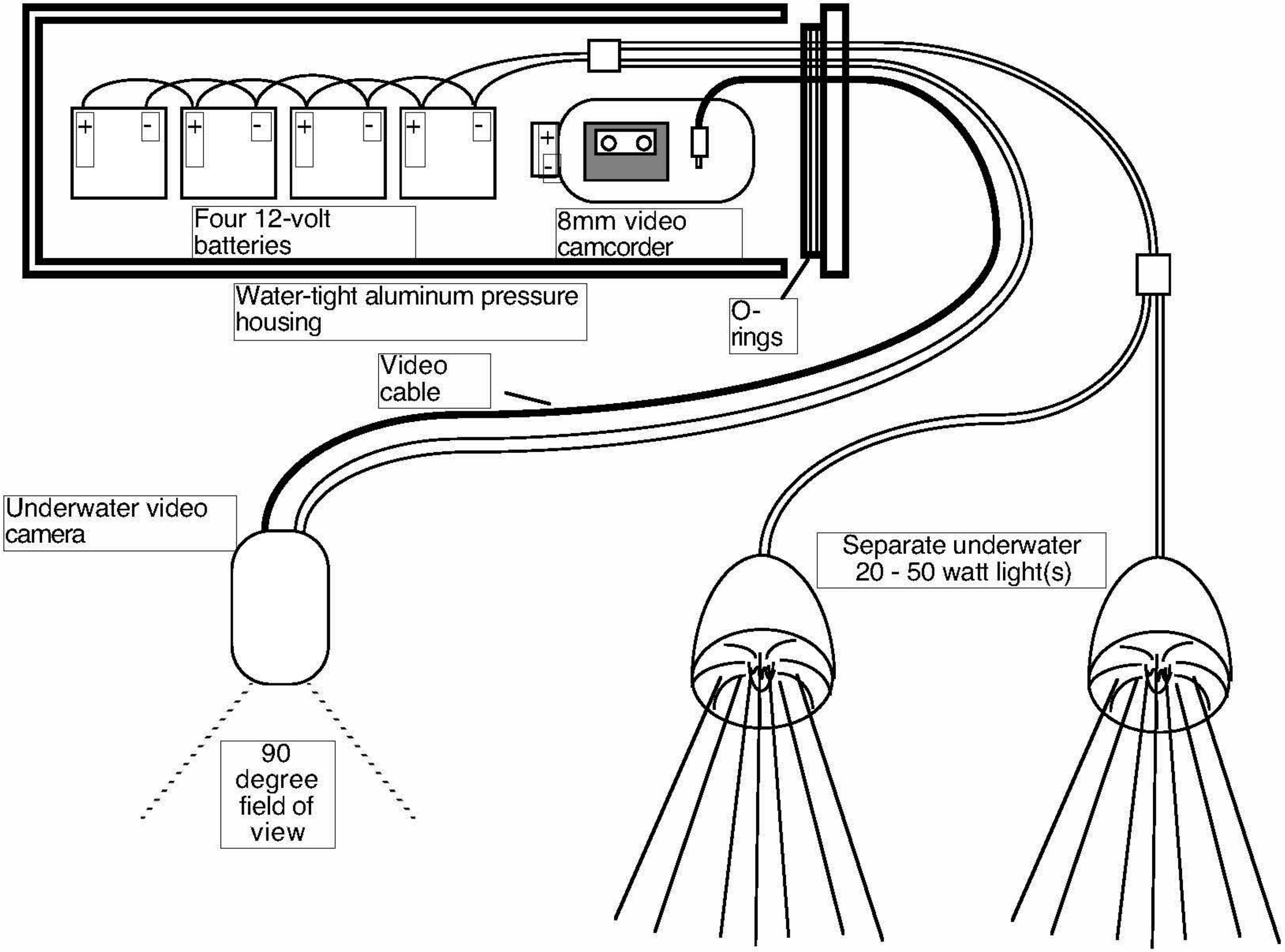

Figure 2. Schematic of the remote underwater video system.

(Hannah and Jones 2003). In this instance the vessel was fishing a "tickler chain" style footrope, so to obtain clear observations under the trawl, we disconnected the tickler chain in the center of the footrope to eliminate the mud cloud it would have produced. Accordingly, the effects of the tickler chain on shrimp behavior on the sea bottom were not observed.

Observations of fish and shrimp interacting with rigid-grate style BRDs were collected with both the Nordmore grate (Isaksen et al. 1992) and also with what has come to be called the "Oregon grate" BRD (Figure 3). Variations of the Oregon grate are becoming the most popular BRD in use in Oregon's ocean shrimp trawl fishery. This BRD was a result of efforts by Oregon fishermen to develop a rigid BRD that had the excellent exclusion and shrimp loss performance of the Nordmore grate, but without it's problems. The problems sometimes noted with the Nordmore grate included clogging in the funnel area (Figure 3) and spinning of the grate when nets were dragged at the surface of the water, as a vessel relocated between hauls. The spinning of the grate was the most common problem reported for rigid-grate BRDs used in Oregon and has been considered a serious problem by shrimp vessel operators. Prior to the development of the smaller, round Oregon grate, the only way to prevent the grate from spinning was to completely reload all nets and doors onto the vessel prior to relocating, a time consuming and at times hazardous process for double-rigged shrimp vessels.

Observations of rigid-grates were obtained from several camera angles, including just in front of the grate looking up from the bottom of the net, from the top inside of of the net looking down at the grate and just outside and in front of the triangular escape hole, looking aft. The Nordmore grate we used was made of high-density polyethylene and employed a bar spacing of 25mm. It was 66cm wide by 134cm tall and was enclosed in an aluminum support frame to allow it to be quickly enabled or disabled (Hannah et al. 1996). Four orange 11cm plastic floats were placed immediately aft of the top of the grate to help maintain the grate in an upright position. The Oregon grate was circular in shape and constructed of 25mm diameter, thick wall, aluminum tube. The grate was 107cm in diameter. Bar spacing was 51cm.

