ICES COOPERATIVE RESEARCH REPORT

RAPPORT DES RECHERCHES COLLECTIVES

NO. 215

MANUAL OF METHODS OF MEASURING THE SELECTIVITY OF TOWED FISHING GEARS

Edited by

D.A. Wileman, DIFTA, Hirtshals, Denmark
R.S.T. Ferro, SOAEFD Marine Laboratory, Aberdeen, Scotland
R. Fonteyne, Rijksstation voor Zeevisserji, Oostende, Belgium
R.B. Millar, University of Otago, Dunedin, New Zealand

International Council for the Exploration of the Sea

Conseil International pour l'Exploration de la Mer

Palœgade 2-4 DK-1261 Copenhagen K Denmark

August 1996

TABLE OF CONTENTS

Section **Page**

Section **Page**

Section **Page**

Section		Page

1 Introduction

1.1 Background for the manual

The only manual currently available to fisheries scientists and technologists describing the methods of measuring the selectivity of fishing gears is that produced within the auspices of FAO (J.A. Pope *et al.*, (1975)).

It was largely based on the report of the ICES Mesh Selection Working Group, 1959-1960. It describes methods for measuring the selectivity of most types of fishing gear: trawl, Danish seines, gill nets and hooks. An expanded review of methods for measuring the selectivity of gill nets was then produced by J.M. Hamley, (1975).

The intervening years have seen many improvements to the experimental methods for measuring the selectivity of fishing gears and in particular towed gears. Improved understanding of the principles of the selection of fish by gears has now changed the list of parameters which are known to have a significant effect upon selection and need to be measured at sea. The recent development of new statistical models and, in particular, the increased availability of powerful computers have resulted in improvements in the analysis procedures for the data produced in experiments to measure a gear's selectivity.

It is the purpose of this new manual to update those sections of the FAO manual referring to methods for measuring the selectivity of towed gears.

The work in preparing this manual has been carried out by a subgroup of the ICES Working Group on Fishing Technology and Fish Behaviour (Appendix 4). The following persons have contributed to the text of the manual:

Dr Robin Cook	SOAEFD Marine Laboratory, Aberdeen, Scotland UK
Chris Cooper	Fisheries and Oceans, Industry Services and Native Fisheries Branch, Halifax, Canada
Dr Erdmann Dahm	Institut für Fangtechnik, Hamburg, Germany
Richard Ferro	SOAEFD, Marine Laboratory, Aberdeen, Scotland, UK
Ronald Fonteyne	Rijksstation voor Zeevisserij, Ostende, Belgium
Dr Rob Fryer	SOAEFD, Marine Laboratory, Aberdeen, Scotland
Bjornar Isaksen	Institute of Marine Research, Bergen, Norway
Roger Karlsson	Lindholmen Utvekling, Gothenburg, Sweden
Klaus Lange	Institut für Fangtechnik, Hamburg, Germany
Roger Larsen	Norwegian College of Fishery Science, Tromsø, Norway
Bob van Marlen	RIVO-DLO, IJmuiden, Netherlands
Dr Russell Millar	University of Otago, Dunedin, New Zealand
Antonio Perez-Comas	Fisheries Research Institute, University of Washington, Seattle, Washington, USA
Dr Ellen Pikitch	Fisheries Research Institute, University of Washington, Seattle, Washington, USA
Jack Robertson	SOAEFD, Marine Laboratory, Aberdeen, Scotland
Graham Sangster	SOAEFD, Marine Laboratory, Aberdeen, Scotland
Petri Suuronen	Finnish Game and Fisheries Research Institute, Helsinki, Finland
François Theret	IFREMER, Lorient, France
Wilfried Thiele	Institut für Fangtechnik, Hamburg, Germany
Dr Stephen Walsh	Dept. of Fisheries and Oceans, St. Johns, Newfoundland, Canada
Bill West	Fisheries Research Institute, University of Washington, Seattle, Washington, USA
David Wileman	DIFTA, Hirtshals, Denmark

Those sections dealing with the specification and formatting of trials data have been edited by Ronald Fonteyne, those dealing with practical methods of conducting sea trials by Richard Ferro and those dealing with the analysis of trials data by Dr Russell Millar. Overall editing was done by David Wileman.

The editors are grateful to Dr Frans van Beek, Dr Robin Cook, Bill Dickson, John Foster and Jimmy Pope who read and provided detailed comments to a draft of the manual.

1.2 Describing the selection of fish by a towed gear

1.2.1 Selection and mesh selection

In the widest possible sense the selection of fish by a fishing gear can be considered to be the process which causes the catch of the gear to have a different composition to that of the fish population in the geographical area in which the gear is being used. There are many causes of these differences with chance playing a big part in the capture process. The selectivity of a fishing gear is a measurement of the selection process. It describes the relative likelihoods that different sizes and species of fish would have of being caught by the gear if there were equal numbers of each in the population. Gears will select by species and for each species there will also be size selection. This manual is solely concerned with size selection for a given species.

This manual is restricted to describing methods for measuring the probability of a fish of a given species and size being retained by a gear once it has encountered it. It is further restricted to examining towed gears and will in fact also concentrate on the parts of the gear made of netting, i.e. the trawl or seine itself and will ignore the selection that has taken place when fish have encountered the otter boards, sweeps, bridle wires and ground rope. The probability will be examined that fish will be retained by the netting and hauled to the surface as opposed to escaping out through the meshes during some part of the towing or hauling process. This is normally referred to as mesh selection.

1.2.2 Mesh selection in the whole gear and the codend alone

In principle it should be possible to measure the mesh selection of fish through any part of a gear. Traditionally experiments carried out to measure the mesh selectivity of a towed gear have only measured the selection in the codend. Observations made by divers and towed underwater vehicles certainly show that large amounts of fish do escape in the codend and for most species this is where the main mesh selection is thought to occur. Experiments investigating the mesh selection in *Nephrops* trawls (Hillis and Early, 1982) show that there can be, however, substantial selection of *Nephrops* in the main body of the trawl. This may also be the case for other species of crustacea.

Many of the methods described in this manual can be used for measuring either codend mesh selectivity or whole gear mesh selectivity. A decision on whether to study whole gear or codend mesh selection should be based on a careful evaluation of all available information on which parts of the trawl the species in question is likely to escape through and the mesh sizes in these parts of the trawl compared to the mesh size in the codend. For example in the case of a *Nephrops* trawl made in the same mesh size throughout it would be most appropriate to study whole trawl mesh selection. If the codend mesh size on the other hand was much smaller than for the rest of the trawl and the main objective of the experiment was to evaluate the effect on *Nephrops* catches of relatively small increases in minimum mesh size then it would be sufficient to study codend mesh selection.

1.2.3 The selection curve

In a codend selectivity experiment measurements are required of the fish that have been retained by the codend under test and the total numbers of fish that have entered the codend. A small mesh cover is often fitted around the codend under test in order to catch the fish escaping through the meshes. Alternatively an identical trawl fitted with a small mesh codend of equal overall dimensions to the test codend is towed under conditions that match that of the test trawl as closely as possible. The first method gives a direct measurement of the total numbers of fish that have entered the test codend; the second gives an estimate of the numbers that should have entered the test codend.

The lengths of the fish retained in the test and small mesh codends are measured. Although it is, in principle, mainly the girth of a fish that determines whether or not a fish is able to pass through a mesh opening, it is normally far easier to measure fish length (see Section 5.2.2). For most fish species there is a significant linear relationship between length and girth but this will vary with condition, with season and between different fishing areas.

A mathematical model is chosen that will describe the probability that a fish of a given length which enters the test codend will be retained by it. Several possible models will be presented in Section 6 of the manual. The model is fitted to the haul by haul catch data analysing the numbers of fish of a given length found to be retained in the test codend and the total numbers of that length found or estimated to have entered the codend.

The resultant measurement of mesh selectivity is illustrated graphically, e.g. Figure 1.2.3, and is usually termed the mesh selection curve. The horizontal axis represents the fish length, the vertical axis the proportion of fish that have been retained in the test codend.

Figure 1.2.3 is in fact the result of a haul made with an otter trawl catching Baltic cod in a 123 mm mesh size codend which was fitted with a small mesh cover. The codend selection curve can be seen to be sigmoidal in shape. In this particular example, fish under 30 cm have been so small in girth compared to the opening of the meshes that most have escaped. Fish above 53 cm have been so large in girth that none could force their way out through a mesh. Between these two lengths probability of retention has increased. Selection is not "knife-edged", there is not a critical length below which all fish escape and above which all fish are retained. Only a proportion of the fish small enough to pass through the meshes actually do so. The probability of escape is dependant upon many factors such as how tired the fish is when it encounters the netting and tries to escape, whether or not the meshes are open, how well the towing shape of the open mesh corresponds to the fish's cross-sectional shape and whether the appropriate stimulus is present to encourage the fish to escape.

1.2.4 50% retention length, selection range and selection factor

Two parameters are widely used to characterise the mesh selection of fish in a codend. The first is the 50% retention length which is the length of fish that has a 50% probability of being retained or escaping after entering the codend. It is a basic measure of the selectivity of the gear stating that the gear will retain most of the fish above this length that enter the codend.

The second is the selection range which is the difference in length between the fish that has a 75% probability of retention and that with a 25% probability of retention. This is a measure of the sharpness of selection i.e. the shape of the selection curve. A gear with a large selection range will start to retain fish of a smaller length and fail to retain fish at larger lengths than a gear with the same 50% retention length but shorter selection range. In most models of towed gear selectivity there is a simple relationship between these two parameters and the parameters defining the selection curve.

A further parameter often used to describe a gears selection is the selection factor

$$\frac{\text{50\% retention length}}{\text{codend mesh size}}$$

Mesh size should here be what is commonly referred to as the inside mesh size or more correctly the mesh opening (see Section 5.2.4). Experiments carried out prior to the writing of the FAO manual (Pope *et al.*, 1975) suggested that the selection factor would be a constant for a given fish species and gear. More recent experiments, particularly those of Reeves *et al.*, (1992), found that the selection factor increased with mesh size for demersal round fish. It is, however, often useful to quote that a gear had a particular selection factor value for a species at a given nominal mesh size. This can then easily be compared with results for other gears of slightly different codend mesh sizes.

1.2.5 The uses of selectivity estimates

Selectivity estimates are primarily of importance because mesh selectivity is not constant for all gears but is dependent on many gear design parameters, the most important of which is mesh size. Figure 1.2.5 illustrates the change to a Baltic cod selection curve showing the decrease in retention of cod when the codend mesh size was increased from 107 mm to 123 mm. The 50% retention length was increased from 31.8 cm to 37.5 cm giving what is termed a shift to the right of 5.7 cm in the l_{50} selection point quantifying the basic change in selection. Another parameter that has been found to affect selection is the number of meshes round the codend circumference (Reeves *et al.*, 1992). Increasing the number of meshes has been shown to decrease the 50% retention length for demersal roundfish. This parameter, as well as mesh size, is now specified in European North Sea demersal roundfish fisheries legislation.

Presenting and comparing the mesh selection curves for two different gear configurations is the only fully satisfactory means of describing how the gear selectivity has changed when developing new towed gears. Firstly, it is a means of presenting the results independently of the population being fished. If the results are, for instance, produced in terms of discard rates and numbers of marketable fish retained then they are totally dependent on the population being fished at the time and location of the experiment. The same experiments carried out on a different population could give entirely different results in terms of the discard rates, (Ferro and Stewart 1990). Secondly if the selection curves are determined for two different gears then their absolute selectivity is known. If instead a comparative fishing experiment was carried out where the catches of the two gears were directly compared without measuring the population being fished then only the relative selectivity of the two gears could be determined. A comparative fishing experiment could for instance determine that the catch rate of 20 cm fish had been reduced by 50% with a new type of codend. Determining the new and traditional codends selection curves could show whether the retention rate of the 20 cm fish was in fact reduced from 40% to 20% or from 10% to 5%.

Gear selectivity measurements are required by fishery resource biologists when making stock assessments. They are used in connection with calculating the fishing mortality generated by commercial fleets, recommending codend minimum mesh size and minimum landing sizes for target species. This work is briefly described in Chapter 8. When making predictions of the long term effects of changes to fisheries technical regulations, a detailed knowledge of the selectivity parameters for the commercial fleets is required which ideally incorporates a mathematical description of how selection varies with changes in parameters such as codend circumference and mesh size.

The consequences of introducing gears with improved selection characteristics to commercial fleets are clearly highly dependent upon the fate of fish after escaping through meshes. It is recommended that gear selectivity measurements should whenever possible be supplemented by measurements of the survival rates of fish escaping from the gear (Sangster, 1994; Isaksen, 1995). Experiments made collecting fish escaping through codend meshes and studying their subsequent survival in underwater cages show that for North East Atlantic demersal roundfish species survival rates can be high (Sangster, Lehmann and Breen, 1996; Soldaland Isaksen, 1993).

1.3 Scope of the manual

1.3.1 Types of gears included

The manual is restricted to describing methods for measuring the selectivity of towed gears i.e. otter trawls, pair trawls, beam trawls, dredges, Scottish seines, Danish anchor seines and pair seines.

1.3.2 Aspects of fish selection included

The manual is restricted to describing methods for measuring the size selection of fish due to the netting parts of the gear i.e. the mesh selection. The absolute selection is determined where a measurement or estimate has been obtained of the total numbers of fish that have entered the net. Methods will be described that can measure the mesh selection in a) the codend only or b) the whole gear (netting parts of the gear). The main emphasis and technical detail is given to measurement of codend selectivity as there have been so few experiments carried out to date to measure whole gear selectivity.

1.3.3 Methods of measuring gear selectivity described

The methods described fall into two categories. The first is the covered codend method where a direct measurement of the fish escaping through the codend meshes is obtained by fitting a small mesh cover around the test codend which collects the fish not retained by the test codend. The second category of methods can be referred to as "paired-gear" methods. These are the alternate haul, parallel haul, twin trawl and trouser trawl methods. In each of these two gears of equal overall dimensions are towed alternately or alongside each other. In one gear the rear sections of netting, whose selectivity is to be determined, are made in small mesh such that all fish (above a certain length) must be retained. These methods are therefore suitable for determining both codend selectivity and whole gear selectivity. These methods require a slightly different approach to the analysis of the catch data in order to allow for the probability that unequal numbers of fish have entered the two gears.

1.3.4 Aspects of carrying out a selectivity experiment described

It is intended to cover in the manual all aspects of carrying out a selectivity experiment from conception to the reporting of the results. The aim is to give the manual users sufficient information to:

- choose a suitable experimental method
- design the experiment and the test fishing gear
- determine which parameters should be measured during the sea trials, how they should be measured and the measurements recorded
- conduct the experiment at sea
- choose a suitable data analysis method and calculate the results
- report the results and store the results and experimental raw data in a data base

1.3.5 Intended users of the manual

The manual is aimed at scientists and technologists responsible for conducting gear selectivity experiments. In an ideal world such a person would be an expert gear technologist and statistician fully capable of dealing with the practicalities of designing and rigging the fishing gear as well as the detailed analysis of the large amounts of data generated by the catch measurements. In actual practice few people can combine such abilities and in fact many people wishing to carry out selectivity experiments will not be an expert in either field. Every effort has been made in this manual to describe gear construction, measurement techniques and data analysis techniques thoroughly from first principles, but it is impossible within a manual to teach an average gear technologist the necessary statistics and vice-versa. It has to be recognised that conducting a selectivity experiment requires a team effort and so will gaining a full appreciation of this manual. For most users it will be necessary to discuss the gear design and operation aspects with a competent gear technologist and the data analysis aspects with a competent statistician.

1.4 Content and organisation of the manual

The manual has been organised with a view to leading the user through the logical process of planning, designing, conducting, analysing and reporting an experiment describing each task that would have to be carried out in the correct chronological order.

Chapter 2 deals with the initial planning of the experiment primarily aiming to give users sufficient information to be able to choose which experimental method for measuring selectivity would be best suited to their experiment. Section 2.1 outlines the basic principles of each experimental method together with their main advantages and disadvantages. Section 2.2 gives recommendations on which experimental methods are most suitable for a given type of towed gear and selectivity experiment.

Chapter 3 deals with the basic design of the experiment. It aims to give users advice on how to choose a suitable trials vessel, fishing area and trials programme. Section 3.1 discusses factors which are known to influence the results of gear selectivity experiments and which should therefore be controlled (where possible) if comparing the selectivities of different gears or alternatively which should be representative of normal commercial fishing conditions if the aim is to determine the selectivity of commercial fleets. Section 3.2 describes considerations that have to be taken into account when making the statistical design of the trials programme. Section 3.3 is a check list of items that need to be finalised when planning and costing selectivity sea trials.

Chapter 4 details the design, construction and operation of the fishing gear for each experimental method. Section 4.1 deals with aspects that are common to all experimental methods such as choosing an appropriate mesh size for the small mesh codend or cover. Section 4.2 then gives the specific detail for each experimental method in turn.

Chapter 5 describes how all other aspects of the sea trials should be conducted. Section 5.1 provides a detailed specification of the catch, vessel, gear and operational data that need to be collected. Priority ratings are given to parameters whose measurement is either essential or advisable. Data collection forms suitable for use when taking manual measurements are presented. A recommended format for holding the raw data files on a computer database is also presented. Section 5.2 describes the measurement procedures. Section 5.3 gives advice on how to monitor the data during the experiment, assess its quality and determine when procedures should be modified (e.g. length of haul, catch sampling rate etc.) or when an experiment can be safely terminated.

Chapter 6 describes how to analyse the trials data. Section 6.1 outlines the advantages of modern statistical models of fish selection compared to historical methods of selection curve estimation. Section 6.2 describes the different mathematical models commonly used to describe the selection curve of a towed gear and their properties. Section 6.3 describes the statistical procedures for fitting these selection curves to a single data set when using a) the "covered codend" method and b) a "paired gear" method. Section 6.4 gives a recommended procedure for determining which model gives the best fit. Section 6.5 is a series of worked examples. Section 6.6 deals with non-model based methods of determining selection curves. Section 6.7 gives the details of mathematical models to be used when it has been necessary to sample catches. Section 6.8 shows how the selectivity results from groups of hauls should be combined so that between haul variation can be taken into account when comparing the selectivity of different gears.

Chapter 7 gives recommendations for the reporting of results. Section 7.1 specifies the minimum recommended report content. Section 7.2 gives a suggested structure for reports of selectivity experiments including a one page summary table of the selectivity measurements for a given gear configuration and fish species. Section 7.3 gives a recommended international database format for the storage of results on a haul by haul basis.

Chapter 8 describes the uses of gear selectivity data in fish stock assessment. Section 8.2 describes the relationship between gear selectivity and fishing mortality. Section 8.3 describes how changes to a gears selectivity can change the exploitation pattern for a fish species. Section 8.4 briefly explains how changing gear selectivity can result in technical interactions affecting the performance of completing fleets and biological interactions affecting different species. Section 8.5 discusses the problems associated with determining minimum landing sizes. Section 8.6 discusses the difficulties in determining the selectivity of fleets of vessels. Section 8.7 describes the requirements for determining the selectivity of research vessel sampling gears.

Chapter 9 is a list of the scientific papers referred to in the manual.

Chapter 10 is a glossary defining the terms and expressions used in the manual. Section 10.1 covers the fishing vessel and its gear. Section 10.2 covers the terms and symbols used in the statistical analysis of trials data.

2 Planning - preliminary decisions

A selectivity experiment entails the collection of length frequency data for the fish population available for capture and for the fish retained by the experimental gear. Six different methods for collecting this data set for towed gears are described in this section. The first method is the covered codend method which is only suitable for measuring codend selectivity. The following four methods alternate haul, parallel haul, twin trawl and trouser trawl are the "paired gear" methods suitable for measuring codend or whole trawl selectivity. The last method deals with the special cases of selective devices such as grids and windows inserted into the gear to enhance selection in the forward part of the codend or extension piece. The principles, advantages and disadvantages of each method are discussed in Section 2.1. The details of design, construction and operation are given in chapter 4. A summary of each method's suitability for different gear types and some recommendations are given in Section 2.2.

2.1 Principles, advantages and disadvantages of different experi-mental methods

2.1.1 Covered codend method

Small mesh covers over codends have been used in selectivity experiments for many years to retain the fish escaping from a codend. The catch in the codend and cover together provide a measurement of the population entering the codend and hence allow the codend selectivity to be estimated. Pope *et al.* (1975) stated that for the covered codend method to give a true measure of selectivity, it is essential that the cover does not affect the relative ability of fish of different sizes to escape from the codend. However, it has been recognised since covers were introduced that they may physically mask the codend meshes and prevent fish escape to some extent. Davies (1934) suggested the use of cane hoops to reduce the risk of masking. In recent years this idea has been updated using modern materials, for use on both research and commercial vessels. The cover is held away from the codend by attaching two or more hoops around its circumference on the outside of the cover (Figure 2.1.1). The hoops aim to prevent any contact between cover and codend especially at the point where the catch expands to form a bulge.

The hooped cover method has been used with success on demersal fish and *Nephrops* single trawls, fish and *Nephrops* twin trawls, pair trawls, pair seines and Danish anchor seines. The method may also be suitable for measuring the selectivity of pelagic trawls and shrimp trawls. However, the use of hooped covers may be more difficult (but not imon beam trawls because of the high shooting and towing speeds or for any gear where the codends are close to the sea bed or protected by chafers. In these cases it may be possible to modify the hoop design or use some other method of separating the codend and cover so that the codend meshes are not masked nor the cover damaged.

The main advantages of the cover method are that each haul produces a selection curve, that the estimate of the fish population entering the codend mouth is accurate and that the same method can be used on a wide variety of gears allowing the codend selectivity of different gear types to be compared.

There are some disadvantages. Commercial shooting and hauling procedures must be modified, with more care and time needed to handle the hoops. There may be practical difficulties in handling very large catches in either codend or cover; these can be severe in poor weather conditions. There is a limit to the size of the hoop that can be used dictated by handling and strength considerations. Use of a hooped cover may not be feasible with a codend having a stretched circumference larger than about 10 m.

The net does not fish exactly as in commercial fishing in that the cover may affect fish behaviour or gear performance, perhaps because the flow through the codend reduces or the cover is visible to fish inside the codend or the extra drag of the cover distorts the shape of the net. The fish selection may therefore be different from commercial fishing. The covered codend method may not be suitable for gears with low headlines such as *Nephrops* or flatfish trawls if the cover comes in contact with the seabed and thereby blocks the codend meshes or distorts the gear.

2.1.2 Alternate haul method

This is the first of four different "paired gear" methods which are suitable for measuring whole gear selectivity as well as codend selectivity. Hauls are made alternately with the gear whose selectivity is to be measured and then with the same gear with a small mesh codend; the latter obtains an estimate of the fish population entering the test codend. If whole gear selectivity is being measured then the second set of gear would be made in small mesh throughout. It is essential that the pairs of hauls should be similar in every respect except for the mesh size in the part of the gear whose selectivity is being measured.

Despite improvements in the design of covers (Section 2.1.1), covered codend experiments may not always simulate conditions which occur in commercial fishing. As in the case of all the "paired gear" methods the main aim of this method is to avoid any bias caused by a cover. The test codend is fished as in normal commercial fishing. The major drawback is the need for a larger number of hauls which will increase the cost of the experiment. Two hauls are necessary in order to calculate a single selection curve for one codend.

There are several further potential disadvantages. The population estimate may not represent accurately the population met by the test codend which is fished at a different time, under possibly different conditions of e.g. light level and, to some extent, over a different area of seabed. The fishing powers of the test and small mesh codends may not be equal (see Section 3.1.5). These differences may be minimised but can never be eliminated. They can cause greater variance in the estimated selectivity parameters, resulting in the need for a longer series of hauls. Specialised techniques are required to analyse the catch data as described in Section 6.3.2.

2.1.3 Parallel haul method

The parallel haul method involves two vessels fishing on the same grounds at the same time. The only difference between their gears is the gear design feature whose effect on selectivity is to be measured. When measuring codend selectivity for example, the experimental gear whose selectivity needs to be measured is towed by one vessel and a gear of identical design but with a small mesh codend is towed by the other in order to obtain an estimate of the population of the target species entering the test codend. The two ships fish in the same area and tow at the same speed so that the fishing operation is duplicated closely on the two vessels.

As in the case of the alternate haul method the main aim of this method is to avoid the bias caused by a cover. The test codend is fished as in normal commercial fishing. The two codends are fished at the same time and on adjacent seabed areas which are assumed to have similar populations of fish. The fishing powers of the test codend and small mesh codend may not be equal (see Section 3.1.5).

The major drawback is that the need for two vessels will approximately double the cost of the experiment. Also the two nets will not in general encounter the same populations despite their proximity. This bias can be taken into account in the analysis method (Section 6.3.2) but larger variance is likely in the calculated selectivity parameters, compared to the covered codend method. The variance in the parallel haul method is increased compared to the alternate haul method in that there are more vessel/gear differences but may be decreased because of the reduction in time and environmental differences.

2.1.4 Twin trawl method

One trawler tows two similar trawls simultaneously side by side, using special rigging (Figure 2.1.4). The test codend is attached to one of the twin trawls. A small mesh codend is attached to the other trawl to obtain an estimate of the total fish population entering the test codend. Thus the length-frequency distributions of fish from the two codends allow the calculation of the selectivity parameters of the uncovered test codend as used in commercial fishing. A pair of beam trawls may be considered as a special example of twin trawls.

This method is particularly recommended for fisheries in which twin trawls or beam trawls are commonly used. The twin trawl method can also be used for measuring the selectivity parameters of a conventional single demersal trawl. It may also be used to estimate whole trawl selectivity and to conduct catch comparison trials. The twin trawl method is free from any bias caused by the use of a cover and improves the simulation of commercial fishing conditions.

It is however, true that a twin trawl rig has some features which are different from a conventional single trawl. The behaviour of the fish ahead of the trawl and hence their susceptibility to capture may be affected by the change in wire rigging between the trawl and the vessel. The two twin trawls will have smaller dimensions than a single trawl towed by the same vessel. Hence, if the aim is to estimate the selectivity of a trawl suitable for a given size of trawler it may be necessary to conduct the experiment on a trawler approximately double the power to ensure that two trawls of the original size can be towed side-by-side.

Although the two trawls are working close to each other in the same conditions there is no certainty that the same population of fish will enter each trawl. Generally, there is a haul-to-haul variation in catches and a somewhat larger number of hauls are usually required to achieve the same precision of estimation as is given by the covered codend. The fishing powers of the nets with the test codend and small mesh codend may not be equal (see Section 3.1.5). Specialised methods are needed to analyse twin trawl data as described in Section 6.3.2.

It should be noted that if there is confidence that a hooped cover gives an unbiased measure of selection then using hooped covers on both sides of a twin trawl will provide twice as much data as using the uncovered test codend on one trawl and a small mesh codend on the other trawl. It should also be noted that if the selectivity of two codends are to be compared, the effects of haul to haul variability are likely to be reduced if they are tested side by side in a twin trawl rig with covers over both codends.

2.1.5 Trouser trawl method

The trouser trawl method is a variation of the twin trawl method whereby a standard trawl is divided down the middle by a vertical panel (Figure 2.1.5a). Two codends are attached to the aft end, one on each side of the panel.

The trawl is towed from one vessel and the test codend is attached to one side while the control (small mesh codend) is attached to the other side. The design is based upon the premise that an equal number of fish will enter each side of the trawl. As in the case of the twin trawl, length frequency data are collected from both codends to allow calculation of the fish selection characteristics of the test codend.

The trawl can be handled in a similar manner to a standard trawl and no special rigging is needed. There are no covers to impede escape of fish from the codend. The trouser trawl can also be used to make direct catch comparisons between codends.

While the trouser trawl does not have any special rigging which may affect the behaviour of fish in front of the trawl, it nevertheless can show significant haul-to-haul variation as in the twin trawl method. Sometimes the test codend collects more of the larger fish than the small mesh codend. Also, strong currents, inaccurate wire lengths or other effects can cause bias towards one side of the net. The same specialised techniques as employed in twin trawl analysis are recommended for the trouser trawl. If the net needs significant redesign, e.g. in the last belly section to accommodate two codends, it is advisable either to build a model for testing in a flume tank to ensure that the net fishes correctly (Chopin, 1988) or to observe the full-scale net using underwater television before the selectivity trials begin.

Large commercial trawlers often use trouser codends with no dividing panel ahead of them. These gears have been used in selectivity experiments, perhaps with a short dividing panel ahead of the codends, but there is a greater risk of unequal catches in the two codends and hence a greater variance in calculated selectivity parameters. It is recommended therefore that the panel should extend the full length of the trawl, from the footrope to the codend openings. It may not be satisfactory to use a full length dividing panel in a large pelagic trawl because the panel will usually need to be a substantial height. It will be difficult to design it so that it maintains a vertical position without distorting the upper or lower sheet. A shortened panel may be the best compromise in this case.

Danish and Scottish seines may not be suitable for the trouser trawl method because the height of the net mouth varies considerably as the speed of the net through the water and the distance between the ropes vary.

The reduced dimensions of each side of the trawl may cause different behaviour in the fish. Because the trawl is divided in half, a fish experiences a reduced area much earlier in a divided trawl and may exhibit changed behaviour prior to reaching the codends. Every effort should be made to ensure that the openings to the codends are about equal to the dimension of a single codend on a single trawl.

Designs similar to trouser trawls, known as divided or siamese trawls, have been used occasionally in which two 'nets' are hung on a single headline and fishing line (Figure 2.1.5b). These have the advantage that each side of the gear resembles a complete net, with taper along both sides, more closely than a trouser trawl. Nevertheless the design still does not simulate a true commercial net and the design is complex, possibly requiring a model to be built and tested in a flume tank. Siamese trawls may be recommended if they are used in a commercial fishery but otherwise are not recommended and are not considered further in this manual.

2.1.6 Methods for special selective devices (e.g. windows, grids)

In the last decade several experiments have revealed that special devices inserted either in the codend or in the aft part of the extension piece have improved the release of undersized fish and unwanted bycatch, by modifying only a small part of the gear in use. These are devices such as square mesh windows (Robertson, 1993) and different designs of grids (Cooper, 1993; Isaksen *et al.,* 1992; Suuronen *et al.,* 1993; Watson *et al.*, 1986). Windows and grids are often designed to take advantage of the general upwards escape behaviour of fish, and will therefore normally be positioned in the upper half of the codend or extension piece.

It is important to decide at the outset what selectivity is to be measured: the overall selectivity of the device and codend together or the selectivity of the device itself and of the codend separately. In the latter case the numbers of fish escaping through the device and also out of the codend must be measured separately. Various alternative schemes are discussed.

a) If only overall selectivity is required then, if practically and economically possible, it should be measured using the twin or trouser trawl, alternate or parallel haul method. The advantages and disadvantages of these "paired gear" methods are discussed in previous sections. Alternatively, depending on the position of the device, it may be possible to use a single cover over the whole area as described in Section 2.1.1. Some modification may be needed to ensure that a hoop is positioned near the device escape area to reduce the influence of the cover on fish escape through the device.

b) If the species whose selection is to be measured escape only through the device, perhaps because the codend mesh size is relatively very small (e.g. selecting whitefish from a shrimp trawl) it may be necessary to use a cover only over the device itself. In this case for the large species, the selectivity of the device and the overall selectivity of the codend and the device together are the same. Special designs for top covers over a device in the upper panel of a codend (Figure 2.1.6) are described in detail in Section 4.2.6. They have been observed to lift well above the escape area, giving no physical masking effect (Larsen and Isaksen, 1993). Most devices are placed near the aft end of the net in the extension or codend where most escapes usually take place; it may not be possible to use a top cover on parts of the net well ahead of these positions.

c) If the species whose selection is to be measured escape through both the device and the codend meshes it may be required to assess the selectivity of the device and the codend separately. To do this, more complex covers could be designed with internal divisions to separate the fish escaping from the device and from the codend. The design and use of such complex covers have not been reported and may be more likely to alter water flow and fish reaction in the codend. Alternatively it may be possible to use a cover over the device in conjunction with e.g. a small mesh blinder to blockthe codend meshes. A blinder may also affect water flow through the device. Another option is to measure the overall selectivity as in (a) above and then, perhaps on an alternate haul basis, to use a top cover (see (b) above) to determine the selectivity of the device alone.

The use of a top cover and small mesh blinder to establish the selectivity of a device alone is a quick and inexpensive method and, as in the case of the covered codend method, gives one estimate of selectivity for each successful haul. However, it must be noted that this is an estimate of the selectivity of the device but not of the overall selectivity of the codend and device together.

The top cover method has been used with good results on demersal fish-trawls, *Nephrops* trawls, pelagic nets for mackerel, seine nets and shallow water tropical prawn trawls. This technique was used during the development of the Nordmore fish-shrimp separator grid (Isaksen *et al.* 1992), successfully introduced into legislation in several countries.

2.2 Recommendations on experimental methods

The gear type to be studied is the major factor in deciding the choice of experimental method. There are some methods which are not recommended for particular gear types (Table 2.2).

Table 2.2 The experimental methods which may be used for a range of gear types.

S denotes a Suitable method which has been used successfully;
P indicates that the method may be Possible but that a better method may be available;
NS indicates that the method is Not Suitable.

Gear type		Cover	Twin trawl	Trouser	Alternate	Parallel
Otter trawl		S	S	S	S	S
Twin trawl		S	S	NS	NS	NS
Pair trawl		S	NS	NS	P	P
Pair seine		S	NS	NS	P	P
Danish seine		S	NS	NS	P	P
Scottish seine		S	NS	P	P	P
Beam trawl		S	S	P	S	S
Pelagic trawl	Large	S	NS	NS	P	P
	Small	S	NS	P	P	P
Low vertical opening trawl		P	S	S	S	S

The alternate and parallel haul methods are not necessarily suitable for seines and pelagic trawls because of the likely variance in fish populations from one haul to the next and the possible dependence of the gear's selectivity on fish density entering these nets. A parallel or alternate haul experiment to measure pair seine or pair trawl selectivity may be ruled out on grounds of cost.

It is not normally possible to design a twin trawl system for seines or pair trawls. The trouser trawl method is also not recommended for pair trawl or the different types of type of seine unless great care is taken to ensure that the sets are symmetrical. In normal commercial fishing the wires or ropes ahead of the net are very long and asymmetries regularly occur in the net mouth because of variable seabed friction, cross-currents or unequal speed or direction of the vessels in a pair team. A Danish anchor seine is the most affected being normally set in an extremely asymmetrical configuration. One side of the gear is laid from the anchor buoy. The other side is laid to a position away from the buoy and then towed to it prior to hauling both sides from the anchored vessel. Hence there may be substantial differences in the numbers of fish entering each side of the net for these gears. Methods of data analysis to overcome these complexities have been developed (see Section 6.3.2) but the resulting variance is likely to be high.

A cover held away from the codend by semi-rigid hoops may not be suitable for a trawl in which the codend may come into contact with the seabed since the hoops may be damaged or may twist the cover so that it closes the mouth of the codend. Hence the cover method may not be suitable for beam or low vertical opening trawls unless special designs are made which overcome this problem.

Redesigning a pelagic trawl so that it can be used as a twin trawl or trouser trawl may be impractical, especially for a large trawl, because considerable gear development work would be needed, perhaps using underwater television. Small pelagic trawls (e.g. less than 500 hp) may be suitable for redesign as trouser trawls.

Apart from choosing a method which is appropriate to the gear type, the design of the experiment will be constrained by many other factors. The most important of these may be the financial constraint. Before the cruise it is essential to check that the likely cost is within budget. An assessment can be made of the number of hauls likely to be needed to achieve the objective and hence the number of days at sea (see Section 3.2). If there may not be enough money to complete the task then it is better to amend the objectives, e.g. by reducing the number of codends to be tested, before starting. A power analysis can help to assess the likelihood of obtaining a significant result within a given number of hauls (Fryer, 1996). There may be a temptation to reduce the number of staff on board the vessel but this may be a false economy if inadequate sampling of the catch for example reduces the quality of the data.

Other constraints may be the need for commercial realism or for using rigorous scientific methods. The required level of accuracy will depend on how the data will be used. Measurement of the selectivity of an individual codend may need a high degree of accuracy. If models are being developed to investigate the dependence of selectivity parameters on certain factors then accuracy may not be as important as covering a suitable range of parameter values. Relative selectivity between gears, years or species may be an objective which could also be less demanding on accuracy.

3 Designing the experiment

3.1 General considerations

The quality of the data and hence the success of an experiment may be affected not only by the choice of the experimental method (Section 2.2) and of the statistical design (Section 3.2) but also by more general factors which should be considered carefully at the planning stage.

To investigate the selectivity of commercial fishing gears it is highly desirable that the trials should be undertaken on commercial fishing grounds, at commercial fishing depths, at commercial catch rates and sizes and during the commercial fishing season.

3.1.1 Fish population and distribution and fishing grounds

It is important to ensure that the population of target species on the fishing grounds should have sufficient numbers in the selection range of all the gears being tested. Such data give estimates of selection parameters with lower variance as the selection curves can be defined with more certainty. Consultation with local fishermen, information on recent fish landings at local ports or historic information from national data banks may provide useful evidence of appropriate fishing areas. During "paired gear" experiments (twin and trouser trawl, alternate and parallel haul) it may also be important to ensure sufficient numbers of large fish are caught. The bias between the two "paired gears" can be tested by examining the members of fish subject to 100% retention in both.

Knowledge of the seasonal or regional abundance of non-target species such as dogfish or jellyfish or of other organisms such as seaweed is important. Their presence may cause practical problems in handling the catch and may affect the size selection of the target species.

Choice of grounds should be made after consideration of the size of vessel and the likely exposure to poor weather, the distance from port and the presence of other fishing activity in the area - for instance an area fished intensively by static gear may not be suitable for towed gears. Rough ground will cause gear damage and may reduce the number of valid hauls; it will also tend to affect gear symmetry due to snagging of ropes or wires in the cases of susceptible gears such as pair trawls, twin trawls and trouser trawls.

3.1.2 Fish behaviour

The behaviour of the target species should be known and taken into account in the experimental design. It is essential that an experiment should not accidentally introduce additional visual, olfactory or auditory variables which may affect fish behaviour and hence selection. The behaviour of fish is primarily determined by their reaction to visual stimuli (Wardle, 1989). The colour and contrast of netting should remain unchanged. Details of rigging such as lifting strops, strengthening bags, chafers, flappers and other attachments should be as on the commercial fishing gear since these items may create visual stimuli.

The swimming capacity of the fish and hence their susceptibility to capture is a function of temperature, state of exhaustion and the speed of the gear through the water. Selection may therefore vary with season, time of day and fish condition. Changes in tides, currents, light level, temperature or other diurnal or periodic factors may cause changes in behaviour, and hence in population or selection.

3.1.3 Type of vessel

Factors which need to be considered are the facilities on board, e.g. working area on deck for handling catch and gear, space for equipment, accommodation for extra people; the flexibility of the operation e.g. in the ability to change fishing grounds or gears; the utilisation of the vessel, e.g. in hauls per day, and hence the cost per unit time. There are advantages and disadvantages in the use of both research and commercial vessels for selectivity trials. Work on a commercial vessel represents typical commercial fishing conditions well and often has the benefit of the local knowledge of the skipper e.g. on fish availability. It is strongly recommended that a commercial vessel is used if the experiment aims primarily to measure the selectivity of a commercial fishing gear. The use of a research vessel might be preferred to a commercial fishing boat in some circumstances, however, to ensure availability of the same vessel for a series of cruises, to maximise control over the experiment or to provide specialised facilities.

3.1.4 Factors affecting size selection of fish

In many selectivity experiments it is important to ensure that the selectivity of the gears under test are not affected except by the variables for which the experiment is designed. This implies a knowledge of the major factors which have been shown, or are thought, to affect fish size selection (Table 3.1.4).

Table 3.1.4 The major factors affecting size selection of fish.

Origin	Parameter	Comments
GEAR	Mesh size	Type of measuring gauge is significant
	Mesh shape	Eg diamond, square, hexagonal
	Codend diameter	Number of open meshes round codend circumference
	Codend/extension length	
	Twine characteristics	Thickness, linear density, stiffness, colour, elongation, elasticity may all be
	Rope hanging ratio	Longitudinal ropes may take tension off codend netting and allow meshes to
	Attachments to codend	Eg strengthening bag, lifting strop, chafer
	Cover type	Good design needed to avoid masking, changes in waterflow and fish
	Design of gear ahead of	Determines diameter of aft end of extension and affects fish behaviour
	Hauling procedure	Loss of fish at surface through eg wave action
FISH	Fish size	Girth is key factor but length usually measured
	Fish shape	Seasonal variation in fish condition
	Fish population available	Target and non-target species, predators
	Rate of accumulation in	Densely packed fish may never encounter open meshes
	Catch size	Selectivity changes as codend shape and tension change
ENVIRONMENT	Water temperature	Affects swimming ability
	Light level	
	Sea state	Affects motion of gear
	Seabed type	Affects gear motion (rough ground), visibility (mud cloud)
	Water depth	Affects light level, also gear motion (long wire lengths)
VESSEL	Towing speed	
	Motion	Can be transmitted to gear; dependent on vessel size

Of the main design features of a diamond mesh codend, mesh size has the most significant effect upon fish size selection (Reeves *et al.*, 1992) with codend circumference, twine type and extension length being less important but still significant. The orientation and hanging of the netting, i.e. how it is rigged onto the selvedge ropes (if any), determine how open the meshes are. In this way, using square mesh netting or shortening the selvedge ropes along a codend has been shown to increase the 50% retention length of demersal roundish although the effect on selection range is less certain (Cooper and Hickey, 1989; Eustachian and Valdemarsen, 1990; Robertson and Stewart, 1988). Selection may also be affected indirectly by the increased occurrence of meshing of fish e.g. in areas where changes in selvedge rope length have improved the opening of the meshes. The taper of the main body of the net may also be a factor as it will determine the diameter of the mouth of the parallel sided extension and codend. An increase in codend twine thickness has been shown to reduce 50% retention lengths of demersal roundish (Shevtsov, 1979; Lowry and Robertson, 1995). Twine characteristics in general have an effect on a gear's selectivity (Ferro and O'Neill, 1994).

Attempts have been made to determine whether towing speed has an effect on gear selectivity but no consistent result has been shown. Duration of tow and distance over the ground are related parameters. The experiments are particularly difficult to do and it is therefore unwise to conclude that these factors may be of less significance than others.