Observations of soft-panel BRDs (Figure 4) were also collected using various camera views. Footage was recorded from in front of the deflection panel looking upwards and aft and also from outside of the net, in front of the escape hole, looking back at it. The soft-panels observed ranged in mesh size from 76-203mm, and like the rigid-grate BRDs, were sewn into diamond mesh sections of "intermediate" netting at various angles. The intermediate netting that carried the grates and deflector panels was generally 38mm mesh polyethylene netting sewn into an untapered tube, 200 meshes around. In most instances the deflector panel was constructed of polyethylene netting, but in one instance, nylon netting was used. Unlike the Nordmore and Oregon grates, the soft-panel BRDs did not employ any device for concentrating and accelerating the catch at the bottom of the net prior to reaching the panel.

Observations of fisheye BRDs (Figure 5) were collected mostly from inside the codend, with the camera positioned near the back of the top of the codend looking up and

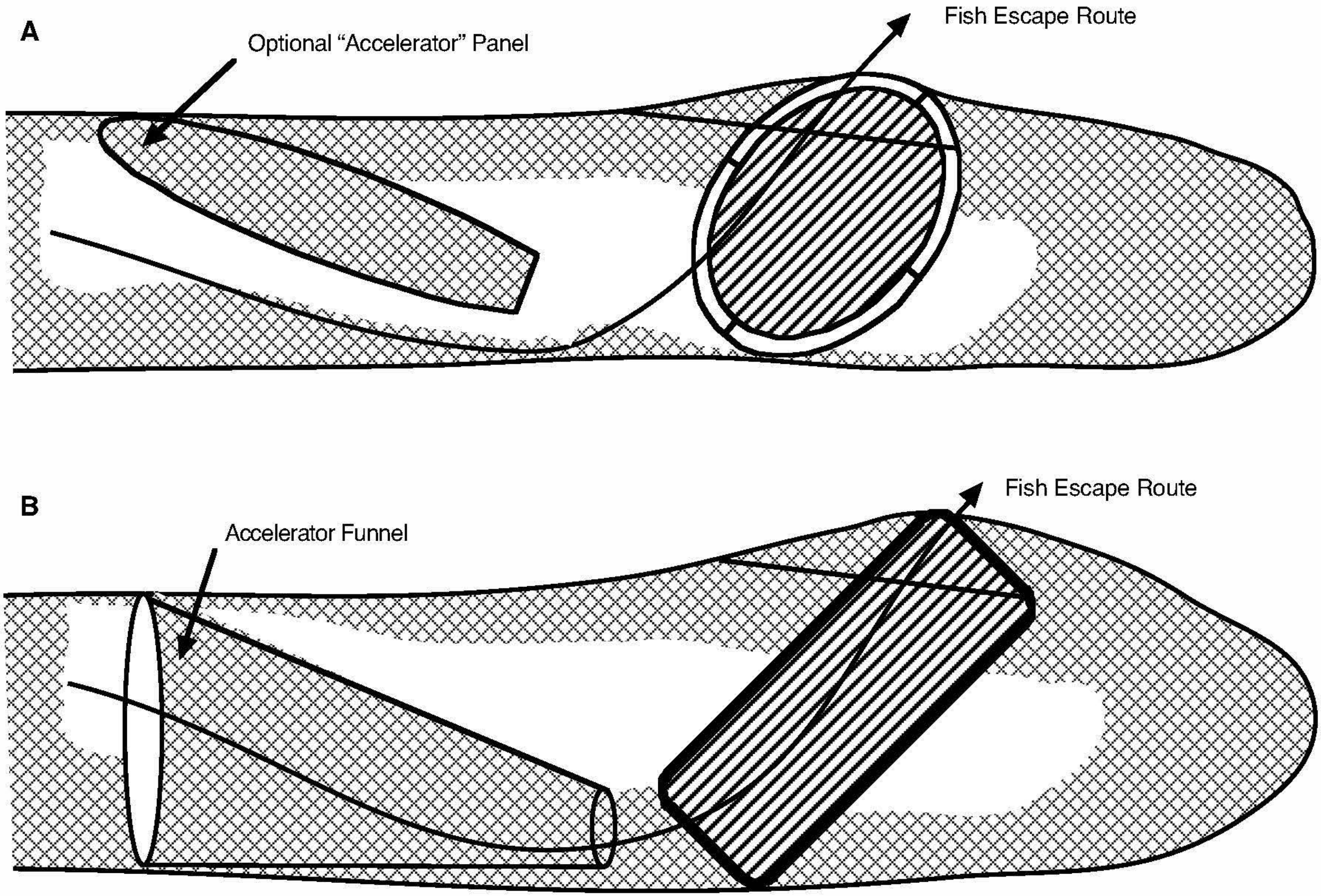

Figure 3. Schematic of the Nordmore (A) and Oregon (B) grate bycatch reduction devices.