For all towed fishing gears using flexible netting it is likely that selection varies considerably during a haul as the catch increases. For instance, during a tow with a trawl, the codend netting is initially slack and may have little or no flow through it. The meshes will tend to be closed. As fish start to accumulate the tension in the netting increases and a bulge starts to form at the aft end. This process continues until the catch bulge attains a maximum diameter. Just ahead of the bulge the meshes are more open and are not blocked by fish. The majority of escapes from a diamond mesh codend have been observed to occur in these few rows of unblocked meshes ahead of the bulge. Further ahead in the codend and extension the meshes are more closed and the diameter of the codend reduces although it may be possible to improve the potential for fish escape in these areas by the use of devices such as windows or grids in which larger openings are maintained. At high catch rates fish retention may be increased because individual fish in a densely packed shoal have less probability of approaching an open mesh. However, only a weak correlation between total catch size and gear selectivity parameters has been found (e.g. Hodder and May, 1964; Suuronen, Millar and Jarvik, 1991; Madsen and Moth-Poulsen, 1994). Hence it is possible that some other factor such as the rate of arrival of the fish or the size composition of the population may be more significant than the eventual total catch size.

A gear's selectivity can also be affected by the dynamic motion of the gear. In calm conditions and over a smooth seabed the gear may have a steady motion but vessel motion or an uneven seabed can cause the gear to pulse. The codend will surge forwards and backwards as the tension in the gear fluctuates; this may allow the meshes to be slack and open at regular intervals and thereby decrease retention rates. Codend catches can be subject to an increased "washing action" in rough weather when lying on the surface awaiting emptying onboard. Polet and Redant (1994) found a clear effect of sea state on *Nephrops* 50% retention length. Also at certain times during the hauling operation the codend meshes become slack.

Other variables such as fish behaviour (Glass and Wardle, 1995) and environmental conditions including light level (Glass and Wardle, 1989) and temperature may not be controllable but may still have a significant effect on the fish catching process.

3.1.5 Factors affecting fishing power

There continues to be uncertainty about the effect of codend mesh size on the fishing power of a gear. Increases in mesh size have been associated particularly with increases in the catch of larger fish and there is some doubt whether the effect is equally applicable over the whole range of fish lengths (Beverton and Holt, 1957; Templeman, 1963; Anon., 1964; Pope *et al.,* 1975). The causes of the effect are likely to be differences in flow through the net or in geometry of the net. The problem of differential fishing power may arise when measuring selectivity using twin trawls or the alternate or parallel haul methods when a net with a small mesh codend is used to sample the available population. A similar problem may occur in trouser trawls using different mesh size codends, caused e.g. by differences in water flow or distortion due to differences in load.

To test conclusively for equality of fishing power when two different codends are being used is very difficult. Comparisons may be made of the catches of fish above the selection range of the largest mesh size being tested. Clearly similar numbers of fish of these sizes should be caught over a large enough series of hauls to take into account variations in population met by the two codends. If however, there are few fish in this larger size range then the only solution is to find fishing grounds with sufficient numbers of large fish. This may not be practical or possible.

Another aim in a twin trawl, trouser trawl or parallel haul experiment may be to test for equality of fishing power of the two nets over the whole range of fish lengths in the population or at least in the range of fish lengths which are subject to selection. This can be done only by using codends of the same mesh size on each net. In this case choice of mesh size is difficult. If a larger mesh size is used the smaller fish will not be sampled effectively and if a smaller mesh size is used, the larger fish may not be sampled fully. A compromise mesh size, perhaps half way between the smallest experimental mesh size and the small mesh codend mesh size may be suitable since it is not essential to sample the very small fish which will all escape and the fishing power of the net for larger fish may not be affected too greatly.

It will be necessary to fish the gears for several hauls to assess equality of fishing power. If the fishing powers are found to be unequal then it is necessary to design the experiment carefully to account for this fact. The gears and/or codends may be interchanged between vessels (parallel haul) or between sides (twin or trouser trawl) at regular intervals as necessary (Section 3.2).

Alternatively the problem may be overcome by analysing the data using a method which determines the bias between the two nets and allows for this in the estimation of the selectivity parameters. This type of analysis assumes that the bias affects fish of all lengths equally, see Section 6.3.2. It will not be known whether this assumption is valid and therefore interchanging nets/codends (see above) is preferable, if time and money permit.

3.2 Statistical design of experiments

The main objectives of statistical design are:

- to ensure valid estimation of key parameters or valid statistical tests of hypotheses
- to ensure that key parameters are estimated with sufficient precision, or hypothesis tests have adequate power.

3.2.1 Validity

When two or more gears are to be compared, the order of fishing them is important. If experimental conditions are likely to vary during the period, it is essential that any differences detected in the comparisons be attributable to differences in the gear and be distinguishable from differences due to external factors e.g. environmental changes. The gears should be fished in a specified random order over a period when the conditions are as uniform as possible (e.g. same ground, same rig apart from the aspect being studied, same fishing operation). Randomisation is important as it provides a basis on which strict statistical tests of significance of experimental differences may be made.

If however, it is likely that there will be systematic variations during these periods, e.g. increased catch rates at particular times of day, then it is acceptable to choose the order of fishing the gears to ensure that all hauls with one type of gear are not made at the same time of day. Such systemisation or blocking can be introduced while still retaining the necessary randomisation. A design based on randomised blocks is a well-known technique (John, 1971).

3.2.2 Precision

The variance of an estimated selectivity parameter for one gear is influenced by a wide range of factors. Some factors are not directly controllable, e.g. those connected with environmental conditions. Indeed, it should be remembered that commercial fishing gears are used in a wide range of conditions so that there may be some justification in testing gears in differing conditions. Inevitably the variance of the results will be increased. On the other hand, some factors affecting variance can and should be controlled. Variance can be reduced mainly by increasing the number of hauls made, the number of fish caught or the rate of sampling the catches. In the case of "paired gears" the evenness of the distribution of fish entering the two gears will also affect variance. This may be controlled to some extent by ensuring that the two gears are rigged in the same way and have mouths of similar dimensions, for instance. The smaller the variance in a set of selectivity parameters for a gear then the smaller the differences in selectivity which can be detected at a given confidence level.

A power analysis (Fryer, 1996) can be very useful in determining, before an experiment, how many hauls are likely to be needed to obtain a significant result. It is extremely important to plan to identify significant differences between a limited number of gear types (perhaps only two) rather than attempt to test simultaneously a large number of gears and fail to obtain a significant difference between any of them due to insufficient numbers of hauls or inadequate sampling. The smaller the difference to be detected then the more hauls must be done to achieve the same significance level.

3.2.3 Planning for bias

In most trials there is the possibility of bias and this should be taken into account at the planning stage. There is merit in comparing the selectivity of an experimental gear with that of a "standard" gear which has been used perhaps on several previous experiments. Not only will the benefits of the new design be assessed with respect to the standard design but a comparison of the new and old selectivity estimates for the standard design may indicate whether there is any bias in the current experiment.

Bias may arise with "paired gears" where, e.g. in the case of the twin trawl, a small mesh codend is used on one side of the gear and the test codend on the other. If the bias is caused by differences in the gears ahead of the codends in a twin or trouser trawl or perhaps in the vessel operation in the case of a parallel haul experiment then the bias may not be constant and one way of dealing with it is to treat it as a component of the random error. It would be necessary to change the codends between gears or vessels according to a predetermined design. If bias is present, it will be necessary to increase the number of hauls in order to obtain a required level of significance. Because the bias may not be constant it is preferable to make these changes rather than to rely on analytical methods (described in Section 6.3.2) to calculate the bias. Practical considerations in making such gear changes may be important - very frequent changes may take up much time, for instance. There may be no advantage in estimating the bias e.g. by fishing the gears with the same codend for several hauls. If the difference is relatively small, a large number of hauls would be needed to demonstrate significance and hence justify correcting it.

A different situation occurs when it is the codends themselves which cause the bias. The bias in these cases may be relatively constant. For instance, in an alternate or parallel haul or twin or trouser trawl experiment the small mesh codend and the test codend may have different fishing powers. A check can be made on the catches of large fish above the selection range in the codends and it is important to ensure that the population being fished contains adequate numbers of these fish when using these methods. It must be assumed that any bias occurring in the catch of large fish also occurs at all fish lengths since it is impossible to distinguish between bias in fishing power and the selective properties of the test codend for fish within the selection range.

A similar problem may occur, particularly when using the alternate or parallel haul method, when fishing species which gather in shoals stratified by length. Clearly if one haul fishes on a shoal of small fish and the alternate haul on a shoal of large fish, then it will not be possible to estimate accurate selectivity parameters since the whole population of fish will not be sampled. A check on whether this situation is occurring can be made by studying the variation of length/frequency distribution for all hauls with one codend.

Potential problems such as these should be borne in mind when deciding on the most appropriate experimental method for a particular fishery.

3.3 Practical planning of sea trials - a checklist

When planning an experiment at sea many different factors have to be taken into account. A checklist makes the planning easier. The key factors are listed here.

TEST METHOD (covered codend, twin trawl, ...)

PROJECT TIME REQUIREMENT
- gear design and manufacture
- planning of experiment
- receipt of permits
- chartering of vessels
- cruise time
- analysis
- report writing

CRUISE TIME REQUIREMENT
- rigging time
- test area, steaming time
- number of hauls
- length of hauls, fishing hours
- allowance for weather, damage, breakdown

TIMING AND LOCATION
- fishing season
- vessel availability
- fishing ground

LEGAL ASPECTS
- fishing period
- mesh regulations
- closed areas
- operation outside legal restrictions, need for permit
- operation in foreign country waters
- notify relevant authorities

VESSEL
- towing capacity
- deck space
- operating range (radius of action, sea-steadiness)
- winch capacity and numbers
- other deck facilities
  gear, measurement equipment (ROV's, instruments)
- catch
  handling, sorting, weighing
- "laboratory" space
  measuring, processing of data
- sleeping quarters
- availability (also for possible future experiments)
- skipper and crew attitude and experience

GEAR
- availability

- design or adaptation (e.g. trouser trawl), manufacture
- testing model of new design in flume tank or at sea using underwater television
- special arrangements for measurements and observation
- design and construction of cover, if used
- similar for other selective devices (grids)

MEASUREMENT EQUIPMENT
Examples of the type of equipment which may be useful are given below. Priorities for each measurement are assigned in Section 5.1.

- gear:	ICES mesh gauge, legal mesh gauge, height and spread sensors, net speed logsdata logging methods
- catch:	length, girth, weight (unit containers etc.), "laboratory" tests, automatic recording of parameters (electronic measuring board or software for typing in length-frequency data)
- environment:	GPS, speed log, light levels, temperature data logging environmental parameters

STAFF REQUIREMENTS

- number:	gear handling, sorting, measuring, preliminary analysis at sea
- qualifications:	ability to check and mend nets, experience at sea, knowledge of data analysis

4 Gear design and construction

4.1 General considerations

4.1.1 Gear design

Because the selectivity of a gear is determined to some extent by the design of the whole gear it is important to ensure that the gear is made correctly. It is sensible to check ashore that the net was constructed according to the design by checking mesh sizes, measuring the important wire lengths (fishing line, groundrope, headline, bridle wires, selvedge ropes, etc.), counting the number of meshes e.g. across the square and belly and counting the number of floats.

The aspects of the gear which are known to affect its selectivity significantly, e.g. codend and extension design, should be checked particularly thoroughly by a skilled person, at the design and construction stages, if possible. It is wise to measure the mesh sizes of the netting from which the codends are to be constructed before the netmaker starts to make them.

A further decision must be made whether to measure the selectivity of the gear with all codend attachments in place, such as strengthening bags and chafers. These devices may not be used by all the commercial fleet. They may, in association with a small mesh cover, cause considerable blockage of the water flow and therefore affect the selectivity measurement.

Unless the gear is most unlikely to be damaged it is recommended that two similar complete gears are available as a damaged net seldom fishes in quite the same way due to imperfect mending perhaps or to the strains imposed when the damage was sustained. If major damage occurs the net should be changed and the wire lengths and rigging checked.

4.1.2 Choice of mesh sizes

All the methods described in Chapter 4 require the use of either a small mesh cover or codend. The mesh size should be chosen small enough so that it does not allow the escape of any fish which are retained in significant numbers by the test codend. A cover mesh size should not be too small however, as it is important that it restricts the water flow in and around the codend as little as possible. In the case of a small mesh codend on a twin or trouser trawl, excessive drag of the small mesh netting may cause asymmetry of the gear such as closing of the net mouth or lifting of the groundgear on that side. Another consideration is the occasional need either to use a smaller mesh size to avoid meshing of large numbers of non-target species in the small mesh codend or to use a mesh size large enough to release them. A possible upper limit is half the mesh size of the test codend.

Care is needed in designing an experiment where a range of mesh sizes is to be tested. Appropriate mesh sizes should be used in the extension and forward sections for all the codends. The question may arise whether the mesh size in the extension may need to be increased in line with the larger codend mesh sizes in order to simulate true commercial conditions which would apply if the legal minimum mesh size was increased. Although few fish may escape from the extension its mesh size may nevertheless affect water flow and hence the gear's selectivity. It is also necessary to consider carefully the choice of the number of circumferential meshes for a range of codends of increasing mesh size. If it is intended to achieve a similar mesh shape (i.e. angle between the mesh bars) the fully extended width of the codend (mesh size x number of circumferential meshes) should remain constant for all codends. On the other hand the experiment may be designed specifically to maintain the number of meshes round the circumference constant.

In general it is recommended that gears should comply with the legal requirements expected to apply to the net when used commercially.

A related problem concerning mesh size arises in the twin or trouser trawl and alternate and parallel haul methods where a small mesh codend is attached to the extension of a standard net. A large reduction in mesh size between the two sections of netting may result and fish may be prompted to escape at the mesh size discontinuity. Underwater television observations at the join of the two mesh sizes would show whether escapes were occurring ahead of the small mesh. If they were, a netting section of an intermediate mesh size ahead of the small mesh codend might be used.

4.2 Details of each experimental method

4.2.1 Covered codend method

4.2.1.1 Aims

The aim of the design is to ensure as far as possible that the escape processes of fish from the codend are not changed by the presence of the cover. Both the physical performance of the codend and the behavioural stimuli imposed on the fish inside the codend should be unaffected. A minimum separation between codend and cover should be ensured so that there is sufficient space for larger fish to emerge from the codend meshes without touching the cover. The water flow through and around the codend should be altered as little as possible because the ability of the fish to escape may be affected by the flow parallel to the netting (Wardle, 1993). There should be an adequate volume within the cover to the rear of the codend so that the escaping fish can collect there without influencing the fish still in the codend. The colour of the cover netting should be chosen with care to reduce its contrast to the background and hence its visibility to the fish inside the codend.

The design should also aim to reduce handling difficulties and allow easy emptying of both the codend and cover, taking into account the layout of the vessel.

4.2.1.2 Cover manufacture

The main part of the cover is made as a cylinder of netting, see Figure 4.2.1.2. It has previously been suggested that the cover should be 1.5 times the fully extended length and width of the codend (Stewart and Robertson, 1985). In practice, this may be too short for all but small catches in the cover and it is now recommended that the cover should be two or more times the fully extended length of the codend. The recommended fully extended width remains at least 1.5 times the codend width. With these dimensions the unblocked area of the surface of the cover (i.e. through which the water can flow) will be greater than that of the codend.

Where fish tend to escape through the upper surface of the codend, it is best to construct the cover with neutrally or slightly positively buoyant material (PE, PP). Negatively buoyant material (PA, PES, PVC, PVD, PVA) may tend to lie on the codend and thus obstruct the meshes. Without prejudicing strength, thin twine is preferable to reduce the bulk of the cover and ease handling.

If diamond mesh netting is used for the cover its diameter will reduce along the section between the hoops (Figure 2.1.1) as the axial load on the netting increases. There is therefore a danger that the cover netting could mask the meshes of the codend. A larger hoop diameter may be required. At first sight it may seem that the use of square mesh netting may avoid this problem since the cover will then form a cylindrical shape along its length. There is a disadvantage, however, in that the square mesh netting does not stretch to allow the hoops to be inserted round the cover easily because there is a row of bars around the circumference of the cover which pull taut; careful matching of the width of the small mesh netting and the hoop circumference is required.

The forward end of the cover is closed by a piece of netting (skirt) attached round the circumference of the cover at its forward end (Figure 2.1.1). This skirt may be tapered towards its forward end and of a larger mesh size than the cover in order to allow a good water flow between the cover and the codend. Escaped fish rarely approach the forward end of the cover during the tow but fall back into the area behind the codend catch where the flow is reduced. Fish may escape during hauling, however, especially on a side trawler, so that larger mesh in the skirt should only be introduced if there is confidence that no escapes occur. The skirt should have the same stretched circumference at its aft end as the cover and should have a fully extended length at least 1.5 times the radius of the hoops. The forward edge of the skirt is mended on to the aft joining row between the codend and the section ahead of it. This join can cause distortion of the net if the cover netting makes too great an angle to the codend netting. Reducing the first hoop diameter or positioning it further aft may reduce this angle.

There is also the possibility that, due to the presence of the cover, the meshes in the extension just ahead of the codend may be opened wider than normal. If this is confirmed e.g. by underwater television and if an estimate of the true mesh opening in the extension can be made than a constrictor rope could be attached round the circumference of the extension perhaps 1 or 2 m ahead of the codend. The length of this rope should be chosen to limit the mesh opening to the estimated true value for a typical catch size.

The colour of the cover and skirt netting and the hoops and zips should be chosen to reduce the contrast of the netting to the background and make the cover as invisible as possible to the fish in the codend; for instance, the upper panel could be made of white netting and the lower panel of black netting. As the majority of escapes are made through the upper panel of most codends it is the colour of the upper panel which is likely to be the more important (Glass, Wardle and Gosden, 1993).

On a vessel where the codend and cover will be hauled up in the air for unloading, zips can be used to simplify emptying the codend catch. Two heavy-duty zips can be inserted along both upper and lower panels of the cover. This ensures that one of the zips is accessible regardless of which way the cover is facing when it is hauled. Each zip is made in two sections, allowing easy repair if one is damaged. They are joined zipper to zipper, opening outwards. They should be inserted lengthwise in the cover in a position such that the mid-point of the zip coincides with the codend codline when codend and cover are brought to the deck for unloading.

4.2.1.3 Hoop manufacture

During trawling, the cover is held off the codend meshes by means of semi-rigid hoops. Plastic water pipe, 60 mm in external diameter has been found to be suitable for smaller vessels up to 600 hp. There is a tendency for the hoops to buckle during the fishing operation and a more rigid pipe may be needed for larger vessels where the forces generated by the catch are higher. A maximum practical diameter for this design of hoop may be approximately 2.5 to 3 m. For larger gears hoops may be made from non-rotating wire with flotation attached to counteract the hoop weight. Plastic hoops are joined in a complete circle with a short solid plastic or steel bar which is inserted in both ends of the pipe. It may be necessary to use a slightly curved bar. One end of the bar is permanently secured and it is important that the bar is long enough and a good enough fit to give the join rigidity. The other end of the bar should be tied carefully so that it can be released easily and the hoop opened to facilitate shooting and hauling. A simple cable tie inserted through a hole drilled through bar and pipe may be sufficient. For solid hoops a short sleeve which fits tightly over the ends of the hoop and flush with the hoop surface can be used and fastened in a similar way.

The diameter of the hoop must be large enough to allow fish to escape easily from the codend at the point of its maximum diameter (the actual diameter of the codend during fishing). Assuming that the codend meshes are set square at its maximum diameter and that the cover diameter is required to be x% larger than this diameter, a suitable value for the cover diameter in metres is given by:

$$7 \cdot 10^{-6} \cdot (100+x) \cdot M \cdot N / \pi$$

where M is an estimate of the knotcentre-to-knotcentre codend mesh size (mm) and N the number of open meshes round the codend. The choice of the value of x depends on the size of fish likely to escape and on the gear size but 10% may be suitable (Table 4.2.1.3). The diameter of the hoop should be close to this cover diameter but will depend on the method of hanging the cover on the hoop, e.g. whether the hoop is internal or external to the cover (see next section).

The thickness of the knots may be a significant proportion of the codend diameter so that knotcentre-to-knotcentre mesh size (mesh length) should be used in the formula. To estimate mesh length from measured opening of mesh (between knots), the knot diameter should be added which may be taken as 3 times the twine thickness for single weaver knot netting.

Table 4.2.1.3 Required diameter of cover (m) during fishing given number of open meshes round codend and knotcentre-to-knotcentre mesh size (mm). The diamond mesh codend is assumed to have a fishing diameter which is 10% smaller than the cover.

Mesh size mm	Number of meshes round											
	60	80	100	120	140	160	180	200	220	240	260	280
20	0.29	0.39	0.49	0.59	0.69	0.78	0.88	0.98	1.08	1.18	1.27	1.37
30	0.44	0.59	0.74	0.88	1.03	1.18	1.32	1.47	1.62	1.76	1.91	2.06
40	0.59	0.78	0.98	1.18	1.37	1.57	1.76	1.96	2.16	2.35	2.55	2.75
50	0.74	0.98	1.23	1.47	1.72	1.96	2.21	2.45	2.70	2.94	3.19	3.43
60	0.88	1.18	1.47	1.76	2.06	2.35	2.65	2.94	3.24	3.53	3.82	
70	1.03	1.37	1.72	2.06	2.4	2.75	3.09	3.43	3.77			
80	1.18	1.57	1.96	2.35	2.75	3.14	3.53	3.92				
90	1.32	1.76	2.21	2.65	3.09	3.53	3.97					
100	1.47	1.96	2.45	2.94	3.43	3.92						
110	1.62	2.16	2.70	3.24	3.77							
120	1.76	2.35	2.94	3.53								
130	1.91	2.55	3.19	3.82								
140	2.06	2.75	3.43									
150	2.21	2.94	3.68									

The forward hoops can generally be of a slightly smaller diameter. A reduction in diameter improves strength, eases handling and reduces the angle of the skirt.

4.2.1.4 Attaching the hoops to the cover

One hoop is attached near the forward end of the cover and another just ahead of the codline where the codend will achieve its largest diameter (Figure 4.2.1.2). With long codends other hoops may be needed and they should be spaced equally along the cover.

A hoop may be attached around the outside of the cover, allowing it to be removed easily during hauling. Each hoop is secured on the outside of the cover by plastic codend rings (e.g. 150 mm in diameter for 60 mm diameter pipe) which are equally spaced around the circumference. For 2 m diameter hoops approximately 20 rings may be needed, each attached to 2 or 3 gathered meshes. The width of the cover netting should be checked against the hoop circumference to ensure that the hoop can be threaded through the rings easily.

Alternatively a hoop may be fitted inside the cover. This may be necessary if the required cover diameter is close to the maximum practical hoop diameter of ca. 2.5 m. The clearance between cover and codend will then be maximised and the risk of masking reduced. In this case the hoop must remain in place from haul to haul without being removed on hauling. It may be tied to the cover netting at 30 cm intervals around the circumference.

4.2.1.5 Vessel design

When choosing a vessel, consideration should be given to the general layout of the deck, especially where hoops are to be fitted to the cover prior to shooting the net. There should be sufficient working space for the crew to heave the cover off the net drum (if one is in use) and thread the hoops through the rings on the outside of the cover.

Hoops may be damaged as they are dragged up the ramp of a stern trawler and a system of hooking the hoops when they are at the lower end of the ramp and supporting them as the codend is heaved up the ramp may be needed.

Vessels which are fully shelter-decked should have sufficiently wide shooting hatches to accommodate the diameter of the cover hoops in use. A power block or lifting tackle near the position where the fishing gear is shot and hauled can be used to raise the codend and cover to a height sufficient to enable the crew to fit the hoops. With only limited experience over a few hauls, most crews can rig the cover quickly.

4.2.1.6 Fitting the hoops and shooting the gear

External hoops to be attached by means of rings should always be fitted before any of the net is shot. If the net is in the water the longitudinal strain on the cover meshes, due to its drag through the water, will make the hoops more difficult to fit.

When shooting in bad weather, it is helpful to reduce ship speed and allow the hooped cover to sink below the surface. Otherwise permanent damage to the hoops may result due to wave action. This can be exaggerated by a pulsing effect on the cover transmitted to the net in heavy seas by the pitching vessel. Deformation of a hoop during towing can result in "masking" of the codend meshes and increased retention of fish.

To reduce the likelihood of twisting during shooting, trawl floats can be attached along the selvedges of the extension or codend. Two or three floats per side should be sufficient but care should always be taken during shooting to ensure that the bag is not twisted. To prevent twisting of the cover, flotation can be added to the top of the aft hoop and the equivalent weights attached to the bottom of the hoop. In some conditions, especially with cross winds or tides, twists can develop in the extension during shooting or towing. This can result in fish escaping, or being meshed in the extension and never passing back into the codend. In this case two or three floats along the top center line of the extension are the best solution.

If, on shooting, the codend, extension or cover are seen to be in even a slightly wrong configuration, e.g. a twist in the extension or cover, the net should be hauled back on board to solve the problem as otherwise it is likely to persist during the haul.

4.2.1.7 Hauling and handling the catch

If the codend, cover and hoops are strong enough they may be hauled up the ramp of a stern trawler. The hoops are normally removed from the cover before any unloading is done as they can be dangerous and are susceptible to damage if allowed to roll across the deck.

When there is no ramp external hoops can often be undone when they reach the ship's side. With large catches it may be impractical to lift the codend and the cover on board at the same time. In this case a quick release strop should be used at the join of the cover and codend so that they can be separated when alongside the vessel. The codend can then be lifted on board first. Such an arrangement has been used on both side and stern trawlers.

When the codend is extracted from the cover the zip should be undone along its full length to avoid damage to the cover. With two or more 'lifts' of the codend it must be replaced in the cover and the zip closed before returning it to the water to take the next lift.

4.2.2 Alternate haul method

4.2.2.1 Aims

This method avoids the possibility of bias in the results due to a cover and does not need the complex gear designs of twin or trouser trawls. The small mesh codend and the test codend are fished alternately on the same net. The catch in the small mesh codend is assumed to be representative of the fish population entering the test codend over the whole length range of fish in which selection takes place.

4.2.2.2 Gear and vessel design

Although the same gear, apart from the codends, and vessel are used throughout an alternate haul trial it is still necessary to ensure that there are no changes in fishing power (see Section 3.1.5), particularly in a pair of hauls with large and small mesh codends. This type of inconsistency increases variance in the selectivity parameters estimated by this method.

The small mesh codend should have similar dimensions (fully extended length and width) as the test codend. However, this will usually mean it has a larger twine area and hence drag. This drag increase may be reduced by the use of a smaller twine size in the small mesh codend.

4.2.2.3 Practical techniques

The data are analysed in such a way that pairs of hauls using the test codend and the small mesh codend are treated together. It is therefore important to minimise the differences in conditions for the two hauls so that the population sample is appropriate to the catch in the test codend. The fishing power of the test and small mesh codends in catching large fish fully retained by both codends should be checked (see Section 3.1.5). Tow direction, towing speed and length of haul should all be replicated as closely as possible.

Ideally the two hauls should be made as close in time and position to each other as possible. This can be very important if there are clear diurnal rhythms in fish behaviour. The vessel should use the same shooting and hauling procedure for both hauls of a pair.

The two hauls should be made in similar environmental conditions. For instance rough weather can cause regular pulsing of the gear which can affect fishing power by lifting the groundrope and allowing the escape of the smaller fish sizes in particular. The estimation of retention at these lengths is thus affected.

4.2.3 Parallel haul method

4.2.3.1 Aims

This method avoids the possibility of bias in the results due to a cover and does not need the complex gear designs of twin or trouser trawls. Two separate fishing operations are conducted on two vessels at the same time towing similar gears on parallel courses. The small mesh codend is attached to one net and the test codend to the other. The catch in the small mesh codend is assumed to be representative of the fish population over the whole length range of fish in which selection takes place.

4.2.3.2 Gear and vessel design

The two vessels used for a parallel haul experiment should be of similar design and main engine power. The two gears should also be as well matched as possible. There are many aspects of gear design which may affect its selectivity (Section 3.1.4). It is recommended that new nets are bought since the fishing power of a net may change with use, e.g. as a result of repair. Whether new or used, the gears should be checked carefully ashore before the cruise starts and their condition should be monitored as the cruise progresses. These comments apply to all aspects of the gear as it is assumed that the same numbers of fish enter the two codends per unit time over the pairs of hauls. Not only the design but also the operation of the gears should be similar. The fishing time during which the two nets are fishing on the seabed should be as nearly equal as possible. Hence the time for the warps to be paid out and for the gear to settle on the seabed should be equal.

The small mesh codend should have similar dimensions (fully extended length and width) as the test codend. However, this will usually mean it has a larger twine area and hence drag. This drag increase may be reduced by the use of a smaller twine size in the small mesh codend.

4.2.3.3 Practical techniques

The data are analysed in such a way that pairs of hauls using the test codend and the small mesh codend may be treated together. It is therefore important to minimise the differences in conditions for the two hauls so that the population sample is appropriate to the catch in the test codend. If possible the two vessels should tow on parallel straight courses at a distance which maintains normal safety at sea. It is an advantage if the fish population is evenly distributed over the sea area being fished. The fishing operations on both vessels should start and stop at approximately the same time also. The fishing power of the test and small mesh codends in catching large fish fully retained by both codends should be checked (see Section 3.1.5).

4.2.4 Twin trawl method

4.2.4.1 Aims

The design of the twin trawl must ensure as far as possible that similar numbers and size ranges of all fish species pass through both net mouths and hence through both codend mouths. The nets should therefore have similar openings and spreads and should be symmetrical to the towing direction throughout the fishing period. The twin trawl method is not appropriate for gears which may not tow evenly. In seining or pair trawling for example, the long ropes in contact with the seabed may become snagged on an obstruction causing temporary asymmetry of the nets.

4.2.4.2 Net design

The two trawls should be made to the same design, having the same lengths of frame lines (i.e. headline, fishing line, footrope and any sidelines). The trawls should also have the same overall length. This will ensure that they achieve nearly the same taper of the netting towards the codend. The objective is to achieve similar headline height and wing-end spread. If the resistance of the trawl with the small mesh codend is high and appears to close the net too much, then the rigging can be changed (e.g. a modest increase in flotation and groundrope weight).

A pair of beam trawls is a special case of twin trawls. Because of the rigid beam there are fewer variables in design but it is still necessary to check wire lengths, beam and shoe weights and the net design carefully to ensure similarity.

The small mesh codend should have similar dimensions (fully extended length and width) as the test codend. However, this will usually mean it has a larger twine area and hence drag. This drag increase may be reduced by the use of a smaller twine size in the small mesh codend. The fishing power of the test and small mesh codends in catching large fish fully retained by both codends should be checked (see Section 3.1.5).

4.2.4.3 Wire rigging of twin otter trawls

There are two methods of a rigging a twin otter trawl: the two and the three warps systems (Figure 4.2.4.3a). Both systems are used in commercial fishing with fishermen normally preferring three warps. The two warp system however, has advantages when measuring selectivity.

<u>Three warp system</u>

The three warp system requires an extra warp winch. The centre warp is connected to a clump weight. The two outer warps connect to the otterboards as usual. Each trawl is then attached between one otterboard and the weight. The lengths of the bridles and sweeps should be made the same as in a conventional single trawl of the same size and type. The weight should be sufficiently heavy so that it is always in good ground contact. The centre warp tows a complete trawl (two halves) plus the weight. The outside warp tows half a trawl plus an otterboard. The tension in the centre warp is therefore higher than in the outside warps. It is estimated that the centre warp takes approximately 45% of the total resistance and the outside warps 27,5% each. In theory the weight should therefore be made heavier than that of one otterboard. In actual fishing practice the situation is normally that the otterboard is heavier than necessary and it is sufficient to have the weight equal in weight to an otterboard. The size of otterboard used should be slightly larger (approximately 10% more in area) than that used by a smaller vessel towing just one of these trawls.

For the two trawls to be towed symmetrically with all 4 wing-ends directly in line it is necessary to have the distance along the wires from the vessel to the centre wing-ends shorter than the distance along the outside wires to the outer wingends. Normally the 4 sets of sweeps and bridles are made equal. The distance from the warp attachment on the otterboard to the aft end of the backstrops is measured carefully. The backstrop wire at the weight is then made shorter than this distance by the required amount to tow the trawls evenly. The distance to shorten the centre wires can be predicted using computer programs which calculate warp profiles. The wire dimensions, towing load in each warp and otterboard spread are required input. Guidelines have been produced (Table 4.2.4.3a) based on the practice of Danish vessels of 200-500 hp catching *Nephrops* and demersal roundish.

The total spread between the two otterboards is twice the value in the above table. For much larger vessels and for fishing in deep water with long warp lengths it is necessary to make individual warp profile calculations.

Shortening the centre wire increases otterboard spread and lengthening the centre wire decreases spread. It is normally observed that adjustments in length of 0.5 m from the ideal length will not cause serious asymmetry.

Two warp system

The two warp system was originally developed for vessels which did not have the possibility of fitting an extra warp winch. A pair of warp bridles are connected to each warp. In commercial fishing warp bridle lengths have ranged from 60 m to 180 m. It is recommended that the length of the warp bridle should be 1.3 to 2 times as long as the distance between the otterboard and the trawl wingend. The outer warp bridle goes to the otterboard and the inner warp bridle to the weight.

Compared to the three warp system the weight is less free to move from side to side. In conditions of cross tides or when turning it is found that asymmetry due to one trawl having more spread than the other is reduced. The possibility of getting such asymmetry is further reduced by dividing the weight into two and having a length of chain separating the two halves (Figure 4.2.4.3b). This is clearly an advantage in selectivity trials where it is particularly important that each trawl has the same spread.

As in the three warp system the centre weight need not usually be heavier than an otterboard. The weight can take the form of hanging lengths of chain, a heavy bobbin filled with metal or cement or lengths of chain incorporated at the

Table 4.2.4.3a Reduction in length of centre wires in a twin trawl three warp system (in metres).

	Warp length					
otterboard spread per trawl (m)	75 fm	100 fm	125 fm	150 fm	200 fm	275 fm
	137 m	183 m	229 m	274 m	366 m	503 m
30	3.4	2.6	2.1	1.8	1.5	1.3
40	6.1	4.5	3.6	3.1	2.6	2.0
50	9.7	7.2	5.7	4.9	3.8	3.0
60	14.1	10.4	8.3	6.9	5.5	4.1
80		18.9	14.9	12.4	9.5	7.0

ends of the warp bridles and backstrops as shown in Figure 4.2.4.3b. The otterboards need to be larger than those used in a three warp system because the warp bridles restrict the spread. The otterboards should be approximately 25% larger in area than the size of otterboards used with a small vessel towing just one of these trawls. As in the three warp system it is necessary to have the distance from the vessel along the outer wires via the otterboard to the outer wingend longer than the distance via the weight to the centre wing-ends. The four warp bridles need to be made of equal length. There then need to be extensions to the centre warp bridles such that when the otterboards are in the gallows these extensions stretch between the gallows (a+b+c in Figure 4.2.4.3b). The backstrops to the otterboards and the weight (Figure 4.2.4.3c) will be made such that the distance from the otterboard warp attachment to the aft end of the backstrop (distance x) is longer than the length from the aft end of the centre warp bridle to the aft end of the weight backstrop (distance y). No satisfactory general method exists for predicting the extra length required in a two warp system. Guidelines based on the practice of Danish trawlers (Table 4.2.4.3b) give estimates for the extra length required with warp bridles of 140 m (75 fm) at different otterboard spreads and different lengths of main warp (from the vessel to the start of the warp bridles). These can be used as a first estimate.

The total spread between the otterboards is twice the value in the above table. The required extra length decreases with increasing warp length and lower otterboard spread. For the case of gears with low otterboard spread, short warp bridles of 60 m and long main warps e.g. 300 m then it has been found to be unnecessary to have extra length in the outer wires. Centre and outer wires can be made of equal length here.

Ideally gear symmetry should be checked by observations with a towed underwater vehicle. When the gear is hauled aboard signs of asymmetry are poor ground contact on the tight side of a trawl but hard ground contact on the slack side or slack meshes with meshed fish in the slack side of the trawl. If both outer wings are slack then the extra length given to the outer wires should be reduced.

The lengths of the centre and outer wires in a twin trawl rig (both two and three warp systems) should be regularly checked against each other to make sure that none has stretched. It should be remembered that new wires stretch more than old wires and to use new wires for a centre wire against old wires on the outer side of the gear will lead to problems.

The above descriptions show that some experimentation can be necessary in developing a new trawl system. The ideal situation will be to find a vessel already experienced in the use of twin-trawls and use or adapt the vessel's existing gear.

4.2.5 Trouser trawl method

4.2.5.1 Aims

A trouser trawl has a vertical dividing panel down its center line, usually from the centres of the headline and footrope to the mouths of the codends. Each half of the trawl leads to a separate codend (Figure 2.1.5a). On one side a small mesh codend samples the fish population on the grounds while on the other side the test codend is attached.

A trouser trawl is designed to ensure that similar numbers and size ranges of all species pass down both sides of the centre panel and hence into the codends. Fish escape should

Table 4.2.4.3b Extra length of the outer warp bridles (in metres) in a two warp system with 75 fm (140 m) warp bridles.

	Main warp length				
Otterboard spread per trawl (m)	25 fm	50 fm	75 fm	125 fm	200 fm
	46 m	92 m	137 m	229 m	366 m
30	2.4	1.8	1.4	0.9	0.6
40	4.2	3.2	2.5	1.7	1.0
50	6.7	5.1	4.0	2.7	1.6
60	9.8	7.4	5.8	3.9	2.3
80	17.9	13.5	10.6	7.0	4.2

occur at the same point in the trouser trawl as in a normal trawl. The dimensions of the net as it tapers towards the codend may affect fish behaviour and hence the gear's selectivity. This is particularly important in small trawls in which the internal volume will be reduced. Conversion of a normal trawl will therefore usually need some redesign of the net, especially at the aft end of the belly where the two codends are attached. Because of the flexibility of the net (especially large pelagic nets), the panel may billow and bias the split of fish. It may be an advantage to start from a design of net which already has trouser codends.

4.2.5.2 Net design

One difficult aspect of designing a trouser trawl is inserting the vertical panel in order to divide the trawl equally without significantly altering the basic configuration of the trawl opening. Some distortion is inevitable because the extra twine causes added resistance. However, for the same towing speed the differences in overall geometry between the trouser trawl and the single trawl from which it was derived should be small. The mesh size and design of the panel must not allow fish of the relevant size range to pass from one side to the other. Normally the panel mesh size will be similar to the mesh size of the small mesh codend.

The panel must be designed so that it is neither too tight nor too loose. A panel which is too tight will tend to lift the groundgear while a loose panel may affect the behaviour of the fish by billowing to one side thus dividing the net mouth unequally. It is difficult to insert a vertical panel in a large pelagic trawl because the panel must be of considerable height. A shorter panel may be an option for some gears but there are then possibilities of unequal division of the catch (Suuronen and Millar, 1992). A full length panel from net mouth to codend mouths is the recommended design.

If the dimensions along the length of the normal trawl at towing speed are well-known then design of the panel should not be difficult. However, the trawl shape at towing speed is not usually known by either the fisherman or the manufacturer unless flume tank tests have been undertaken or the trawl has been instrumented during sea trials. It is recommended that the panel dimensions are taken from geometry measurements of the normal trawl made in a flume tank. Ideally the trouser trawl with installed panel should also be tested in the flume tank. The final product should be observed at sea, e.g. by underwater television, at design towing speed prior to commencing the selectivity tests. An example is given in Figure 4.2.5.2.

The second aspect of a trouser trawl design which needs special attention is the codend attachment. The dimensions of the openings of both codends should be similar to those of the single codend in the normal trawl. This will necessitate cutting back on the normal trawl to obtain a cross-section which can accommodate two codends, each of which has the same dimensions as a single codend. In addition, to smooth the transition to a double codend, a crotch based upon the design by the Marine Institute Flume Tank (Chopin, 1988) should be inserted. Careful design of this area is essential to ensure that the codend mouths have equal areas even when two codends having very different drag are used. Underwater television evidence of correct rigging of the net is highly desirable. Meshing of fish in this area of the net may indicate changes in fish behaviour due to the design changes.

The small mesh codend should have similar dimensions (fully extended length and width) as the test codend. However, this will usually mean it has a larger twine area and hence drag. This drag increase may be reduced by the use of a smaller twine size in the small mesh codend.

4.2.5.3 Hauling and handling the catch

Two equal length codends which are full of fish may create problems during hauling, e.g. in hauling up a stern ramp or when several 'lifts' are required. One solution may be to reduce the length of the small mesh codend (selectivity will be unaffected). It is not recommended to leave the test codend in the water while the other is emptied as fish may be washed out through slack meshes while the codend is stationary in the water.

4.2.6 Methods for special selective devices (e.g. windows, grids)

As described in Section 2.1.6 there are various alternative schemes for measuring the selectivity of gears with special devices such as windows and grids. Some of these use twin or trouser trawl or parallel or alternate haul methods which are described in earlier sections. A whole cover may also be used (Section 4.2.1) to obtain measurements of overall selectivity. In this section only special designs of top cover to collect the fish escaping through selective devices positioned in the top panel of a codend or extension are considered.

4.2.6.1 Aims

The top cover is primarily designed to cover any construction that allows fish to be released from the upper half of the codend or extension piece and hence to collect all fish and bycatch sorted by the device. The cover is designed to be attached onto a two panel extension piece or codend. In a four panel codend the cover should be attached to the gear in a similar manner, going half way down the side panels of the codends, if necessary.

This design is a more complex version of that given in Pope *et al.*, (1975). The aim is to give good clearance between the cover and the release area of the device. Escaping fish should have the opportunity to rise well above the device (e.g. grid or fish release hole) before falling back into the cover. The aim is to minimise changes in fish reactions due to the presence of fish outside the device. Clearance is achieved by the use of buoyant netting material (PE), floats and special tailoring of the cover netting.

The cover has been observed with underwater television when used in combination with grids in shrimp trawls, demersal whitefish trawls and Scottish (flydragging) seines at hauling speeds ranging from 1.5 to 4.5 knots. In all these experiments the cover has had a clearance above the escape area of one metre or more which may not be achieved by simpler versions of the design.

Although the cover was designed as a top cover, it may be possible to use it on the lower side of the gear (e.g. for crab outlets) simply by replacing the PE-netting with heavy PA- or PES-netting (for protection), and the floats by chain weights.

4.2.6.2 Cover manufacture

The cover is made up of five pieces (Figure 4.2.6.2) with two front side panels (A and B) together with a top panel (C) covering the escape area, and two aft (side) panels (D and E) making up the end of the cover. The mesh size and colour of the cover should be chosen as for other cover methods (Sections 4.1.2 and 4.2.1).

The side length b-c (N-cut) of the A and B panels should be at least one metre longer than the escape area to be covered. Lengths b-a, a-f and c-d should be cut on bars, and each should have a length equal to the length of half the number of free meshes across the extension piece or codend when fully extended. Lengths e-d and e-f are cut in the T- and N-direction respectively. The top panel C should have a length equal to e-f, and be tapered in such a manner that d-e, i-h and e'-d' together give a circumference of 250 meshes in 42 mm (10.5 m) in this case. The joining of the three front panels are: a-f to a'-f', f-e to g-i and f'-e' to g-h.