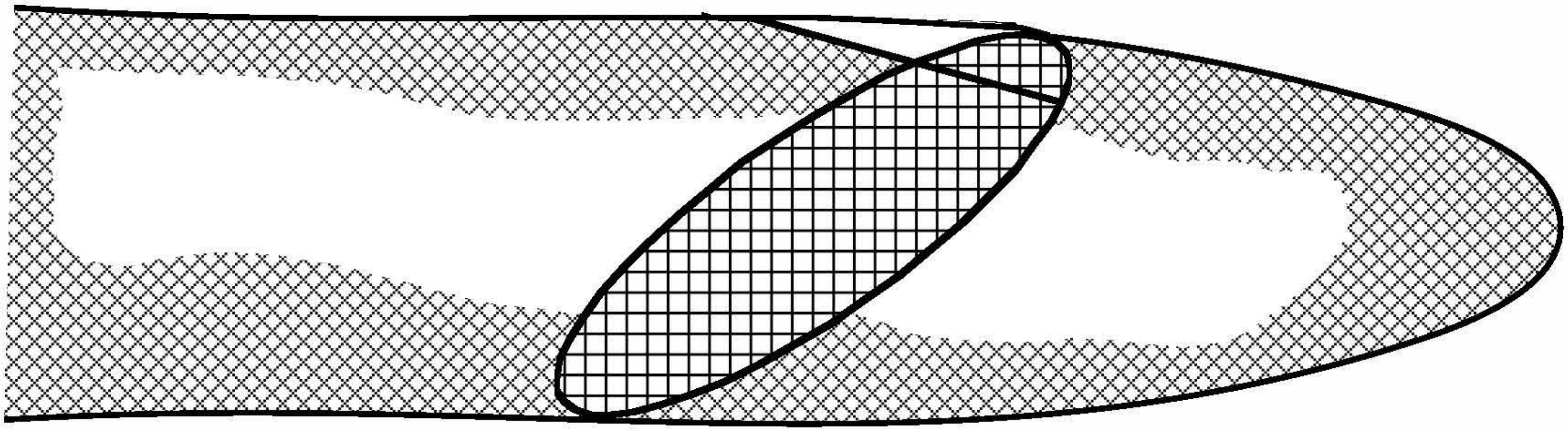

Figure 4. Schematic of a typical soft-panel bycatch reduction device in the ocean shrimp trawl fishery.

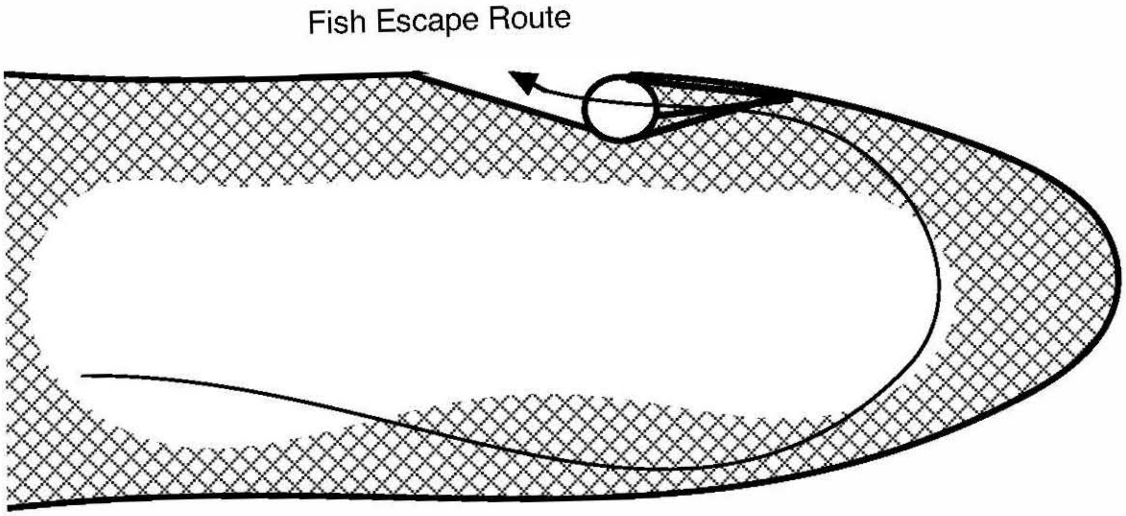

Figure 5. Schematic drawing of “fisheye” bycatch reduction device.

forward towards the escape aperture. The fisheye BRD was constructed out of 8mm stainless steel rod, and employed a forward facing “eye” shaped escape aperture measuring about 35cm across by 22cm deep.

Results

Underwater video observations of shrimp trawls were collected from approximately 62 hauls on 5 different cruises from 1994 to 2002 (Table 1). Observations were collected on 5 different designs of soft-panel BRD and 2 different designs of rigid-grate BRD, including the Nordmore grate and Oregon grate BRDs (Figure 3). Due to the type of video system used, not all hauls in which video footage was collected resulted in useful observations. Accordingly, the observations reported here are based on a collection of about 50 videotapes in which good views of fish and shrimp behavior were obtained. Most of the cruises produced many useful observations of shrimp and fish interacting with various elements of the trawl nets.

Observations in the Codend and of Shrimp Mesh Escapement

Underwater video observations inside shrimp trawl codends were collected on several cruises, however a research cruise in June 1996 on the F/V Lady Kaye (Table 1) focused in particular on observing shrimp behavior inside the codend and as shrimp escaped through codend meshes.

The behavior of ocean shrimp observed inside the trawl net can best be described as “passive” or “reactive”. Shrimp moving backwards in the water flow inside the net did not demonstrate much ability to orient in any fashion to the flow, and were sometimes seen tumbling towards the back of the codend. The shrimp generally assumed a posture with their tail straight behind, and walking legs and antennae spread out to the sides. The pleopods of the shrimp were often seen moving, perhaps in some effort to maintain an orientation, however currents within the net were clearly more than the shrimp could cope with. An escape response, characterized by rapid flexing of the tail section, was observed at times, and when observed it appeared to be a response to contact with the net material, turbulent water flow or contact with other shrimp and fish inside the net.

Although active flow of water was observed in the intermediate section of the net, the codend itself appeared to be a dead-water area with little flow of water towards the back of the net. The catch of shrimp and fish was observed to shift around in the codend, in response to undulating movements of the codend net material, probaby caused by the effect of swell on the towing vessel (O’Neill et al. 2003). Fish in the codend periodically swam forwards away from the crowded aft portion of the codend, often to subsequently drift backwards into view again. Ocean shrimp, however, made no obvious directed movements within the codend.