The width of the two panels D and E making up the aft end should be equal to the length (d-e + i-h + e'-d'), and lengthwise be gently tapered down to the number of meshes wanted as codend circumference. The length of the codend piece d-k (or d'-k') should be chosen at least six metres long to prevent fish being washed forward and back down through the escape area, or for handling it on board the vessel.

After joining the length d-d' to the front of the two aft panels (D and E) mesh to mesh, the two aft panels are joined together, giving a hexagonal "pilot-fish mouth", able to cover the escape area. Before attaching the cover, the edges of netting around the opening should be lashed onto an 8-10 mm diameter rope at a hanging ratio of 1. Three to four meshes should be gathered together for greater strength. On c-d and c'-d' five percent slack in the netting should be taken onto the rope giving the cover better lift. Before joining the top cover onto the gear, a false top selvedge of 4-5 meshes should be made between g and j, onto which a suitable number of floats are attached. The floats should be put inside the cover to prevent entangling with other gear parts.

4.2.6.3 Attaching the cover

Point b (Figure 2.1.6) should be fastened at the port selvedge at least 0.5 m in front of the forward part of the escape area and the side b-c laced securely along the selvedge. To avoid any distortion when attaching the net, points b' and c' should be fastened to the starboard selvedge and the nearest row of knots opposite to b and c. During the attachment of b-c and b'-c' it is advisable to mount the top cover a little slacker than the selvedge to avoid any load from the main net being transmitted to the cover.

The sides b-a and b'-a' are laced forward along the nearest row of bars to meet at the middle mesh of the upper panel of the codend or extension piece. The same procedure is done for sides c-d and c'-d'. If there are problems in meeting at the middle mesh when following the row of bars, the taper of the last 15-20 cm of these sides can be altered.

To ensure adequate clearance between the cover and the top of the codend, a plastic hoop should be mounted at the join of panel A,B,C and D,E.

If it is likely that a large load may be put onto the cover or a forward pull when handling on deck, a 14-16 mm rope should be laced along the whole lower selvedge of the aft part of the cover (d-k) and fastened well to the codend and/or extension piece. The aft end of the cover should be reinforced with roundstraps or a lifting bag, especially if the catch is lifted on board.

4.2.6.4 Shooting and hauling

The ease with which the top cover is shot and hauled is mainly dependent on the device to which it is attached. For rigid devices such as grids or on side trawlers, extra care will be needed to ensure that the whole assembly is shot away cleanly without twists. For stern trawlers with sufficient space on deck there are few problems in handling the top cover. With a flexible device the cover may be heaved both off and onto a net drum together with the device. When shooting the gear from a drum, a check should be made that there is no twist in the cover or codend. When the cover has some flotation attached, however, such a twist will often unravel in the early stages of the tow. When shooting the codend and cover from a stern trawler the cover may be placed on top of the selective device and will very rarely twist.

During hauling if the cover is too short, heaving the sweeps or trawl too quickly followed by a sudden stop may "wash" the cover catch forward, and some of the fish may reenter the codend through the escape area. Precautions should be taken when heaving the cover up a stern ramp to avoid squeezing the cover catch between the ramp and the main codend causing the cover to rupture.

4.2.6.5 Handling the catch

Very large catches in the top-cover should be avoided as these may change the configuration of a window as well as the angle of attack of a grid. These devices may, however, not be affected by catch size accumulated in the codend, especially if they are placed well forward of the aft end of the codend and they will then maintain fairly stable selection properties throughout the haul. The haul length may therefore be reduced without giving a different measure of selectivity of the device.

The cover and codend are well separated and there should be no problem in keeping the catches in them separated. On stern trawlers the catches in cover and codend are taken on board at the same time; on side trawlers the catch in the main codend should be lifted on board first to avoid further escape if no small mesh blinder is inserted.

5 Conducting the experiment

5.1 Data to be collected

The present section defines the data and information to be collected during selectivity experiments. How the parameters are measured is described in Section 5.2 - Measurement procedures. Basically there are two categories of data collected 1) fishing gear and vessel data and 2) haul data.

The first category of data to be collected can also be referred to as 'material and methods' data and will be constant for all hauls with a given test gear.

Length selection of fish in towed gears is affected by a number of gear parameters. Some appear directly in mathematical models currently used to describe the between gears variation in selectivity. There are a limited number of these parameters and they are considered as being the most important in explaining the selection process. This group includes the gear parameters codend mesh size, codend circumference and the extension length. Data on other gear and vessel parameters can help to further explain the variability in selectivity and should also be recorded.

The results of selectivity experiments may be biased by the experimental method used. Masking of the codend by the cover used in the covered codend method, for example, can occur and can have a serious impact on the outcome of the experiment. Detailed information on the experimental method is therefore of the utmost importance for future evaluation of the validity of the results and should be recorded.

The second category of data collected is the 'haul data'. Catch data collected from selectivity experiments form the main part of this data and consist of the individual fish lengths in the different codends, the sample size measured, etc. Fishing operational and environmental factors are also included as these can affect the selectivity of fishing gears. Examples are towing speed, haul duration, time of day (light intensity), weather conditions etc. Codend mesh size(s) can change with use and therefore is the one gear parameter that is best included in the haul data.

Clearly not all data are equally important. Here, distinction is made between data that are really indispensable for each selectivity experiment and those data giving other useful information which should be recorded if at all possible. The level of importance of the data is indicated as follows:

(**) must be recorded
- experimental data essential for data analysis
- parameters known to have an effect upon codend selectivity and which must be recorded

(*) should be recorded
- parameters which are suspected to have an effect upon codend selectivity

() optional
- other parameters which may be useful for future reference.

5.1.1 Data on materials and methods

There are two types of data, vessel data and gear data.

5.1.1.1 Vessel data

Size parameters of fishing vessels are assumed to have some influence on the selectivity of the gear but the number of investigations to support this view are not very numerous (Wileman, 1992). Main engine power (brake horse power) is obviously the most important one given its significant impact on the towing speed. Vessel parameters are also needed to judge if vessel size and gear size are correctly matched. In the case of pair trawling the data for both vessels should be recorded.

The vessel data are:

- vessel name/registration no (**)

- vessel type (**) (side/stern trawler, beam trawler, seiner)
- research or commercial vessel (**)
- length overall (*)
- GRT (*)
- engine power (**)
- fixed or variable propeller pitch
- presence of nozzle
- bollard pull

5.1.1.2 Gear data

Experimental method used

Selectivity parameters are subject to variations induced by the experimental method used. These methods, fully described in Section 2.1, are:

- covered codend
- twin trawl
- trouser trawl
- alternate haul
- parallel haul

Design and construction data for twin and trouser trawls are best recorded as a net drawing and a rigging plan.

General gear data

Selectivity data are normally presented for a specific gear. Different gears of the same type may vary in size, design and construction, materials used, rigging and operation, and all may have an effect on selection. The gear size is especially important in relation to the fishing vessel. The basic gear dimensions (fishing circle, headline/groundrope length) should be recorded as well as the codend extension length which has a direct influence on the selection, as discussed in Section 3.1.4. A net drawing is recommended to give details of mesh sizes in the net, taper, hanging ratios and other constructional details. A rigging plan will give useful information, especially when comparing the selectivity of two gears. If multiple rig gears (twin trawls, triple trawls) are used the number of trawls in the combination should be given. An example of a rigging plan and a net specification are given in Figures 5.1.1.2a and b (Anon., 1992a and b).

General gear data are:

- gear type (**)
  - OTB : otterboard bottom trawl
  - OTM : otterboard midwater trawl
  - PTB : bottom pair trawl
  - PTM : midwater pair trawl
  - SDN : Danish anchor seine
  - SSC : Scottish fly dragging seine
  - TBB : beam trawl (specify : tickler chains or chain matrix array)
  - SPR : Scottish pair seining
  - TTB : bottom twin trawl
  - DRB : dredge

- no of gears (multiple rig gears) (**)
- gear size (**)
  - fishing circle (**)
  - headline length
  - groundrope length
  - beam length (**)
  - belly length (*)

- codend extension length (**)
- net drawing (*)
- type/construction of groundrope (*)
- otterboards (*)
  - type
  - size
- rigging plan (*)

Codend data

The codend data are undoubtedly the most important data in codend selectivity experiments. Codend mesh size, width and length can strongly affect selection. For justification for recording these parameters refer to Section 3.1.4.

Due to their importance, most codend data must be recorded:

- nominal mesh length (*)
- no of meshes round
  - open meshes (selvedge meshes excluded) (**)
  - including selvedge meshes
- stretched length
  - in m (**)
  - no of meshes
- mesh type (**)
  - diamond, square or other (specify)
- selvedges (**)
  - number
  - selvedge ropes
    - number (**)
    - length (**)
    - diameter
    - material
- netting material (PA, PE, PES, PP ...) (**)
- knotted/knotless (**)
- twine type (monofilament, multifilament, split fibre, staple fibre)
- twine construction (twisted, braided) (*)
- single/double twine (**)
- linear density (**)
- twine diameter (*)
- flexural stiffness
- twine colour (**)

Codend attachments (**)

Fish escapement can be affected by codend attachments such as chafers and protecting pieces. The use of such devices should be noted as well as where and how they are attached. A short description of these devices should be made. Examples of such devices are

- lifting bag
- strengthening bag (polish chafer)
- topside or underside chafers
- strengthening ropes

The description should include information on materials (e.g. netting or canvas for underside chafers), dimensions and mesh sizes.

Data on special selective devices

Devices to improve a gears selection of fish exist in a variety of designs and constructions. Moreover, most of these devices are relatively new and will certainly be subject to a number of changes in the near future. Therefore it is difficult to standardise and even list all data. Consequently the list of data below is by no means exhaustive and researchers should take care to record all parameters which they think may be relevant for a complete understanding of the selection process.

At the moment the two major types of devices for the improvement of a towed gear's selection of fish are windows and grids:

- Windows
  - mesh type (**)
  - position (preferably by means of a drawing showing the position of the window in the codend or net) (**)
  - size (length and breadth in m) (**)
  - nominal mesh opening (**)
  - netting material (PA, PE, PES, PP) (*)
  - knotted/knotless (**)
  - twine type (monofilament, multifilament, split fibre, staple fibre)
  - twine construction (twisted, braided) (*)
  - single/double twine (**)
  - linear density (**)
  - twine diameter (*)
  - twine colour (**)
  - same colour as other netting?
- Grids
  - detailed description (diagram) (**)
  - construction (**)
    - size (**)
    - number of grid elements (**)
    - grid bar shape and size (e.g. diameter) (*)
    - material (*)
    - distance between bars (**)
  - position (**)
  - setting angle (*)

Small mesh cover data

These data apply to covered codend selectivity experiments. A full description of this method is given under Section 4.2.1. Information on the cover dimensions, construction and the netting material used allow judgement of whether masking is likely to occur. The cover mesh size gives an indication of whether the selection curves of codend and cover will overlap and hence lead to an underestimation of retention rate of small fish.

The small mesh cover data are:

- type of cover (**)
  - cover without hoops
  - with hoops
  - covers for special selective devices (specify)
- nominal mesh opening (**)
- no of open meshes round (**)
- length in m (**)
- mesh type (**)
  - diamond, square or other
- netting material (PA, PE, PES, PP ...)
- knotted/knotless
- twine type (monofilament, multifilament, split fibre, staple fibre)
- twine construction (twisted, braided)
- single/double twine
- linear density
- twine colour
- hoops to keep the cover open (**)
  - number (**)
  - position (**)
  - diameter (**)
  - material
- other devices used to open cover (e.g. floats) (**)
- plan of cover for special devices (*)
- attachment specifications (*)
  - distance in front of the codend (*)

Small mesh codend data

Small mesh codends are used in those experimental methods in which the length distribution of the target population is obtained independently from the test codend. These "paired gear" methods (twin, trouser and divided trawls, alternate or parallel haul method etc.) are fully described in Sections 4.2.2 to 4.2.5. The main parameter is the mesh size which is used to check for the possibility of overlapping of the selection curves for the two codends.

The small mesh codend data are:

- nominal mesh opening (**)

- no of meshes around (**)
- length (**)
- mesh type (**)
  - diamond, square or other
- netting material (PA, PE, PES, PP ...)
- knotted/knotless
- twine type (monofilament, multifilament, split fibre, staple fibre)
- twine construction (twisted, braided)
- single/double twine
- linear density
- twine colour

5.1.2 Haul data

5.1.2.1 Operational and environmental data

Operational and environmental data should be recorded for each haul. These data are needed when several hauls are pooled according to certain criteria (e.g. day/night hauls) prior to further analysis. They are also required to measure causes of haul by haul variations. Haul duration, towing speed, towing direction in relation to the tidal stream probably affect a gear's selectivity but so far little is known about the mechanisms involved. Severe weather conditions may also influence the experimental results. For example, it is well know that with heavy swell more fishes will escape through the codend meshes when hauling the gear. Fish behave differently under distinct light levels and it is assumed that this may have repercussions on their selection. Therefore light measurements at the depth of the gear should be recorded whenever possible. Obviously any deviation from the normal fishing operation should be noted so that inadequate hauls may be deleted.

The operational and environmental data are:

- date (**)
- haul number (**)
- shooting time (**)
- hauling time (**)
- ICES statistical rectangle (**)
- geographical position (**)
  - start fishing
    - latitude
    - longitude
  - stop fishing
    - latitude
    - longitude
- depth (*)
- warp length
- vertical net opening (*)
- wing spread
- otterboard spread
- depth of net (pelagic) (*)
- average vessel speed (**)
    - through the water
    - over the ground
- net speed (*)
- towing direction
- towing direction in relation to current direction (with/against/across tide)
- weather and environmental conditions (*)
  - wind direction
  - wind speed
  - sea state (*)
  - light level
    - measurement method
- any deficiency from normal operation (e.g. minor gear damage, speed and course changes) (*)

The mesh size of the codend should be measured at regular intervals (see Section 5.2.4.4):

- mesh opening data of the test codend
  - measuring device (**)
    - measuring force (**)
  - mean mesh opening (**)
  - standard deviation (**)
  - number of measurements (**)

5.1.2.2 Catch data

These experimental data are directly used in the analysis procedure and should be recorded with the greatest care. Most important is the length distribution of the target species in both the test codend and the cover or small mesh codend. A detailed description of the sampling technique must be given (see Section 5.2.1). Further information consists of the general catch data such as species and weights caught. Usually catch volumes are estimated using an appropriate unit (e.g. number of baskets or boxes). The weights are calculated by multiplying this volume with a unit weight.

The catch data to be recorded after each haul are:

- haul no
- for each codend (experimental and small mesh co ver/codend)
  - total catch weight (target species + by-catch) (**)
  - fish by-catch weight (**)
  - debris by-catch weight (**)
- for each target species
  - species name
  - total weight of the catch (**)
  - sample size measured (fraction) (**)
  - body or carapace length of individuals within the sample (**)
  - maximum girth or width (flatfish) of sub-sample (*)

5.1.3 Standardised data format

Complete data sets should be stored for possible future research and further analysis. There is an ever increasing amount of international cooperation in the field of fishing gear selectivity studies. Different institutes regularly cooperate to carry out projects in partnership and there is a need for being able to transfer raw data between institutes according to a standard format. A proposal for a standardised database is presented in Appendix 1. The database has been made comprehensive and includes all the parameters listed in Sections 5.1.1 and 5.1.2. In most experiments many of the parameters will not be relevant and it will be impossible to measure some of the less important parameters due to lack of time during the sea trials. The database can therefore be reduced in size in most circumstances.

The database format presented here is based on a hierarchical system of data blocks as shown in Figure A.1 of Appendix 1. The main block identifies the selectivity project. The project may encompass one or more cruises. Each cruise is characterised by the vessel involved. In the case of the parallel haul method the cruises in which each of the vessels participate are identified by different cruise files. One or more experiments may be carried out within the same cruise. Each experiment is characterised by the gear used, the test device (e.g. codend, square mesh window, grid) and/or the control device (e.g. cover, small mesh codend). A number of hauls will be made in each experiment. Each haul has its operational and environmental data and its catch data.

The contents of each file are given in the tables of Appendix 1. To standardise the format of the data for input into computer networks the database file structure of dBase III PLUS has been chosen. dBase is a generally available software package that has the advantage that its field structure is easily accepted by most other packages (databases, spreadsheets, statistical programs) for further analysis. The catch files containing the data for the length frequency distributions can be initially stored, if preferred, in the form of spreadsheets. Examples are given in Tables 12 and 13.

The data files presented in Tables 1-11 contain all data discussed in Sections 5.1.1 and 5.1.2. It will usually not be necessary to collect the full set of data in each selectivity experiment. The identification files (Tables 1-3) operational and environmental files (Tables 4.5 and 11) are always required. Which of the other files (Tables 6-10) are needed depends on the nature of the experiment. The data to be recorded in each file is also experiment dependent. A minimum requirement is the data which have been given the highest level of importance (**). The requirement of additional data is dependent on the aims of the experiment and is left to the discretion of the project leader.

During the experiments at sea the data can either be collected on printed forms or directly stored in appropriate computer files. Examples of printed forms are given in Appendix 2. The shading of the different cells corresponds to the level of importance of the data and the ratings given in Section 5.1. A separate sheet should be used for each vessel, gear, test device, control device, cruise, experiment or haul. For the catch data, forms similar to those in Tables 12 and 13 of the database should be used.

5.2 Measurement procedures

5.2.1 Weighing and sampling catches

5.2.1.1 Handling the catch

On stern ramp trawlers the catches in the test codend and the cover or small mesh codend are taken on board at the same time. On other designs of trawler the catches may have to be handled one after the other, e.g. to lift them into the processing area. It is most important that the codends and covers, if present, should be taken on board as soon as possible. The contents of the test codend should always be taken on board first. If not, there may be losses of fish from the test codend at the surface due to "washout" through the larger mesh, particularly in bad weather when slack codend meshes will open and close due to wave action.

The catch in each cover and codend should be kept well separated. To make this easier, it is convenient to empty each into a separate container. When emptying the test codend, care should be exercised to ensure that all fish gilled in the codend meshes are removed and included in the codend bulk. Fish gilled in meshes other than the codend should also be removed but not included in the codend selectivity calculations. The number of gilled fish may also be recorded separately if it is considered an important factor in net performance. Once all the catches are emptied on board they can be processed separately, while the trawl is being prepared for the next haul.

5.2.1.2 Preliminary estimate of total catch weight

Before making a detailed assessment of total catch weight in each codend or cover, it is recommended that the quantity be estimated visually while the catch is still in the codend. This can usually be done by someone with experience such as the skipper or a trained observer. This estimate would only be used as a check of the final answer.

5.2.1.3 Catch weight by species

The catch of each codend or cover should be separated into individual target species, fish bycatch and debris. These catch components should be placed in suitable equal sized containers (baskets or boxes) and the number of containers recorded. A representative value for the weight of fish in a container should be determined during the experiment in order to convert catch volume to catch weight by species.

When catches are very large sampling may be necessary (see Section 5.2.1.4). If possible the total catch should still be sorted by species prior to sampling and the catch weight by species determined directly. If this is impossible then total catch weight by species will have to be determined from the catch weight by species for the measured sample and the overall sampling ratio.

5.2.1.4 Catch sampling procedures

It is not unusual to find a catch has been so large that it is impossible to take length measurements of each fish caught before the next haul is taken aboard. A sample of the target species catch (or the whole catch if separation by species is impossible) has to be taken from a codend or cover and weighed. Recent work, described in Section 6.7.3, suggests that a sampling strategy which takes equal numbers of fish or equal fractions of the total numbers from the test codend and the small mesh codend or cover should be satisfactory.

The most efficient sampling procedure will vary according to conditions and requirements, and so no optimum scheme under all circumstances can be specified. Mixing of the bulk catch is extremely important and should always be performed prior to taking any samples. However, depending on the physical layout of the vessel, mixing of the entire bulk may not be possible. For instance when a hopper/conveyor and pumping system is used, representative samples have to be taken after the bulk catch has been assessed either by visual estimation or by numbers of containers.

If the major species is taken in very large quantities over its entire size range, the simplest procedure is to take a uniform fraction from the entire bulk. Ideally, strictly valid statistical sampling entails the random selection of fish, a requirement which can rarely be met under usual "at sea" working conditions. However, something closely approximating this can usually be attained. The proportion of the catch to be taken as a representative quantity is chosen and then, as the fish are put into uniform sized containers, that proportion is set aside for subsequent sampling and measuring. For example, if it was decided that one third of the catch was appropriate then, from the very start of putting fish into containers every third container would be set aside and the rest rejected. Then, from this sample a further sub-sample might be taken after a thorough mixing. Other methods have been devised for handling large catches (e.g. Hughes, 1976).

When there are only small numbers of large fish present it is recommended that all the large fish are measured separately and consequently no raising factors applied to the large fish. This may apply particularly to a cover where only a small number of fish at the upper end of the selection range escape through the codend meshes.

When very large "bulk catches" of pelagic fish are on deck or in large containers, only a small quantity can practically be selected as a sample and measured. Care must be exercised because the usual tendency in the absence of a proper sampling system is to take the desired sample from the top (layer) of the catch or container. Since such fishes can be larger in size than the fish below, the resulting estimates of size composition based on the measurements of these fish thus selected may not be representative of the entire catch and thus introduce bias. The selection of specimens should consciously be taken from all layers.

The sampling ratio and weight of the sample must be recorded for each species sampled in a codend or cover.

5.2.2 Fish length and girth

The length measurement method adopted e.g. whether overall length, or fork length, should be noted on the length record form. Normally the length definition used in the fishery for legal purposes will be most appropriate (e.g. Article 5 of Anon., 1986).