Observations from the outside of the codend showed that many shrimp were escaping from more forward areas of the trawl. These shrimp could be seen passing by from

Table 1. Summary of shrimp cruises and underwater video observations of shrimp nets and BRDs.

Fishing Vessel	Dates of Fishing	Hauls Observed	Main Target of Observations
Prospector	October 9-12, 1994	15	Soft-panel and Nordmore grate BRDs.
Lady Kaye	June 19-23, 1996	19	Shrimp behavior and mesh escapement.
Calamari	June 5-13, 1997	15	Soft-panel and fisheye BRDs.
Miss Yvonne	May 11-13, 2001	10	Soft-panel BRD with support ring.
Miss Yvonne	September 2, 2002	3	Oregon grate BRD.

behind the camera, and given the size and height of the trawl, most likely exited the larger meshes of the trawl body prior to being observed.

Shrimp were seen escaping from the 35mm mesh codend throughout the entire tow. We did observe a slight increase in escapement on a few tows just as the net neared the surface and began to surge. We also observed sea birds feeding on fish escaping from the meshes at the surface. Although we did see some shrimp consumed by birds, the birds showed an obvious preference for small fish, seeming to mostly ignore the ocean shrimp.

In general, mesh escapement was also a "passive" or "reactive" process for ocean shrimp. Shrimp were not observed in any directed movements in relation to the trawl netting, but rather floated around passively inside the net, with legs and tail stretched out, showing no particular directional orientation. Most escapement occurred tail first. In most instances, escapement was a two stage process. First, a shrimp would bump into an open mesh tail first, and partially exit the net. Then, after hanging there for anywhere from a few seconds to many minutes, some stimulus would cause the shrimp to flex its tail in an escape response and, as a result, the shrimp would pop out of the mesh completely and drift off. Various stimuli caused shrimp to flex and exit the net, including movements by fish inside the net and periodic undulating motions of the net material itself. Increases in mesh escapement were observed in conjunction with major movements of the catch inside the net. In general, the shrimp looked to be in good condition as they exited the meshes.

Observations at the Net Mouth

During the 1996 cruises on the F/V Lady Kaye, we also obtained video observations underneath the belly of the trawl, and at the net mouth just above the footrope. The footage looking downwards from the underside of the trawl showed many flatfish, hagfish and shrimp passing underneath the trawl fishing line, which was well above bottom. Interestingly, the hagfish were often coiled up in small depressions in the sea floor. The observations from the belly of the trawl, above the fishing line, showed the fishing line was stable and running 20-50cm above the sea bottom. The large scale of the trawl in this area made it difficult to see much, given the limited wattage of the lights being used and "back scatter" caused by suspended particulates. The video only showed some shrimp and fish going by, sea pens encountering the fishing line and brushing underneath it, and a short expanse of net receding into the darkness.

Observations of Rigid-grate BRDs

We first obtained underwater video footage of the Nordmore grate BRD (Figure 3) in 1994, working aboard the F/V Prospector. Anticipated problems with the Nordmore grate included fish clogging the funnel area, the tall grate potentially falling over on its side during trawling and an improper angle of the grate (45-48° angle to the horizontal is recommended, Isaksen et al. 1992). Observations showed the Nordmore grate to be quite stable underwater, and showed little clogging in the funnel area, however very large fish were not observed using the funnel. Video footage of an underwater inclinometer showed however that the angle of the grate was too shallow. The grate was re-installed at a higher angle and continued to work very well.

With the Nordmore grate system, shrimp were seen to be jetted out of the accelerator funnel at high velocity towards the bottom of the angled grate, with most jetting right through the narrow bars. Some shrimp hit the bars and bounced upwards, however most shrimp drifted through the vertical bars without rising very far towards the escape hole.

Some small fish exiting the accelerator funnel were seen to be jetted through the grate along with the shrimp. Larger fish exiting the funnel generally bumped into the grate and drifted upwards along it. The most common behavior was for a fish to "station keep" just in front of the grate, periodically drifting back into the grate and moving upwards and backwards until reaching the escape hole and exiting the net. For fish exiting the accelerator funnel head first, they sometimes swam quickly right up the inclined grate and out of the net. Some fish swam forward and spent some time above the accelerator funnel before exiting the net. In most instances, the fish looked to be in good condition prior to exiting the net. However, some fish were seen to rest on the grate for several minutes before exiting the net. In other instances, exhausted fish, particularly Pacific whiting, were seen to roll sideways up the inclined grate and out of the net.

In fall 2002, we collected underwater video observations of the Oregon grate BRD (Figure 3). These observations showed a very predictable and stable net configuration, as found with the Nordmore grate. The large triangular escape hole was also maintained in a wide open configuration by the grate. The aperture between the inner and outer ring of the Oregon grate was not observed to either help or hinder shrimp passage or water flow back into the codend, although it may reduce flatfish exclusion rates. Small and medium sized flatfish were frequently observed swimming through the external ring area back into the codend. The accelerator panel (also called a "down panel") which was designed to bring all catch to the bottom portion of the net prior to reaching the grate, was observed to be very effective. Nearly all of the shrimp were seen to pass through the grate within the lower 2/3 of the grate surface. The water flow under the accelerator panel was also clearly accelerated by the constriction, as designed. The jet of water created was instrumental in pushing shrimp through the grate before they could rise up towards the escape hole.

As in most of our other underwater observations of ocean shrimp nets, we observed a periodic undulation in the codend and intermediate netting material. This phenomenon was characterized by a period of several minutes during which the codend was very stable and fully open and upright, followed by a pulse lasting perhaps 3-10 seconds in which the netting surged forwards and/or rotated sideways causing a brief period of slack in the netting. This was accompanied by undulations in the netting of the accelerator panel, followed by the codend netting quickly stretching out into a stable configuration once again. The periodic movements of the netting were associated with increased movements of fishes and also with fluctuations in the vertical distribution of shrimp passing through the Oregon grate. Often, during a pulse in the netting, undulations in the accelerator panel would send a puff of water and shrimp upwards towards the escape hole. It was clear from the observations that without the accelerator panel the undulations in the codend and intermediate netting would likely have sent shrimp out the escape hole.

Although the Oregon grate was shown to be highly effective at reducing bycatch, the behavior of fish using it showed some of the remaining problems with even the best BRDs in shrimp trawls. Many of the small and medium sized fish appeared quite tired by the time they reached the grate, suggesting the possibility of reduced survival of escaping fish. Larger fish, such as Pacific halibut (*Hippolglossus stenolepis*) appeared much more vigorous when reaching the grate. Halibut and other fish that exited the accelerator panel swimming towards the grate, usually swam up the grate and out of the escape hole quickly with no problems. However, most fish exited the accelerator panel facing forwards, the typical "station-keeping" swimming behavior, in which the fish is swimming forwards but gradually loses ground and drifts backwards in the net (Wardle 1993, Kim and Wardle 2003). The halibut and other fish that exited the accelerator panel facing forwards had a variety of difficulties and generally took longer to exit the net. Since the accelerator panel ends quite close to the bottom of the Oregon grate we observed, very large fish had some difficulty getting out from under it. After getting out, they would often react to the close presence of the grate by swimming forwards into the area above the accelerator panel. Some halibut and smaller sole would also simply lay on the inclined grate for periods of time, and some Pacific hake were observed wedged between the vertical bars of the grate. If more than one halibut blocked the grate for very long, increased shrimp loss was observed at the escape hole. The pulsing in the codend material noted earlier often stimulated additional movements of halibut and other fish that were blocking the grate, eventually resulting in them exiting the escape hole. Most halibut that did spend more time in front of the grate actually exited the escape hole tail first after drifting upwards, a seemingly inefficient mode of escape for a large flatfish.

Observations of Soft-Panel BRDs

In 1994-95, and again in 1997, we had opportunities to collect underwater observations of soft-panel BRDs (Figure 4). Our underwater observations of soft-panel BRDs revealed a large number of problems with these devices that interfere with their efficiency. In a few instances, the video showed soft-panel BRDs working effectively.

The principal problem with soft-panel BRDs seems to be that the fishermen or net manufacturers that construct them have no way of knowing for certain what shape the net will take when actually fishing or what the actual cross-sectional diameter of the net will be in the area where the BRD is installed. They can only guess whether the net will be more "sock" or "mushroom" shaped (Figure 6) in the intermediate section. Observations of the occasional soft-panel BRD that did work effectively showed that the net was generally well filled out (more sock like) in the vicinity of the BRD. In those instances, we observed the mesh panel to be well spread from side to side (Figure 7, panel A), with only a minimal "belly" and minimal distortion (Figure 7, panel B). The angle of the panel was also shown to be more upright, in the range of about 30-40° to the horizontal. Fish behavior was similar to that observed with the Nordmore grate BRD, with larger fish