Since fish can shrink on drying, they should be measured while they are fresh and wet, i.e., as near to the relaxed live condition as possible. Fish in *Rigor mortis* should be flexed gently before they are measured.

In the case of small pelagic fish species, a large proportion of the fish in a sample may be more or less damaged. Generally, the larger fish have the least damage but the smaller fish are often so badly damaged that it may be impossible to measure their total lengths. To ensure damaged fish are included in the samples, alternative procedures may have to be adopted such as using head length to calculate total length.

The recognized measurement for crustacea (shrimps, lobsters, prawns, crayfish) is the "carapace length". This is usually measured from the inside of the eye socket to the posterior margin of the carapace (Anon., 1986).

Fish can be measured to the length interval below or above, but the method adopted should be noted on the record form. The choice of unit for the length group interval will depend upon the range of the fish length distribution, on the size of fish being selected and on the sharpness of selection. The unit of measurement is usually 1 cm for species which grow larger than 30 cm, and 0.5 cm for species which do not reach 30 cm. For very small species it may be necessary to choose an even smaller unit of measurement.

It is recommended that in addition to the major target species, the lengths of all other species caught be measured and recorded. This may permit further analyses of the data that are not contemplated at the time the experiment is planned or carried out.

The dimension of a fish which determines whether it escapes or is retained by a mesh is not directly its length but its maximum girth. Selection factors for a given mesh size and different populations of the same fish species may therefore vary if different girth/length relationships are exhibited by the different populations. Even within the same population there may be seasonal or longer-term changes in the girth/length relationship, associated with the stage of maturity, with variations in feeding rate, with different growth patterns in different year classes, etc. If an objective of the experiment is to determine the effect upon selection of factors affecting fish girth then stratified samples throughout the length distribution of the catches should be taken regularly for girth measurements (Wydoski and Wolfert, 1968; Hunter and Wheeler, 1972). A sample of 100 fish should be sufficient to obtain a reliable relationship between length and girth for the population. In the case of roundfish, the girth may be measured at two points along the body, either at the point of maximum head girth, or at the point of maximum body girth. The decision as to which is the best position on the fish for girth measurement will depend not only on fish species but also on the type of gear under test, and to some extent upon the information sought; for example, for investigation of the effect of season of the year on trawl codend selectivity, it will be the position of maximum girth, wherever that is along the body. Caution should be exercised to ensure that girth measurements are not obtained from fish with extended swim bladders. For flatfish species, the maximum width may be measured.

5.2.3 Twine characteristics

The main characteristics of codend twine which may affect a gear's selectivity are listed by Ferro and O'Neill (1994a). Of these, there are some such as linear density and thickness which may be considered basic characteristics and which should certainly be recorded for selectivity experiments. Other characteristics such as flexural rigidity and elongation may also affect a gear's selectivity significantly but the methods of their measurement are more complex or less well developed.

An ICES Study Group has recommended that twine thickness is measured by either of two equivalent optical methods (Ferro, 1989). The advantage of these methods is that the twine is not affected by the measuring instrument, unlike for instance methods described in von Brandt and Carrothers (1964). It is important to measure the thickness of a sample of the twine extracted from the actual codend tested, if possible. Thickness can change with use. Twine taken from a spool before it is made into netting should not be used as heat or chemical treatment to the netting after manufacture is likely to alter its characteristics and thickness.

It is recommended that a standard technique for measuring the elongation of twine should be used (ISO, 1976). Linear density has no such standard technique. A sample of twine of at least 1 m (longer for thin twines) should be taken from a spool before it is made up into netting. This should be obtained at the time that the codend is constructed. Care must be taken to ensure that twisted twine does not untwist when being handled. The length of the sample (L m) is measured, applying only sufficient tension to straighten it. The weight (W g) of the sample is then measured and the resultant tex (Rtex) calculated as 1000 W/L in g/km or Rtex.

A method of measuring twine flexural stiffness or rigidity under a chosen set of conditions has been described by von Brandt and Carrothers (1964). Dahm (1974) proposed improvements to this method. It may be possible to measure absolute twine flexural stiffness as defined by EI, Young's Modulus x moment of inertia of a cross-section of the twine (O'Neill and Xu, 1994). A gear's selectivity, however, may be dependent not only on twine flexural stiffness but also on the properties of the made up netting. This combined effect O'Neill and Xu call the mesh resistance to opening. It will be affected by e.g. the type of knot and mesh size. No direct measurement of these effects on selectivity have been made although they may be significant (Lowry and Robertson, 1995).

5.2.4 Dimension of mesh or selective part of gear

The aim of a selectivity experiment is to relate the size of fish retained by a fishing gear to a physical dimension of the gear which is related to retention, such as mesh size or bar separation of a grid.

This dimension is one of the most important parameters to be measured in a selectivity experiment, yet too often it has been measured inadequately either because of poor sampling (frequency and number of measurements) or because of poor technique (inaccurate and non-standard method).

5.2.4.1 Alternative definitions of mesh size

For a trawl codend experiment on roundfish such as haddock, when a mesh size of about 100 mm is used, a variation of only 3 mm in the recorded mesh size represents a variation of about 0.1 in the calculated selection factor. Minimising variance in mesh size measurement is therefore important. Ferro and Xu (1996) suggest that variance is due to the manufacture of the netting as much as to the method of measurement.

It is to be expected that escapes of fish through a codend will be related to the shape of the meshes occurring during fishing, but this cannot easily be measured directly. Hence mesh size is measured according to an arbitrary standard.

The International Standard Organisation (ISO, 1974) defines size of mesh in the following ways:

- length of mesh side : the distance between two sequential knots or joints, measured from centre to centre when the yarn between those points is fully extended.

- length of mesh : for knotted netting, the distance between the centres of two opposite knots in the same mesh when fully extended in the N-direction (i.e. the direction at right angles to the general course of the netting yarn), and for knotless netting, the distance between the centres of two opposite joints in the same mesh when fully extended along its longest possible axis.

- opening of mesh : for knotted netting, the inside distance between two opposite knots in the same mesh when fully extended in the N-direction, and for knotless netting, the inside distance between two opposite joints in the same mesh when fully extended along its longest possible axis.

Thus the length of mesh side (sometimes called bar length) is half the length of mesh measured to include a knot at one end. The opening of mesh is directly related to the perimeter of the mesh lumen. The more useful measure of mesh size in selectivity experiments is therefore the opening of the mesh. However, it is clear that there are other physical characteristics of the mesh and twine which may affect whether a fish escapes from a specific mesh.

5.2.4.2 Measurement gauges

The opening of a mesh has been measured in many different mesh experiments and in a variety of ways. The recorded measurement may be dependent on the loading imposed by the gauge on the mesh to extend it; the characteristics of the measuring device; the loading on the netting during measurement; the twine and knot type (Ferro and O'Neill, 1994b). The accepted methods for scientific work and for enforcement of mesh regulations in a fishery may differ. Consequently, it is essential to record the measurement method in some detail until a standard is adopted for all mesh measurement.

Two major groups of mesh-measuring device have been used. They are :

i) a wedge gauge - a flat tapering piece of metal of graduated width which is inserted into the meshes between opposite knots at right angles to the plane of the netting, possibly with a means of measuring and controlling the force applied in inserting the gauge such as a hanging weight. This method is commonly used for enforcement.

ii) a gauge which exerts a longitudinal force between opposite knots of the mesh, i.e. a force across the inside of the mesh in the plane of the netting, often controlled by a spring and stopping device limiting the applied load to a preset value; the ICES gauge (Westhoff, Pope and Beverton, 1962) has been recommended for scientific work.

Different gauge types may provide different absolute measures of mesh size. Hence mesh sizes, or parameters which depend on mesh size such as selection factor, may not be comparable when dissimilar gauges have been used.

The vertical force applied to a wedge gauge at right angles to the netting plane induces a force in the mesh bars which is dependent on the taper of the gauge and the friction between the twine and the gauge. While a measure of agreement has been reached on the standard force to apply in measuring the meshes of codends, this decision was reached mainly on the grounds of requiring the bars of the meshes to be fully straightened but not elastically stretched nor the knots tightened more than occurs in fishing. In Europe scientists have chosen a spring force for the ICES gauge of 4 kg for codend mesh sizes greater than 35 mm,, and of 2 kg for smaller mesh sizes. For these mesh size ranges European Union legislation requires masses of 5 and 2 kg respectively to be hung on the wedge gauge if the fisherman does not accept the measurement obtained by hand force by the enforcement officer. Alternatively a dynamometer may be attached to the wedge gauge to indicate when forces equivalent to these masses are being applied. When generated by hand the vertical force will vary from one operator to another.

The majority of variance in mesh size is thought to be due to either netting manufacture or random effects such as the way in which the gauge is inserted into the mesh or the tension under which the netting is held during measurement. Under controlled conditions similar levels of variance are found for the different gauges (Ferro and Xu, 1996). Consistency in operation should be sought by measuring with the gauge in a position which gives the largest mesh size and by holding the netting with the minimum necessary tension.

Table 5.2.4.2 A comparison of the features of different mesh measurement gauges.

	Wedge gauge operated by hand	Wedge gauge with hanging weight	Gauge applying longitudinal force (e.g. ICES)	Tape measure or ruler
Accuracy	Poor	Good	Good	Fair
Ease of use	Good	Poor	Good	Fair
Cost/ complexity	Average	Average	High	Low
Relevance to selectivity	Good	Good	Good	Poor
Main factors affecting reading	Operator Netting tension Twine	Netting tension Twine	Netting tension Twine	Netting tension Knot type

There are arguments in favour of making mesh size measurements which relate to the legislation governing the commercial fishing industry even though it may have greater variance. One solution may be to make measurements with both a 'scientific' and an 'enforcement'gauge. Alternatively one gauge could be used throughout the cruise and a calibration between both types undertaken at the end of the cruise. A summary of the features of the four main alternative methods of measuring mesh size are shown in Table 5.2.4.2.

If no gauge is available, a useful measure of mesh opening can be obtained by pulling the netting lengthwise (in the N-direction) so that the meshes are closed with their side knots touching and then measuring with a tape measure or ruler the distance between the inside edges of opposite knots in the N-direction. The netting tension will affect the readings, especially when the netting is made from nylon twine.

For some nets, especially very small-meshed ones, measuring the opening of the mesh is scarcely practical. A method such as counting the number of rows of knots or of meshes per unit length of netting may be more appropriate. However, this will provide a measure of the length of mesh and conversion to opening of mesh must take account of knot size. An estimate of twine thickness should be obtained in order to estimate knot diameter. For a single weaver's knot, the knot diameter is often close to 3 times the twine thickness.

It should be noted that neither wedge nor ICES gauge may be suitable for measuring mesh sizes of netting used in other fishing gears, such as gill nets. The twine may be much finer and therefore significantly elongated by the applied loads.

5.2.4.3 Dimensions of other types of selective devices

The previous discussion relates to netting with meshes having four equal length sides. For hexagonal or quadrilateral meshes with unequal sides it is recommended that the same principle should be applied - the measurement of the longest inside dimension when a mesh is fully extended and closed completely.

For rigid or semi-rigid netting with meshes which will not close, no standard definition can be applied. An appropriate dimension should be chosen and measured, such as the longest inside dimension in any direction or half the inside perimeter of the mesh. For a grid or other device not made of netting, measurement of the average width of the gap through which the fish pass may be appropriate. The material and design of the device should also be recorded.

5.2.4.4 Method of measurement

In practice the meshes of a codend will vary in size, due to e.g. variations occurring during manufacture or differences in loading on the netting in different parts of the codend when in use. When relating 50 per cent retention lengths to mesh size it is therefore necessary to work with an average mesh size.

The number of meshes to be measured in order to give a sufficiently accurate estimate of the average will depend on the variance of the measurements. For any given codend this can be determined only by measurement, although experience may enable the minimum number of meshes to be stated in advance. In Europe the legal requirement is for 60 meshes to be measured by enforcement officers. Over a whole codend, it is recommended that a minimum of 100 meshes is measured.

Since the number measured will be considerably less than the total number of meshes in the codend, the question naturally arises as to where in the codend the measurements should be taken. They should be in the area where the majority of escapes occur. Most fish escape through the after part of the codend and from the netting sections in the upper part of the codend. Therefore more meshes should be measured in these areas than in the forward or lower parts. As a routine the measured meshes should be located on the topside in a line running parallel to the long axis and starting from the after end of the codend some two or three meshes from the codline. Measurements should be recorded serially to enable any fore-aft trend to be detected. The line should not be located near the selvedges and meshes near to strengthening ropes and lacings should not be included.

At the start of the cruise, especially if the codend is unused, measurements should be made immediately after each haul while the codend is still wet. This should be continued until the meshes have stabilised and thereafter they may be measured at longer intervals, e.g. every 5 hauls. This is especially important for twine with low elasticity such as polyethylene (PE) or vegetable fibres (e.g. manila, cotton) since they suffer greater permanent elongation after repeated loading than other synthetic twines such as nylon (PA), polyester (PES) or polypropylene (PP). Significant change in mesh size with time may also occur in netting where knots have not been chemically treated, heat set or pre-stretched.

5.2.5 Counting meshes

5.2.5.1 Number of meshes round the codend

It is the number of meshes round the codend which lie between the selvedges, are free to open and through which the fish can escape that is important. This has to be measured on the codend itself, before use. Reference to a net specification will almost certainly give the number of meshes including those closed in the selvedges and the difference can be large. For instance, a 2 panel codend may have 60 meshes across each panel with 5 meshes taken in the selvedge each side making 100 open meshes but 120 meshes including those in the selvedge.

To count the open meshes round the codend, start from one of the selvedges and choose a line A of knots running across the netting (Figure 5.2.5.1). Take the first knot that is free of the selvedge B1 and mark it with a piece of twine or tape. Count the number of knots in line across the panel B1, B2 etc until the selvedge C is reached. Count this also. The number of meshes across the panel is the number of free knots plus 1. Continue round the codend counting the meshes in the next and subsequent panels until the first selvedge is reached opposite the marked knot B1. Move one row down the codend (line D) and repeat counting the knots E1 etc. The totals for the mesh counts at lines A and D could differ by 1 mesh per panel. The mean is the number of open meshes.

It should not be assumed that the number of meshes round the codend is constant along the length of the codend and it is recommended that a check is made by counting the number at each end and if different, then another count near the middle. This should indicate whether the codend is composed of two sections of different width joined together forming in effect a codend and extension of different width. Another possibility is that a commercial codend has been deliberately made wider at the aft end in order to increase retention of small fish - a so-called balloon codend.

5.2.5.2 Number of meshes round the codend including the selvedge

This information would normally be given on a trawl specification. To determine the meshes closed in the selvedges, open up each selvedge at 3 different locations. Count the number of knots closed in the selvedge for each panel side (see Figure 5.2.5.1). The number of closed meshes is one less than the number of knots.

5.2.5.3 Number of meshes down the length of the codend and extension

The length of the codend or extension may affect selection because the meshes of such cylindrical sections tend to close under tension. Reeves *et al.,* (1992) found that extension length had a significant effect on 50% retention length but not on selection range.

Locate the join between the codend and belly or extension piece. Normally the join will be made by a readily identifiable twine, e.g. of different colour. If this is not the case then an experienced fisherman would normally be able to locate it by the knots of the joining round being hand made, not machine made. Take a point at the joining round away from the selvedge. Take a knot F1 (Figure 5.2.5.1) in the second line of knots in the codend. This gives the first mesh. Count the knots diagonally opposite each other F1, F2, etc. down the length of the codend until the codline is reached. The number of knots is the number of meshes. Any last thick rows of heavy twine through which the codline is passed would not normally be included. A simple check of the measurement is sufficient. The result could be an exact number of meshes or could include a half mesh. For the length down the extension piece count in the same way from the join to the belly down to the codend join including one of the joins in the extension length. The selectivity of a codend and extension is reduced if the length of the upper section is less than that of the lower (Isaksen and Valdemarsen, 1987) and it may be important to check the length of both upper and lower netting sections.

5.2.5.4 Square meshes

Counting meshes round a square mesh codend can follow exactly the same procedure as for diamond meshes. The successive knots G1, G2, etc. (see Figure 5.2.5.4) being connected by a bar.

Counting the length in meshes follows a similar procedure counting the successive knots, H1, H2, etc.

5.2.5.5 Hexagonal meshes

Counting the meshes round can be carried out as for diamond meshes, treating the longitudinal side of the mesh, J1, J2, etc. (see Figure 5.2.5.5) exactly as if it was a knot in a diamond mesh.

For hexagonal mesh, the mesh opening (as measured by a wedge gauge e.g.) will be the distance between opposite knots in the longitudinal direction of the netting i.e. L1 to L2 (Figure 5.2.5.5). This relates to the hole through which the fish must escape and corresponds to the mesh opening for diamond mesh or square mesh.

However, this distance cannot be used to compute the length of a hexagonal mesh netting section. To estimate the fully extended netting length, a mesh unit can be defined as one longitudinal mesh side and one diagonal mesh side (as drawn in Figure 5.2.5.5) i.e. K1 to K2. The longitudinal and diagonal mesh sides are not necessarily the same length. The length of a mesh unit must be measured when fully extended and the number of such units along the netting section counted. Counting the number of successive longitudinal mesh sides (which start at K1, K2, K3, etc) along the panel may be a simple way to do this. The section length is equal to the product of mesh unit length and number of such units.

5.2.6 Codend and extension length

The effect of extension and codend length on a gear's selectivity is significant but the selectivity parameters are not as sensitive to small changes in these lengths as they are to changes in mesh size, for example. Reeves *et al.*, (1992) indicate that the haddock l_{50} changes by 2 mm per metre of extension for a demersal trawl. It is therefore not necessary to measure the length to greater accuracy than perhaps 0.5 m. However, if the selectivity experiment aims to measure the effect of codend selvedge rope hanging ratio then it is clearly important to measure the relative lengths of netting and ropes to a greater accuracy.

Whilst the codend of a towed gear (e.g. a trawl) may be well defined, the extension piece may be more difficult to identify. Normally the extension piece forms the elongation between the codend and the trawl's body (belly), either untapered or tapered with a lower cutting rate than the belly, see Figure 10.1 in the glossary.

If the upper section of a codend or extension is shorter than the lower section (giving slack to the lower netting sheet), selectivity may be adversely affected (Isaksen and Valdemarsen, 1987). Hence measuring the length of both sections may be important.

To measure the length of codend or extension piece both the total lengths of the sections and the numbers of meshes along and across them should be recorded. The total length may be measured by fully extending, but not stretching, the netting section in the N-direction and measuring from the row of knots defining the forward edge of the section to the row of knots at the aft end of the joining round at the aft edge of the section. Alternatively, the length may be estimated by counting the number of meshes along the length of the section and multiplying by the measured length of mesh (i.e. knot centre to knot centre).

Table 5.2.8 Sea state code and description.

Sea state	Description	Average wave height m
0	Calm (like a mirror)	0
1	Calm (rippled)	0-0.1
2	Smooth (wavelets)	0.1-0.5
3	Slight	0.5-1.25
4	Moderate	1.25-2.5
5	Rough	2.5-4
6	Very rough	4-6
7	High	6-9
8	Very high	9-14
9	Phenomenal	Over 14

5.2.7 Vessel and net speed

There are three speeds that can be measured during a selectivity test:

- the speed of the net itself relative to water, which is most easily measured using a sensor mounted on the net. There are commercially available speed logs using electromagnetic sensors for instance.

- the speed of the vessel over the ground. This can be measured using GPS (Global Positioning System), or an equally accurate navigation system for position measurement. Actual speed over the ground during each haul is then calculated from the measured distance travelled whilst the gear is fishing.

- the speed of the vessel through water, measured by the ship's log. This will differ from the net speed through water if there is any tide or current present which varies in magnitude or direction with water depth.

It is recommended (Anon., 1992a; Walsh *et al.,* 1993) that the standard speed should be the gear speed through the water. When conducting experiments on commercial vessels it is however, often not possible to measure this and the vessel speed over ground should be used, taking note of the bias that can be caused by currents.

5.2.8 Measurement of sea state

Motion of a fishing vessel may affect fishing gear selectivity significantly because the motion is transmitted to the net through the towing wires. Codends have been observed to pulse with the frequency of the waves in rough weather. This motion causes the codend meshes to become alternately slack and taut and hence may give fish more opportunity to escape (Polet and Redant, 1994).

Sea state and its direction relative to the vessel towing direction are the important factors. The greatest motion may be generated when the vessel is head into the sea although this will depend on vessel design and operation. The direction of travel of the waves (usually the same as the wind direction) should be recorded.

There is an international code (e.g. Anon., 1995) used in meteorology which is suitable for defining sea state (Table 5.2.8).

Sea state is determined by the characteristics of the waves and these are defined by wave length, period and height. If sea state is to be quantified then average wave height must be estimated. The other two parameters are optional.

Care must be taken to ensure that the observations are not influenced by the waves generated by the vessel. Waves generally travel in groups with patches of dead water between them, the wave height being a maximum at the centre of each group. Therefore only the well-formed waves in the centre of wave groups should be observed. Average values should be obtained by observing at least 20 selected, not necessarily consecutive, waves.

Detailed information about how to estimate wave height from vessels is available from e.g. HMSO (1969, pp. 57-59). It may be satisfactory to rely on the knowledge and experience of the skipper of the fishing vessel. Alternatively wave height estimation from a stationary ship can be made easier with reference to a dan buoy of known height. The wave length can be observed by streaming the buoy on a rope to a distance such that the buoy is exactly one wave length away from the vessel. The length of rope is an estimate of wave length. At the same time the period can be obtained by noting the time taken for a wave to travel between the vessel and the buoy.