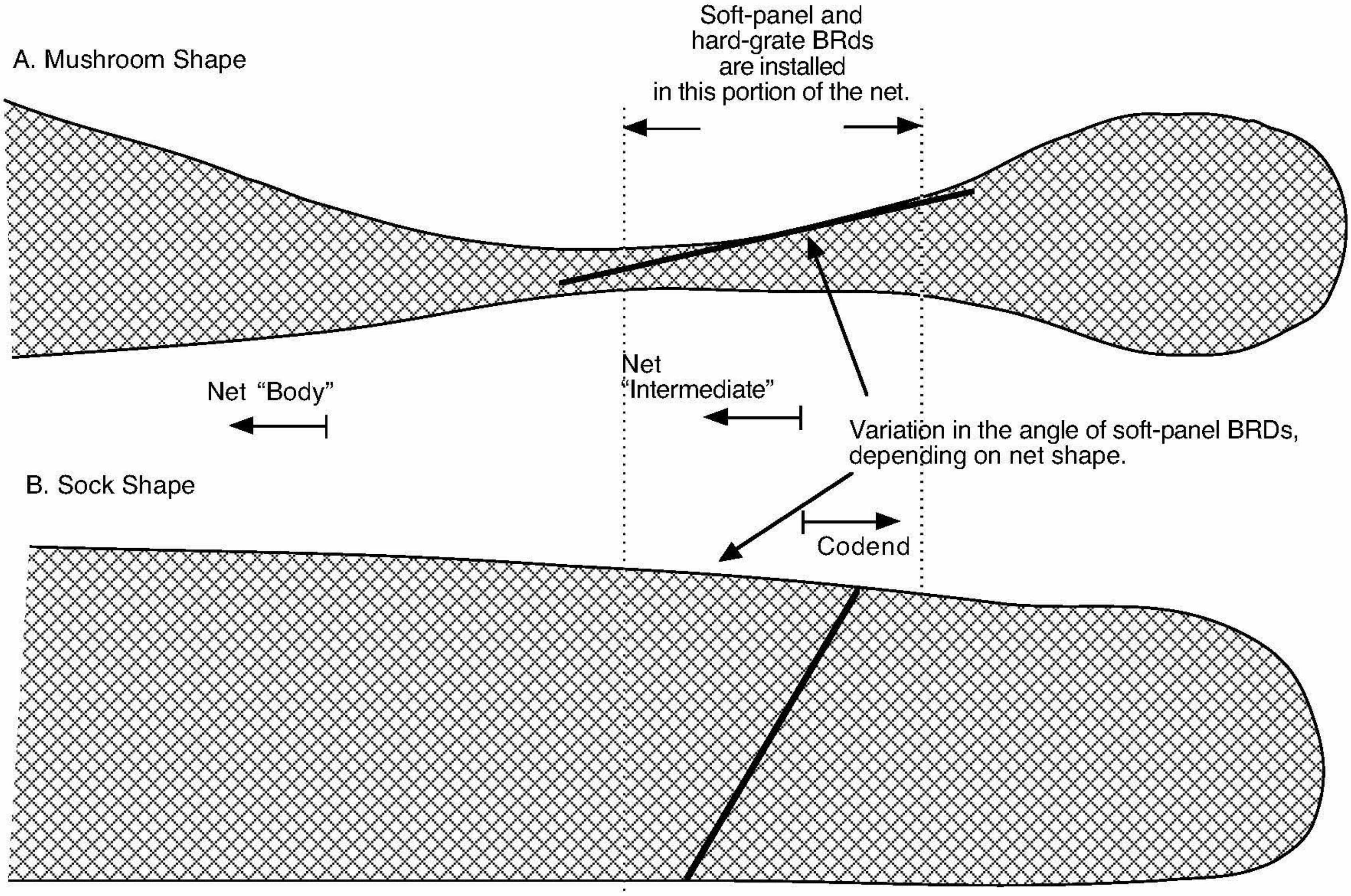

Figure 6. Stylized drawing of the aft portion of an ocean shrimp trawl, showing hypothetical extremes in the cross-sectional diameter of the "intermediate" section where hard-grate and soft-panel BRDs are installed, and the effect on the angle of a soft-panel BRD.

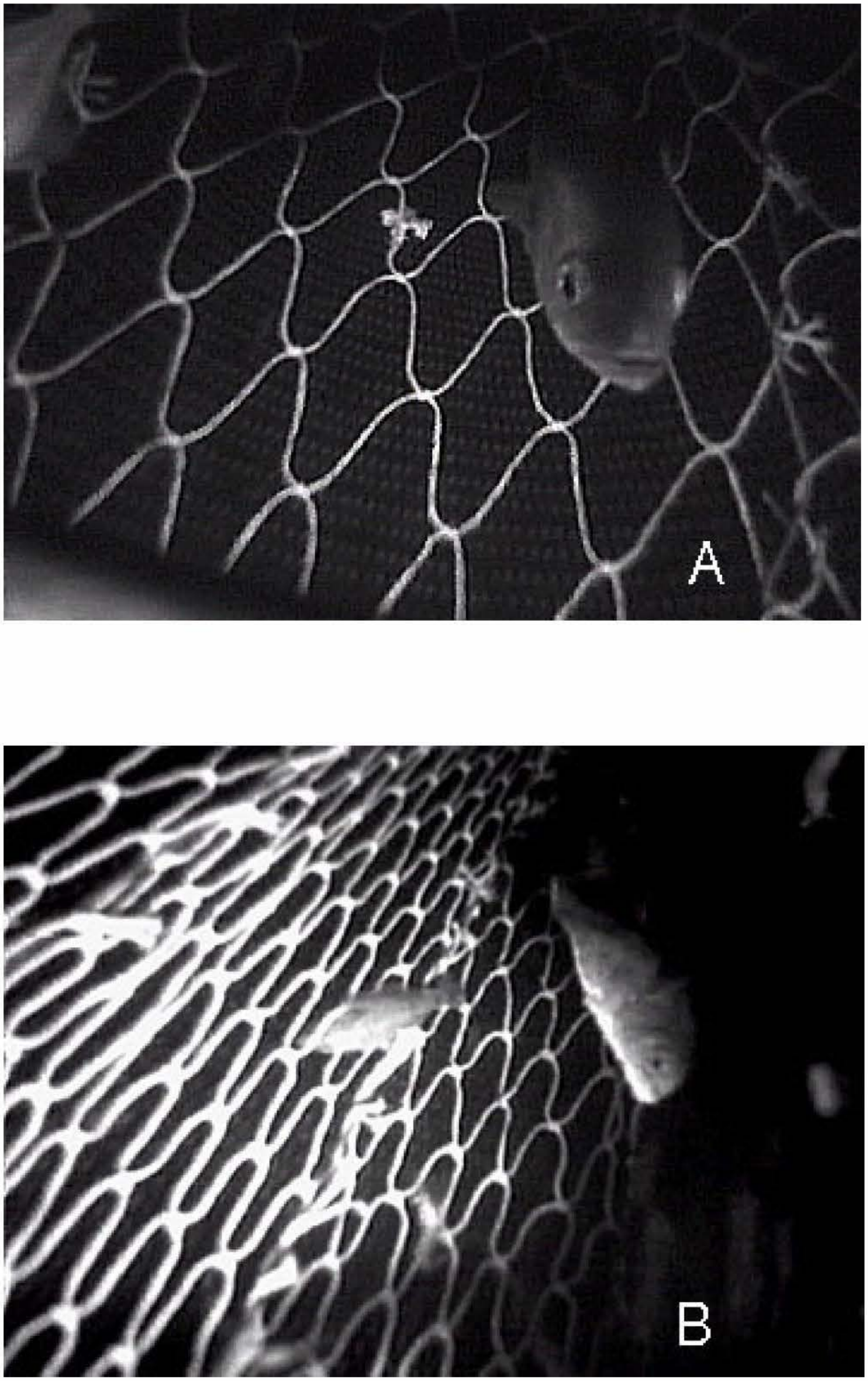

Figure 7. Picture of a soft-panel BRD that was in the correct geometry and working well (A) and one that was stretched hard in the fore-aft direction and causing excessive shrimp loss (B).

swimming forward, then drifting backwards and bumping their way up the inclined panel and out of the net. Some water flow and shrimp loss out of the escape hole could be seen at times, however when the BRD shape looked good, it was not excessive.

Soft-panel BRDs that were working poorly and causing large amounts of shrimp loss generally looked quite different in underwater video observations. Panel angle was very flat, and panel meshes sometimes appeared excessively stretched in the fore-aft direction, almost closed down (Figure 7, Panel B). In some instances, the deflector panel could also be seen to have an excessive amount of belly from side to side or showed some tendency to fold in on itself. Sometimes the net above the BRD also showed folds, as if it was being stretched for and aft and was poorly filled out laterally. The net above the BRD also showed meshes that were stretched hard in the fore-aft direction, somewhat closed down. The escape holes of ineffective soft-panel BRDs were also often distorted from being stretched hard in the fore-aft direction. Underwater video showed that these ineffective BRDs had high water velocities along the panel and rapid transport of shrimp out of the escape hole. Fish directed towards the exit also frequently became gilled near the escape hole or became trapped where the BRD panel attached to the trawl net near the escape hole. The trapped fish building up in these areas sometimes increased the flow of water and shrimp out of the escape hole. The observations were all consistent with a net that had less hydrodynamic pressure and was collapsed in the “mushroom” shape in which the intermediate was of very small diameter (Figure 6).

All of our attempts to fix soft-panel BRDs that were collapsed and causing shrimp loss were unsuccessful. We tried restricting the escape hole to help inflate the intermediate and codend of the net and in one instance switched the BRD section that wasn’t working with one that had worked well in another net, all to no avail. We concluded that the design and geometry of the net body is probably the determinant of how much hydrodynamic pressure or water flow remains back in the intermediate section, where BRDs are installed.

Observations of Fisheye BRDs

We collected underwater video observations of fisheye BRDs (Figure 4) primarily in 1997. At the outset, it was unclear just how fisheye BRDs might work in ocean shrimp trawls. In the Gulf of Mexico and south Atlantic penaeid shrimp trawl fisheries they have proven to be effective at reducing bycatch without excessive shrimp loss (Watson 1995). Observations by ODFW staff also suggest they can be very effective in the short trawls used to fish for spot prawn (*Pandalus platyceros*).

Comparative fishing experiments with fisheye BRDs in ocean shrimp trawls showed that they could be somewhat effective, but performance was extremely sensitive to placement in the codend (Table 2). Moving the fisheye only 6 meshes forward reduced bycatch reduction efficiency, while 6 meshes backwards increased shrimp loss.

Underwater video observations showed how the fisheye worked in ocean shrimp nets and why performance was so sensitive to placement. Video observations of the fisheye

Table 2. Comparison of bycatch reduction for large fish and shrimp loss for three different positions of the fisheye BRD in an ocean shrimp trawl.

Net (Number of Tows)	Fisheye Position (meshes in front of the pursing rings)	Shrimp Catch (lbs)	Shrimp Loss (%)	Combined Catch (lbs) of Pacific Hake, Large Rockfish and Large Flatfish	Bycatch Reduction (%)
Fisheye (11)	88	54.7	3.4	22.7	24.8
Control		56.6		30.2	
Fisheye (6)	82	365.1	8.7	58.3	65.6
Control		399.9		169.5	
Fisheye (2)	76	345.3	17.1	47.9	59.2
Control		416.4		117.4	

showed that the catch in the codend, both shrimp and fish, tended to drift forwards and backwards in the codend, in response to the undulating movements of the codend netting, as mentioned above. As the catch moved forwards along the top of the codend, some of the fish and shrimp were seen to drift out of the mouth of the fisheye BRD, and then drift back in again. The shrimp, which were drifting passively, nearly always drifted right back into the net, however the fish would sometimes turn away or swim upwards and escape the net. Surprisingly, no directed movements towards the fisheye escape hole were observed. If the observed behavior is a valid depiction of how the fisheye works, it is easy to see why placement in the codend is so important. Placed too far back, catch would drift well outside of the fisheye, and would be less likely to drift back in reliably, resulting in high shrimp loss. Placed too far forward, catch would never drift outside of the escape hole and bycatch reduction would not result.

Observations of Other BRDs

In May of 2001, we collected some video footage of a 20.3cm mesh soft-panel BRD employing a 107cm aluminum hoop, behind the BRD, in an attempt to stabilize net configuration. The video showed that the hoop prevented net collapse, but had actually been constructed with too *small* a diameter for the diameter of the net it was attached to. This net appeared to assume more of a "sock" configuration (Figure 6), and the constriction of the aluminum ring caused excess hydrodynamic pressure in front of the hoop and expansion of the net in this region, again resulting in a large flow of water out of the escape hole and high shrimp loss. Various adjustments to the escape hole, including a chain weight on the forward end and a weighted "curtain" in front of the escape hole on the inside did not appear to reduce shrimp loss. The large water flow simply carried shrimp around the curtain and out the escape hole. When the hoop was moved to the outside of the codend, catch built up heavily in the expanded netting in front of the hoop. When enough catch had accumulated in this area, the twine securing the hoop to the net actually parted from the strain. The hoop was driven backwards by the accumulated catch until it contacted the video camera.

Discussion

The behavior of ocean shrimp and fish we observed inside shrimp trawls was generally consistent with the findings of other researchers (Watson et al. 1992, Kim and Wardle 2003). Fish exhibited both the "station keeping" behavior often characterized as the optomotor response, as well as more erratic behaviors as they moved backwards in the trawls and contacted BRDs, other fish or portions of the trawl net (Godø et al. 1990). Ocean shrimp showed much more passive and reactive behaviors, generally similar to the observed behavior of penaeid shrimp inside trawls (Watson et al. 1992). One difference is that penaeid shrimp were observed clinging to the trawl netting and crawling along it, a behavior we did not observe with ocean shrimp.

Our video observations showed that mesh escapement for ocean shrimp was generally a two-stage process beginning with a shrimp becoming lodged, tail first, in an open mesh.