5.3 Implementing experimental design

5.3.1 Gear operation and length of haul

After each haul the whole gear should be examined for damage. Any damage or abnormal catch, such as quantities of weed, should be recorded. A decision can then be made whether the data for that haul are valid. The gear should be checked and minor damage should be repaired. Obvious gear malfunction may be seen if the gear is observed by underwater camera or monitored by instrumentation measuring net geometry, for instance. Instrumentation is also useful to check that gear performance does not vary from one haul to the next or from one net to the other in a twin trawl or alternate haul experiment.

The fishing operation during a selectivity experiment should deviate as little as possible from commercial fishing conditions including the shooting and hauling procedures.

It is recommended that the size of the test codend catch is approximately the same as in commercial fishing. The length of haul can be altered to achieve the required size. However, this may result in very large catches in the small mesh codend or cover if many small fish are present in the population fished. This may cause practical problems in handling or may cause the net to close significantly due to the increased drag. A compromise is then necessary and the haul duration reduced until the catches can be handled adequately and the net geometry is not affected. Alternatively it may be necessary to change grounds to reduce the proportion of small fish being caught.

5.3.2 Gear malfunction

If the gear is known to have functioned incorrectly it is justified to ignore the data from that haul. There are many causes of malfunction and the gear operation should be continuously monitored to ensure that such incidents are noticed. It is not however, permissible to discount a haul simply because the selectivity parameters do not agree with other hauls using the same gear - it is inevitable that there is some unexplained variance.

There may be damage to the net or other part of the gear. Even small holes in the netting in the extension or codend can have a major effect on a gear's selectivity.

The codend or extension may twist during the haul. This will prevent the fish from falling back into the codend and hence reduce their opportunity for escape. Such twists are often still visible when the net first breaks the surface on hauling while the strain is still on the net.

If there is a delay in hauling a net and it lies more or less stationary in the water for some time then it is possible that the fish may have time to escape out of the mouth of the net or through the slack meshes. This can be a particular problem during rough weather.

Abnormal catches may affect a gear's selectivity. The presence of a very large fish or object may distort the codend shape. The presence of a predator of the target species has been thought to affect fish selection e.g. by triggering escape reactions.

Other causes of gear malfunction may never be evident to the observers on the vessel but may be inferred from instrumentation measuring gear geometry (e.g. mouth opening or spread) or from atypical fish length/frequency distributions. After such observations the gear should be checked before the next haul and a decision made on the validity of the data.

5.3.3 Changing gear to be tested

If a series of codends for instance are to be tested then decisions must be made when sufficient data have been collected for each. The monitoring of invalid hauls is therefore essential. It is also helpful to obtain preliminary estimates of the selection curves so that more hauls can be done if there appears to be large variance. (See Section 3.2 and Fryer, 1996).

It is desirable when measuring the selectivity of a series of different codends to change codends at regular intervals so that each codend is not fished only in one set of conditions e.g. during only one day. Sea state, fishing ground and fish population available may affect selection and may be constant for a short time but change over a longer timescale. A simple method of avoiding this problem is to divide the cruise into two halves and plan to test all the codends in both halves in a random order (see Section 3.2).

5.3.4 Catch composition

It is important to ensure that the length/frequency distribution of the catch includes fish in the selection range of the codends under test. It is quite possible to catch good quantities of fish in both codend and cover for instance but to be unable to construct a selection curve because there were only small fish in the cover and very large fish in the codend, subject to 0 and 100% selection respectively with no fish of intermediate length. It is possible that the selection for a given species may change depending on the presence of significant quantities of other species

6 Statistical analysis of trials data

The main purpose of this chapter is simply to present the basic statistical model for analysis of data from selectivity experiments with towed gears and to show how it has advanced the analysis of fish size selection data since Pope *et al.,* (1975). Application of the model to the covered codend method is a "standard" statistical analysis of count data, and in fact, the maximum likelihood approach of Pope *et al.,* (1975) was effectively fitting this model (subject to computational inaccuracies). Application of the model to "paired gear methods" is a very intuitive modification of the standard analysis, but provides an approach very different from, and superseding, that described in Pope *et al.,* (1975).These considerations are presented in Sections 6.2 to 6.6.

It has become clear, however, that the application of statistical models to the analysis of fish selection data has afforded the opportunity to ask many more very legitimate (and often difficult) questions that have not previously been considered in a rigorous fashion. These include models for trials with "multiple gears" (where different gears have been tested), between-haul variation within a single gear, and the effect of sampling from the catches. Procedures for incorporating these relevant aspects of the analysis of gear selectivity data are very recent developments and some may be subject to further refinement. The accepted approaches at the time of writing are covered in Sections 6.7 and 6.8.

A glossary of notation is provided in Section 10.2.

6.1 Statistical modelling of towed gear selectivity

An appropriate statistical model avoids the (often subjective) data manipulation required of some historical curve fitting recipes. Moreover, the properties of the resulting estimated parameters are known and it is therefore possible to formally address questions such as:

- Do the two codends in a trouser trawl have equal fishing power?
- Are model assumptions satisfied?
- Does the selection curve fit the data adequately?
- Is the length of 50% retention equal to some prescribed value?
- Is there significant between-haul variation?
- How does the selectivity of different gears differ?

The historical methods of selection curve estimation (Section 6.6) are not model based and simply specify a numerical methodology for estimating the selection curve parameters, without consideration for the origin of the data. An obvious example is the analysis of "paired gear" data where, in the case that the two codends fish with equal power, it has been assumed (e.g. Pope *et al.,* 1975) that the number of fish caught in the small mesh control codend gives the number entering the test codend. The inadequacy of this assumption becomes apparent when the researcher is faced with the prospect of data manipulation to cater for length classes with higher catch in the test codend. Also, the properties of the resulting estimates are not known and inferences about these estimates cannot be defended.

A statistical model of selection attempts to capture the structural and random components of a selectivity experiment. For example, an appropriate model for "paired gears" with equal codend fishing powers is that fish approaching the codends enter either the control or test codend with equal probability. It is typically assumed that the meshes of the control codend are sufficiently small such that all fish entering it are retained, while fish entering the test codend may or may not be retained with probability depending on their size and the selection curve of that codend.

Structural parts of the model of fish selection specify probabilities, and include:

- The probability of retention, as specified by the selection curve (Section 6.2) .
- In the case of "paired gears", the probability that a fish will enter the test codend side (Section 6.3.2).
- In the event that the catch is sampled, the probability that a fish will be measured (Section 6.7).

The random part of fish selection data is modelled using the standard techniques for count data (Sections 6.3.1 and 6.3.2).

The model can sometimes be implemented directly using readily available statistical software. At other times it may require the use of an optimising algorithm for purposes of maximising the fit to the data (e.g. Millar, 1993a). Such optimisers are increasingly becoming a standard part of statistical software. At the time of writing, general purpose software for implementation of many of the procedures presented in this chapter is under commercial development (ConStat 1995).

6.2 Selection curves

Definition: The selection curve, $r(l)$, is the probability that a fish of length l is retained given that it entered the gear.

The above definition of the selection curve does not incorporate avoidance behaviour. In "paired gears" experiments (e.g. twin, trouser, alternate or parallel trawling) such behaviour is quantified in terms of the relative fishing powers of the gears (Section 6.3.2) and it is modelled as an additional structural component of the experiment.

6.2.1 Parametric selection curves

The above definition of the selection curve makes it extremely plausible to assume that selection curves are non-decreasing functions with range between 0 and 1. These same properties are shared by cumulative distribution functions of random variables and indeed, four of the five curves described below (logistic, normal, extreme value, and negative extreme value) are named after the distribution function they represent. The extreme value curve is also known as the Gompertz curve because of its initial application to mortality studies. The fifth curve, the Richards curve, takes its name from previous applications to growth studies.

The logistic and normal selection curves are symmetric about the length of 50% retention, l_{50}. The extreme value curve has a longer tail to the right of l_{50}, implying that some very large fish may not be retained. The negative extreme value curve has longer tail to the left of l_{50}, implying that some very small fish may be retained. The Richards curve is a flexible generalisation of the logistic curve obtained by using an asymmetry parameter, the value of which determines the nature of the asymmetry.

Fits of the logistic, normal, extreme value and negative extreme value curves are commonly called logit, probit, log-log and complimentary log-log analyses, respectively. This second set of names arises from the form obtained by rewriting the selection curve formula, as shown below.

6.2.1.1 Logistic (logit)

This selection curve is so named because it is the cumulative distribution function of a logistic random variable. It is specified by

$$r(l) = \left(\frac{\exp(a+bl)}{1+\exp(a+bl)} \right) \qquad (1)$$

where a and b are parameters to be estimated. This curve is also known as the logit because it can be rewritten

$$a + bl = \log_e \left(\frac{r(l)}{1-r(l)} \right) \equiv \operatorname{logit}(r(l)).$$

Note that the length of 50% retention, l_{50}, is such that $r(l_{50}) = 0.5$ and therefore

$$a + bl_{50} = \log_e \left(\frac{0.5}{1-0.5} \right) = \log_e(1) = 0.$$

That is

$$l_{50} = -a/b.$$

Similar algebra gives the selection range, SR, to be

$$SR = l_{75} - l_{25} = \frac{2\log_e(3)}{b} \approx \frac{2.197}{b}.$$

6.2.1.2 Normal probability ogive (probit)

This selection curve is the cumulative distribution function of a normal random variable,

$$r(l) = \Phi(a + bl)$$

where Φ is the cumulative distribution function of a standard normal (mean 0 and variance 1) random variable. Φ does not have a closed form and is expressed as an integral, but most statistical software packages include it as a built in function. Note that

$$a + bl = \Phi^{-1}(r(l)) \equiv \operatorname{probit}(r(l)).$$

Similarly to the logistic curve,

$$a + bl_{50} = \operatorname{probit}(0.5) = 0$$

so

$$l_{50} = -a/b \quad \textit{and also,}$$

$$SR = l_{75} - l_{25} = \frac{2\text{ probit }(0.75}{b}$$

$$\approx \frac{1.349}{b}.$$

6.2.1.3 Extreme value/Gompertz (log-log)

The Gompertz selection curve is

$$r(l) = \exp(-\exp(-(a + bl)))$$

which derives the name log-log curve because it can be expressed

$$a + bl = -\log_e(-\log_e(r(l))).$$

Thus

$$l_{50} = \frac{-\log_e(-\log_e(0.5)) - a}{b}$$

$$\approx \frac{0.3665 - a}{b} \quad \textit{and also,}$$

$$SR = \frac{\log_e\left(\dfrac{\log_e(0.25)}{\log_e(0.75)}\right)}{b} \approx 1.573/b.$$

6.2.1.4 Negative extreme value (complimentary log-log)

This selection curve is the "compliment" of the Gompertzlog-log) curve, i.e.,

$$r(l) = 1 - \exp(-\exp(a + bl))$$

which can be rewritten as

$$a + bl = \log_e(-\log_e(1 - r(l))).$$

Thus

$$l_{50} = \frac{\log_e(-\log_e(0.5)) - a}{b} \approx$$

$$\frac{-0.3665 - a}{b} \quad \textit{and also,}$$

$$SR = \frac{\log_e\left(\dfrac{\log_e(0.25)}{\log_e(0.75)}\right)}{b} \approx 1.573/b$$

6.2.1.5 Richards curve

The Richards selection curve includes an asymmetry parameter, δ, in the form

$$r(l) = \left(\frac{\exp(a + bl)}{1 + \exp(a + bl)}\right)^{1/\delta}$$

When $\delta > 1$ the curve has a longer tail to the left of l_{50} and with $0 < \delta < 1$ it has longer tail to the right. When $\delta = 1$ it reduces to the (symmetric) logistic curve. Being a generalisation of the logistic curve, the null hypothesis of a logistic selection curve can therefore be tested against the asymmetric Richards alternative by a statistical test of the hypothesis $H_0 : \delta = 1$.

The form of the Richards selection curve can be rewritten

$$a + bl = \text{logit}\,(r(l)^{\delta})$$

and hence

$$l_{50} = \frac{\text{logit}(0.5^{\delta}) - a}{b}$$

and

$$SR = \frac{\text{logit}(0.75^{\delta}) - \text{logit}(0.25^{\delta})}{b}$$

6.2.2 Properties of the parametric selection curves

GLM's: The logistic, normal, extreme value, and negative extreme value curves belong to the class of *generalised linear models* (McCullagh and Nelder 1989) by virtue of the fact that the linear term, $a + bl$, can be expressed as a function of $r(l)$ (and no other parameters).

Comparison of the GLM's, Figure 6.2.2a: Logistic, normal, extreme value and negative extreme value selection curves are plotted in Figure 6.2.2a. The parameters a and b of each curve have been chosen so that the curve has l_{50} of 40 and selection range (SR) of 10.

The two symmetric selection curves (the logistic and normal) differ only slightly, with the normal having slightly sharper retention below l_{25} and above l_{75}. In practice there will be little difference between the fits of logistic and normal curves to fish selection data.

Shapes of the Richards curves, Figure 6.2.2b: Richards curves can be grossly asymmetric with extremely long tail to the left of l_{50} ($\delta >> 1$) or right of l_{50} (δ close to 0).

Parameters *a* and *b*: For each of the above models, requiring retention to increase with fish length implies $b > 0$. Also, retention of "zero" length fish should be effectively zero, implying that a will be a suitably large negative number.

Reparametrisation: In the previous section the parametric curves were defined using parameters a and b (and δ in the Richards curve). However, inferences about the selection curve will typically be with respect to l_{50} and SR. The statistical properties of the estimates $\hat{l}_{50}$ and $\hat{SR}$ can be inferred from the statistical properties of $\hat{a}$ and $\hat{b}$ (Section 6.3.3), but in some situations it may be more convenient to work directly with the selectivity parameters. For example, for the purposes of implementation in SAS, Millar (1993a) writes the logistic selection curve (Equation (1)) as

$$r(l) = \frac{\exp\left(\dfrac{k*(l-l_{50})}{SR}\right)}{1+\exp\left(\dfrac{k*(l-l_{50})}{SR}\right)}$$

where $k = 2\log_e(3)$. This allowed for SAS to output $\hat{l}_{50}$, $\hat{SR}$ and their estimated standard errors.

6.2.3 Non-parametric and semi-parametric curves

These curves do not follow any prescribed parametric form, but are typically specified via general conditions. These could include smoothness conditions such as bounds on derivatives, bandwidth of kernel smoother (Buja *et al.*, 1989, Hastie and Tibshirani, 1990), span of local regression (Cleveland and Devlin, 1988), or the requirement that the curve be symmetric.

Nonparametric curves may also be fitted under a general shape requirement, such as requiring the curve to be symmetric and/or sigmoidally shaped (Schmoyer, 1984). It is also possible to simply require that the selection curve be non-decreasing (Barlow *et al.*, 1972).

6.3 Curve fitting

Although the statistical models for analysis of the size selection of fish by fishing gears (Kirkwood and Walker, 1986; Millar, 1992; Millar and Walsh, 1992) have been independently developed specifically for this application, the same models are used in other areas of research. For example, there is a close analogy with the science of resource selection (Manly *et al.*, 1993), with the models differing only in their structural components. In resource selection the animal selects the resource whereas in our application the animal is selected. Furthermore, the methods of parameter estimation used in Manly *et al.*, (1993) are identical with those presented in this section. They are maximum likelihood methods.

6.3.1 Fitting selection curves to covered codend data

The basic premise is that the data are binomially distributed. This is a standard assumption for "coin tossing" experiments and hence is immediately appropriate to covered codend studies. The "coin toss" corresponds to a fish entering the trawl, and the observed outcome is (instead of being a head or a tail) whether the fish is retained in the codend or retained in the cover. The binomial distribution is specified by two parameters, the first being the number of "coin tosses" (i.e., number of fish entering the trawl) and the second being the probability that the coin comes up heads (where heads corresponds to retention by the codend).

The binomial distribution assumes that the "coin tosses" are independent, i.e. that the fate of one fish is independent of the fate of other fish. This assumption can be verified through model checking diagnostics, (see Section 6.4) and, moreover, the estimated model parameters are robust to violation of this assumption and adjustments to inferential procedures can be made if required (McCullagh and Nelder, 1989).

Let n_{l1} and n_{l2} be the number of length l fish (i.e. fish in the length class with midpoint l) that are taken in the codend and cover respectively, and let $n_{l+} = n_{l1} + n_{l2}$ denote the total catch of length l fish. The probability of a length l fish being retained in the codend is (by definition) the selection probability $r(l)$. Then, assuming n_{l1} to be binomially distributed with parameters n_{l+} and $r(l)$, the log-likelihood function for the data is

$$\sum_l (n_{l1} \log_e r(l) + n_{l2} \log_e (1 - r(l))). \qquad (2)$$

The maximum likelihood fitting of logistic (logit) or normal (probit) curves to binomial data is commonplace in many other areas of scientific research (e.g. bioassay) and consequently most well known statistical packages have these capabilities built in. This is less likely to be the case for the other parametric curves (extreme value, negative extreme value and Richards), but such software is presently under commercial development for the particular application of selectivity studies (ConStat 1995).

If suitable software is unavailable then the maximum likelihood fits of the parametric curves can be achieved using any general purpose optimisation function to maximise equation (2) with respect to the parameters defining the curve. Alternatively, with the exception of the Richards curve, an algorithm using iteratively weighted least squares may be used (McCullagh and Nelder, 1989; Collet, 1991).

Millar (1993b) found that none of the parametric curves (Section 6.2.1) provided an adequate fit to catch data of scallops in covered dredge selectivity experiments. Non-parametric monotone non-decreasing curves were fitted to these data using the PAV (pool adjacent violators) algorithm (Barlow *et al.,* 1972, p. 13.) to maximise the likelihood in equation (2).

6.3.2 Fitting selection curves to "paired gear" data

An appropriate statistical model for analysis of data from "paired gear" experiments was developed in 1990 (Millar and Walsh, 1990, 1992). It was subsequently published in the mainstream statistical literature (Millar, 1992) where is was established as a statistically rigorous approach. The methodology is now the most widely used for analyses of "paired gear" data and is commonly known as the SELECT (**S**hare **E**ach **LE**ngths **C**atch **T**otal) method.

SELECT makes use of the binomial assumption, in a way that is a natural generalisation of a covered codend analysis. In the "paired gear" situation, the "coin toss" corresponds to whether a captured fish was taken in the test codend or in the control codend. Note that one does not consider the unobserved fish escaping the test codend (the statistically rigorous argument behind the SELECT methodology establishes this as being appropriate). As with the covered codend analysis, the binomial assumption assumes that the fate of one captured fish is independent of the fate of other captured fish. Here, the "fate" of a captured fish is whether it was taken in the test or control codend. Bear in mind that the fate of a fish is determined by which of the two codends it entered, in addition to its ability to escape the test codend should it have entered that codend. Thus, independence of fish is with respect to their entry into the two codends and ability to escape the test codend.

The independence of codend entry assumption may not be valid in general, particularly with schooling fish. However, catches of schooling fish are likely to contain extremely high numbers of fish and the probable sampling of the catches will largely mitigate this effect . Also, as with the covered codend analysis, violation of this assumption does not invalidate the analysis and can be quantified and compensated for.

The following theorem demonstrates the statistical basis of the SELECT method for analysis of "paired gear" data. To see its applicability, let gear "compartments" 1 and 2 be the test codend and control codend respectively. Gear "compartment" 3 is assigned to those (unobserved) fish that escape the test codend. Note that the Poisson distribution is the usual assumption made for arrival processes.

<u>THEOREM</u>
Let the number of fish entering a gear be a Poisson distributed random variable. Suppose that the gear has three "compartments", with ρ_1, ρ_2, ρ_3 (where $\sum_{i=1}^{3} \rho_i = 1$) being the probabilities that a fish entering the gear is retained in the first, second or third compartment respectively. Let m be the total of the number of fish in compartments 1 and 2. Then, the number of fish in compartment 1 is binomially distributed with parameters m and $\dfrac{\rho_1}{\rho_1 + \rho_2}$.

PROOF

In brief, Feller (1968, example 1(d), pp. 216-217) shows that the numbers of fish in each compartment of the trawl are independent Poisson random variables. The theorem follows from a well known result on the conditioning on the total of two independent Poissons (Feller, 1968, problem 6, p. 237).

In determining the probability that a captured fish is taken in the test codend we may wish to consider the possibility of a difference in fishing power between the test and control codends.

Definition: The relative fishing power p of the test codend is the probability that a fish entered the test codend, given that it entered the combined (test and control) gear.

This definition is a special case of "relative fishing intensity" which Millar (1992) uses to include relative fishing power, differences in fishing effort, and localized fish concentrations. (Millar uses the alternative term relative fishing efficiency instead of relative fishing power). Relative fishing intensity can also be used to quantify differences in sampling fractions when the codend catches are not fully measured (see Section 6.7.2).

Let n_{l1} and n_{l2} be the number of length l fish (i.e. fish in the length class with midpoint l) that are taken in the test and control codends respectively, and let $n_{l+} = n_{l1} + n_{l2}$ denote the total catch of length l fish. The probability that a fish entering the gear is retained in the test codend is $pr(l)$ i.e., the probability that it enters that codend multiplied by the retention probability. The probability that a fish entering the gear is retained in the control codend is simply the probability of entering that codend, $1 - p$. Thus, by the above theorem, the number of fish in the test codend is binomially distributed with parameters n_{l+} and

$$\phi(l) = \frac{pr(l)}{pr(l) + (1-p)} \tag{3}$$

The log-likelihood function for the data is therefore

$$\sum_{l} (n_{l1} \log_e \phi(l) + n_{l2} \log_e (1 - \phi(l))). \tag{4}$$

If $r(l)$ is logistic then $\phi(l)$ in equation (3) simplifies to

$$\phi(l) = \frac{p \exp(a + bl)}{(1-p) + \exp(a+bl)}$$

In general, if $r(l)$ is a nondecreasing function ranging between 0 and 1, then $\phi(l)$ is also non-decreasing and ranges from 0 to p.