After a period of time lasting from seconds to many minutes, the shrimp then freed itself from the mesh by a tail flip in response to various stimuli, including fish movements in the codend and periodic undulations in the netting material. These behaviors suggest that sorting ocean shrimp by mesh size is a relatively inefficient process that could be influenced by many factors. With shrimp blocking most codend meshes for periods of time, small shrimp in the interior portion of the codend would be less likely to escape. Escapement rates could also depend strongly on factors which influence the likelihood of an escape response, such as catch density, ocean swell (O'Neill et al. 2003) or the presence of many large fish in the net. It's possible that use of a BRD to reduce fish bycatch could actually increase codend retention of ocean shrimp, by reducing the stimuli for an escape response. If true, this effect could partially explain instances in which a shrimp net incorporating a Nordmore grate BRD caught more shrimp than the control net with no BRD (Hannah et al. 1996). However, differences in net efficiency caused by a different height of the fishing line above bottom can also easily explain this amount of catch variation (Hannah and Jones 2003).

The incorrect angle we obtained with the Nordmore grate upon first installation is symptomatic of a general problem encountered in designing and installing new BRDs. We attempted to get the correct angle for the grate by having it installed by a professional net shop. However, the angle for installing the grate as the net section is built is chosen based on the netmaker's concept of the shape of any particular net as it is fishing and the degree to which the diamond meshes are stretched backwards and closed down, or conversely, pushed open by water pressure. At the extreme, the aft portion of the net can take on two shapes as shown in Figure 6. Nets with low hydrodynamic pressure in the intermediate and codend can take on a "mushroom" shape, with the narrow mushroom "stem" located in the intermediate portion of the net where BRDs are often installed. A net with higher dynamic pressure can be more "sock" shaped; more fully inflated. The rigid nature of the Nordmore and other rigid-grates limits the ability of the net to change shape, making it easier to obtain and maintain any particular net diameter and grate angle. However, the fact that the grate angle was incorrect upon initial installation shows how difficult it is for net shops to be certain of the angle of any BRD they install, because they have no information on the shape any particular net takes while fishing.

In combination, the video observations fit well with the results of comparative fishing experiments with soft-panel BRDs showing that performance is highly variable from BRD to BRD and between different trawl nets. Tests of soft-panel BRDs in the ocean shrimp fishery have measured shrimp loss rates as high as 31%, as compared to only 10% for the Nordmore grate (Hannah et al. 1996). We observed soft-panel BRDs that were well filled out and in the proper shape and many that were stretched very hard in the fore-aft direction and fishing at a very low angle, with lots of water flow out the escape hole. The video observations also fit well with fishermen's comments that most soft-panel BRDs just don't work well in most nets; they cause excessive shrimp loss. The most likely explanation for the highly variable performance of soft-panel BRDs is variation in cross-sectional diameter of shrimp nets in the areas in which soft-panel BRDs are normally installed. The inability to predict net diameter in this area results in soft-panel BRDs that are designed for a larger diameter and therefore assume a very low angle, causing a large loss of shrimp out the escape hole. In contrast, it's easy to see how rigid-grate BRDs define net diameter where they are installed and accordingly, provide much more consistent performance. One possible solution for soft-panel BRDs that has not been tried is to dramatically shorten the intermediate section of the net to help inflate the net more fully in the area with the BRD (Reeves et al. 1992). However, it should be noted that due to changes in loads on the netting from increased catch, even a properly configured soft-panel BRD is likely to be less effective as catch increases, at least with conventional diamond mesh (Broadhurst et al. 1998). Another approach might be to install soft-panel BRDs in tubular sections of square-mesh, which should assume a more predictable shape (Robertson and Stewart 1988). Given the consistent performance of rigid BRDs and recent developments to make and test hinged rigid BRDs that can be wound onto net reels (Madsen and Hansen 2001), pursuit of better soft-panel BRDs may simply not be warranted.

These video observations suggest that the mechanism by which a fisheye reduces bycatch in ocean shrimp trawls involves passive transport of catch out of the escape hole, as a result of wave-like movements of the catch in the codend. Although our underwater video observations are consistent with the measured performance of the fisheye BRD in the ocean shrimp fishery and its sensitivity to placement (Table 2), it seems unlikely that this is the only way that a fisheye reduces bycatch. The device is too effective in the Gulf of Mexico and south Atlantic shrimp fisheries for this to be the only mechanism at work (Christian et al. 1995). It is likely that once the net reaches the lighted portion of the water column, some fish actively seek the escape route provided by the fisheye BRD, however, we did not observe this. Our observations were more consistent with increased "belching" of shrimp and bycatch out of the fisheye from pulsing of the net in swell as it is being retrieved, as noted by Christian et al. (1995), however, we did not observe fish floating at the surface during net retrieval. The buoyancy of fish with expanded swim bladders compared to the generally neutral or negative buoyancy of shrimp could contribute to bycatch reduction during the process of retrieving a net in swell. In the Gulf of Mexico and south Atlantic shrimp fisheries there also may be more available light on the bottom, facilitating a more active net escapement response from those species of fish. It should be noted however, that in the Gulf of Mexico and south Atlantic shrimp fisheries, the fisheye was also found to be sensitive to placement.

The fish behaviors observed with the Oregon grate BRD suggest some additional design criteria for an effective rigid-grate BRD in this fishery. Accelerator panels or funnels are helpful in minimizing shrimp loss and preventing a buildup of shrimp in front of the grate, however they shouldn't end too close to the grate to allow room for larger fish to move upwards towards the escape hole. Escape holes should be kept large so that large fish such as Pacific halibut, which can be common on the shrimp grounds at times, can readily fit through in various orientations. If methods can be developed to encourage fish to exit the accelerator panels swimming towards the grate, a more rapid escape from the trawl could be facilitated.

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