Maximisation of equation (4) is with respect to parameter p and the parameters specifying the selection curve $r(l)$. This likelihood is particular to "paired gear" selectivity studies and requires the user to deploy an iterative non-linear optimiser. This model has been implemented in the CC Selectivity software developed by ConStat (1995). Alternatively, Millar and Cadigan (1991) and Millar (1993a) provide FORTRAN and SAS code (respectively) for the logistic selection curve case.

One can fit the model under the assumption that the two codends fished with equal power by fixing p equal to 0.5. However, one should always also allow the model to estimate p because, despite the best efforts while conducting the selectivity experiment (see Section 3.1.5), it is often the case that the two codends do not fish with equal power.

Fitting nonparametric curves to "paired gear" data is frustrated by the need to estimate relative fishing power p. Skalski and Perez-Comas (1993) give an implementation based on a heuristic modification to the likelihood.

6.3.3 Calculation of estimated variances and standard errors

The calculations will be given for the logistic selection curve only. For the other parametric curves these can be derived analogously. If fitting nonparametric curves then, depending on the software used, certain standard errors may be provided. Otherwise, it may be necessary to utilise a computer intensive re-sampling method (e.g. bootstrap, Section 6.8.2).

The variances of the parameter estimates $\hat{a}$, $\hat{b}$ (and $\hat{p}$ in a "paired gear" model) are obtained from maximum likelihood theory; see Appendix A of McCullagh and Nelder (1989) and Lehmann (1983, pg. 126). These variance formulae are functions of the unknown parameters and so we must replace them by the estimated parameters to obtain the estimated variances. The estimated variances and standard errors of $\hat{l}_{50}$ and $\hat{SR}$ are then derived from the estimated variances and covariance of $\hat{a}$ and $\hat{b}$.

6.3.3.1 Variance of â and b̂

Covered codend

The covariance matrix of $\hat{a}$ and $\hat{b}$ is the inverse of the 2 x 2 Fisher information matrix *I*. With I_{ij} denoting the element of *I* in the *i*'th row and *j*'th column, *I* = 1,2, *j* = 1, 2, we have

$$I_{11} = \sum_l \frac{n_{l+}\, d^2(l)}{r(l)(1 - r(l))}$$

$$I_{12} = I_{21} = \sum_l \frac{n_{l+}\, l d^2(l)}{r(l)(1 - r(l))}$$

$$I_{22} = \sum_l \frac{n_{l+}\, l^2 d^2(l)}{r(l)(1 - r(l))}$$

where

$$d(l) = \frac{\exp(a + bl)}{(1 + \exp(a + bl))^2}$$

is the partial derivative of *r(l)* with respect to *a*. The summations above are over all length classes.

In most circumstances the researcher will not be required to undertake these calculations because fitting logistic selection curves to covered codend data is a standard statistical technique incorporated into most general statistical software packages.

"Paired gear" model with *p = 0.5*

The elements of the 2 x 2 Fisher information matrix *I* are

$$I_{11} = \sum_l \frac{n_{l+}\, d^2(l)}{\phi(l)(1 - \phi(l))}$$

$$I_{12} = I_{21} = \sum_l \frac{n_{l+}\, l d^2(l)}{\phi(l)(1 - \phi(l))}$$

$$I_{22} = \sum_l \frac{n_{l+}\, l^2 d^2(l)}{\phi(l)(1 - \phi(l))}$$

where

$$d(l) = \frac{\exp(a + bl)}{(1 + 2\exp(a + bl))^2}$$

which is the partial derivative of ϕ (*l*) with respect to *a*.

"Paired gear" model with estimated *p*

In this case the Fisher information matrix is 3 x 3 because it incorporates the effect of the third parameter, *p*. Elements I_{11}, I_{12}, I_{21} and I_{22} are given from the *p = 0.5* case above but with

$$d(l) = \frac{p(1 - p)\exp(a + bl)}{(1 - p + \exp(a + bl))^2}$$

The other elements of *I* are

$$I_{13} = I_{31} = \sum_l \frac{n_{l+}\, d(l)\, h(l)}{\phi(l)\,(1 - \phi(l))}$$

$$I_{23} = I_{32} = \sum_l \frac{n_{l+}\, l d(l)\, h(l)}{\phi(l)(1 - \phi(l))}$$

$$I_{33} = \sum_l \frac{n_{l+}\, h^2(l)}{\phi(l)(1 - \phi(l))}$$

where

$$h(l) = \frac{\exp(a + bl)(1 + \exp(a + bl))}{(1 - p + \exp(a + bl))^2}$$

is the partial derivative of ϕ (*l*) with respect to *p*.

The 2 x 2 covariance matrix for $\hat{a}$ and $\hat{b}$ is given by the upper-left 2 x 2 submatrix of I^{-1} .

6.3.3.2 Variance of $\hat{l}_{50}$ and $S\hat{R}$

The estimated length of 50% retention, $\hat{l}_{50}$ and selection range $S\hat{R}$ are determined from parameter estimates $\hat{a}$ and $\hat{b}$ of the fitted logistic curve by the equations given in Section 6.2.1.1. Determining the standard errors of $\hat{l}_{50}$ and $S\hat{R}$ requires use of the delta theorem (e.g. Lehmann, 1983, pg. 344).

For a logistic selection curve fit, let σ_a^2, σ_b^2, and σ_{ab}^2 denote the variance of $\hat{a}$, variance of $\hat{b}$, and their covariance respectively. Then,

$$Var(\hat{l}_{50}) = \frac{\sigma_a^2 + 2l_{50}\sigma_{ab}^2 + l_{50}^2\sigma_b^2}{b^2}$$

and

$$Var(S\hat{R}) = \left(\frac{2\log_e(3)}{b^2}\right)^2 \sigma_b^2$$

These two formulae are valid for both covered codend and "paired gear" (with p fixed or estimated) models. The standard errors are given by the square root of the variances. From these the usual inferences can be made. For example, an approximate 95% confidence interval is given by an interval that includes plus and minus two standard errors around the estimate. Bear in mind that construction of such a confidence interval is implicitly assuming that the model is appropriate and that there was sufficient data to ensure that the estimated parameters are approximately normally distributed.

6.3.4 Residuals and model checking

A plot of residuals against length is an essential part of any analysis. In defining the residuals, y_l will be used to denote the proportions n_{l1}/n_{l+} and $\hat{y}$ the value fitted to y. For covered codend experiments $\hat{y}_l = \hat{r}(l)$ where $\hat{r}(l)$ is just the value of the retention probability obtained from the estimated selection curve. For "paired gear" experiments $\hat{y}_l = \phi(l)$ where $\hat{\phi}(l)$ is given by equation (3) using the estimated selection curve parameters and estimated relative fishing power $\hat{p}$.

The data y_l are observed proportions and their variability depends on the true (unknown) underlying probability and the number of fish in the length class, n_{l+}. Hence, the difference between observed and fitted proportions, $y_l - \hat{y}_l$ also depend on these quantities. For this reason it is not enough to simply examine a plot of the fitted proportions overlaid against the observed proportions.

Two different residuals are commonly used when analysing proportions (McCullagh and Nelder, 1989, pp. 37-40), the Pearson residual and the deviance residual. These residuals are approximately independent and identically distributed when the model is correct. If they appear otherwise then departures from model assumptions are indicated. Measures of goodness of fit are obtained by squaring and summing the residuals over all length classes.

<u>Pearson residual and χ^2 statistic:</u>
The Pearson residual for length class l is

$$P_l = \frac{\sqrt{n_{l+}}\,(y_l - \hat{y}_l)}{\sqrt{\hat{y}_l\,(1-\hat{y}_l)}}$$

and the generalised Pearson χ^2 statistic is

$$P = \sum_l P_l^2$$

<u>Deviance residual and model deviance:</u>
The deviance residual for length class l is

$$D_l = sign\,(y_l - \hat{y}_l) \bullet$$

$$\left\{2n_{l+}\left[y_l\log_e\left(\frac{y_l}{\hat{y}_l}\right) + (1-y_l)\log_e\left(\frac{1-y_l}{1-\hat{y}_l}\right)\right]\right\}^{1/2}$$

where

$$sign(x) = \begin{cases} 1 & if\ x>0 \\ -1 & if\ x<0 \end{cases}$$

and the model deviance is

$$D = \sum_l D_l^2$$

Both the Pearson χ^2 statistic and model deviance have approximate χ^2 (chi-square) distributions when the model is correct and provided that there are sufficiently many fish of each length class. The degrees of freedom (d.o.f.) of the χ^2 distribution is usually taken to be the number of length classes present in the data minus the number of parameters. The presence of length classes for which only one or two fish were caught can make the d.o.f. very approximate. Nonetheless, it provides a rough test of goodness of fit.

The model deviance has the advantage that it can be used for hypothesis testing between nested models, for example, to determine whether a Richards selection curve is significantly better than a logistic. In these tests the difference in model deviances is approximately a χ^2 statistic with d.o.f. given by the difference in number of parameters.

6.3.5 Overdispersion

Lack of fit (as indicated by a significantly large model deviance or Pearson χ^2 statistic) does not necessarily imply that the fitted selection curve is not a good model of the selection of the fish. If a plot of residuals versus length shows no clear structure then the lack of fit is due to over-dispersion (McCullagh and Nelder, 1989), that is, the failure of the assumption that fish behave independently (Sections 6.3.1 and 6.3.2).

The ratio of model deviance over its degrees of freedom can be used as an estimate of Overdispersion. All likelihood ratio test statistics should be divided by this estimate and standard errors of estimated parameters should be multiplied by the square root of this estimate.

6.4 Recommended sequence of analysis

The researcher must ensure that the estimated selection curve provides a parsimonious fit to the data. A typical approach to the analysis of fish size selection data from a single haul is given below. In practice the data may be a sample of the catch and/or be replicate haul data and/or be multiple gear data. In each of these cases the researcher must consider the modifications to the analysis that are described in Sections 6.7 and 6.8.

For data from a single, fully sampled haul:

1. Plot the data (proportion in the test codend versus length class).
   - Note that, regardless of experimental method deployed, one always plots the proportion of each length class taken by the test codend, i.e., n_{l1}/n_{l+}. In a "paired gear" study, one hopes that these proportions will increase (subject to random variability) with length and then level off around an asymptote corresponding to the relative fishing power parameter p.
   - Bear in mind that proportions corresponding to rare length classes will be very variable. (It is possible to show this variability on the plot (e.g. see Millar 1995)).
2. Fit a logistic selection curve (equation (1)).
3. Check for lack of fit using goodness of fit statistics, residual plots and insight gained from plotting the data in Step 1.
   - Lack of fit may be due to overdispersion (Section 6.3.5) rather than inadequacy with the fitted selection curve. If this is the case, go to step 4.
   - Inadequacy with the fitted selection curve will be indicated by structure in the residuals.

   If the fit is found to be lacking then the options include:
   - Try fitting a different parametric curve. Return to 3.
   - If the difficulty is with data from very small or very large fish, then consider omitting these data. Return to 3.
   - Fit a nonparametric curve. Return to 3.
4. If a satisfactory fit was achieved then determine the standard errors of the estimated selection parameters, and perform any *apriori* hypotheses (e.g. some prespecified value of l_{50}, or equal fishing power of control and test codends used in a "paired gear" haul). If overdispersion was encountered then the standard errors and likelihood ratio test statistic should be adjusted appropriately (Section 6.3.5).

Application of these steps is illustrated in the following examples.

6.5 Examples

6.5.1 Example 1: Covered codend haddock data from Pope *et al.*, (1975)

As a simple first example, we re-analyse the data from Table III of Pope *et al.*, (1975).

Table 6.5.1a Covered codend haddock catch data from Table III of Pope *et al.*, (1975).

Length (cm)	Number in codend	Number in cover	Total
23.5	15	60	75
25.5	6	14	20
27.5	14	11	25
29.5	16	3	19
31.5	11	1	12

Step 1. Data inspection:
The proportion retained data (Figure 6.5.1, uppermost plot) appear to be consistent with a sigmoid shaped selection curve. (With so few length classes it would be unlikely that one could reach any strong visual inference concerning the shape of the selection curve.)

Step 2. Logistic selection curve:
To achieve an approximate maximum likelihood fit of a logistic selection curve, Pope *et al.*, (1975) used a crude version of iterative least squares in which the least squares line was fitted by eye. The exact maximum likelihood fit (Figure 6.5.1) is almost identical (Table 6.5.1b). (This may not hold in general, and particularly not on more extensive data sets where the fitting by eye procedure could be deceived by variable data from rare length classes.)

Table 6.5.1b Approximate and exact maximum likelihood fits of logistic selection curve to the data of Table 6.5.1a. Data from Pope *et al.*, (1975). Standard errors are given in parentheses.

	Approx ML	Exact ML
a	-13.02	-12.60 (2.10)
b	0.4876	0.4725 (0.0810)
l_{50}	26.70 (0.44)	26.66 (0.44)
SR	4.51	4.65 (0.80)
Model deviance		0.98
d.o.f		3
p-value for fit		0.81

Step 3. Residuals and model checking:
The degrees of freedom (d.o.f.) for the fit was calculated as the number of length classes (five) less the number of estimated parameters (two). The model deviance of 0.98 on 3 degrees of freedom does not indicate any problems. The plot of deviance residuals shows no obvious structure (Figure 6.5.1), which is to be expected with just five data points.

Step 4. Inference:
From Section 6.3.3, standard errors for the selectivity parameters were determined (Section 6.3.3) and are shown in parentheses (Table 6.5.1b). The standard error of $\hat{l}_{50}$ estimated by Pope et al. (1975) is also given.

6.5.2 Example 2: Covered codend haddock data from Clark (1957)

The data are given in Table 6.5.2a. They are the total haddock catches from three hauls each of 20 min. duration and 60 min. duration (Clark 1957).

Table 6.5.2a Catch data for haddock in 20 min. and 60 min. covered codend hauls with 113 mm experimental mesh. Data from Clark (1957).

	20 min hauls		60 min. hauls	
Length (cm)	codend count	cover count	codend count	cover count
18.5	0	0	0	0
19.5	0	2	1	4
20.5	0	5	1	25
21.5	0	11	2	69
22.5	0	28	10	151
23.5	1	53	13	190
24.5	5	46	10	192
25.5	1	35	14	146
26.5	3	27	7	102
27.5	1	5	1	62
28.5	0	3	1	24
29.5	1	2	0	4
30.5	0	0	1	8
31.5	0	2	2	12
32.5	3	2	5	19
33.5	4	4	2	16
34.5	5	12	16	27
35.5	8	9	18	31
36.5	13	14	23	37
37.5	29	15	36	32
38.5	29	8	57	34
39.5	34	9	46	24
40.5	30	3	55	17
41.5	29	3	42	8
42.5	18	2	26	1
43.5	16	1	18	2
44.5	11	0	22	2
45.5	12	0	6	0
46.5	9	0	6	0
47.5	3	0	8	0
48.5	5	1	3	0
49.5	3	0	0	0
50.5	5	0	8	0
51.5	2	0	4	0
52.5	2	0	3	0
53.5	1	0	0	0
54.5	1	0	2	0
55.5	4	0	13	0

For brevity, the analysis of the data from the 20 min. hauls is summarised in Table 6.5.2b and Figure 6.5.2a. There are 36 length classes in which fish occurred and of these 30 have 3 or morefish. Subtracting 2 degrees of freedom for the fitted parameters, it is probably reasonable to assume that the "appropriate" degrees of freedom for the model deviance lies between 28 and 34, in which case the model deviance of 23.4 from the logistic fit does not indicate any problems. The plot of deviance residuals contains no extreme values (i.e., larger than 2 in magnitude). There are noticeably more positive deviance residuals for lengths above 38 cm, but this is not too severe and to some extent is expected when retention probability approaches 1 because the observed retention rate is then often exactly 1.

Table 6.5.2b Selection curve parameter estimates and hypothesis tests for haddock selection in a 113mm double manila codend. The logistic curve corresponds to $\delta = 1$. Standard errors (based on binomial theory) are given in parentheses for the acceptable fits. The standard errors for the 60 minute hauls must be multiplied by 1.33 to account for between-haul variation (Section 6.8.2). Hypothesis H_0 tests $\delta = 1$, the hypothesis that the selection curve is logistic. (Correcting this test for between-haul variation requires dividing the deviance value by 1.78. In this particular case, the conclusions would not be altered).

	20 minute hauls all lengths		60 minute hauls all lengths		60 minute hauls subset of lengths	
# hauls	3		3		3	
# length classes	36		35		27	
# fish in total	590		1721		784	
	Logistic curve	Richards curve	Logistic curve	Richards curve	Logistic curve	Richards curve
a	-10.6 (0.9)	-14.5	-9.0	-25.7 (7.0)	-13.7 (1.1)	-14.9
b	0.30 (0.02)	0.39	0.25	0.62 (0.16)	0.37 (0.03)	0.39
δ		1.6		3.7 (1.1)		1.2
l_{25}	31.4 (0.6)	31.8	32.0	33.2 (0.3)	34.2 (0.4)	34.2
l_{50}	35.0 (0.4)	35.5	36.5	37.4 (0.3)	37.2 (0.2)	37.2
l_{75}	38.6 (0.5)	38.7	41.0	40.4 (0.3)	40.1 (0.3)	40.1
Selection factor	3.10 (0.04)	3.14	3.23	3.31 (0.03)	3.24 (0.02)	3.25
Selection range	7.2 (0.6)	6.9	9.0	7.2 (0.4)	5.9 (0.5)	5.9
Model deviance	23.4	22.3	46.9	25.4	10.6	10.5
$H_0: \delta = 1$						
Deviance	1.1		21.5		0.1	
d.o.f.	1		1		1	
p-value	0.3		<0.001		0.99	

It would be appropriate to stop with the logistic fit to the 20 min. data. For interest, results of the Richards fit are given (Table 6.5.2b). Consistent with the logistic being an adequate fit, the Richards curve does not provide a significant improvement (p-value ≈ 0.3).

Analysis of the data from the 60 min. hauls is more challenging. With 35 length classes in which fish occurred and 34 with 3 or more, the model deviance (Table 6.5.2b) for the logistic selection curve has p-value ≈ 0.055 using d.o.f. = 33 and p-value ≈ 0.043 using d.o.f. = 32. The deviance residuals (Figure 6.5.2b, upper case) show that the high model deviance is due to lack of fit. The logistic selection curve is clearly not acceptable for these data.

Two other analyses were performed. Firstly, a Richards curve provided a significantly better fit (p-value< 0.001) with a major reduction in model deviance (Table 6.5.2b). The deviance residuals (Figure 6.5.2b, centre case) are much improved, but do show a long run of negative residuals from 26.5 to 33.5cm.

A second additional analysis was performed with length classes below 27.5cm removed. This cut off was chosen because it appears to eliminate the long left hand tail of the observed retention proportions while retaining as many length classes as possible. The logistic and Richards fits to the reduced data set were almost identical (Table 6.5.2b, Figure 6.5.2b, lower case).

Whether one prefers the Richards fit to the full data, or logistic fit to the reduced data, would depend on the objectives of the study. The Richards fit to the full data is the best model of the entire selection curve and is particularly effective at quantifying the capture of extremely small fish. The logistic fit to the reduced data might be acceptable if one is simply interested in l_{50} and *SR*.

Note that these two fits (Richards to full data and logistic to reduced data) give reasonably similar inferences and in particular the estimated l_{50}'s differ by only 0.2 cm. The flexibility of the asymmetric Richards curve enables it to accommodate the relatively high retention of very small fish while also modelling the retention of larger fish.

NB: Although Table 6.5.2b gives the standard errors for the selectivity parameters, these standard errors have not been corrected for possible between haul variation. See Section 6.8.

6.5.3 Example 3: Alternate haul haddock data from Pope *et al.*, (1975)

These data (Table 6.5.3a, from Table II of Pope *et al.*, 1975) were analysed using a general nonlinear optimiser in the statistical package *Splus* to obtain the maximum likelihood parameters.

Table 6.5.3a Alternate hauls haddock data from Table II of Pope *et al.*, (1975). The experimental and control codends used 87 mm and 35 mm mesh respectively.

Length (cm) codend	Number in control codend	Number in experimental codend	Proportion in experimental codend
24	1	0	0.000
25	1	0	0.000
26	3	0	0.067
27	14	1	0.143
28	30	5	0.279
29	49	19	0.326
30	60	29	0.505
31	50	51	0.565
32	70	91	0.526
33	108	120	0.573
34	88	118	0.560
35	84	107	0.534
36	68	78	0.580
37	37	52	0.548
38	33	40	0.586
39	12	17	0.773
40	5	17	0.700
41	6	14	0.500
42	10	10	0.800
43	1	4	0.500
44	6	6	0.500
45	2	2	0.833
46	1	5	1.000
47	0	1	1.000

Table 6.5.3b Maximum likelihood fits for a logistic selection curve to alternate haul haddock data (Table II, Pope *et al.*, 1975) for an 87 mm diamond mesh test codend. Parameter estimates are given for both the equal ($p = 0.5$) and unequal relative fishing power assumptions. Values in parentheses are standard errors. The deviance values (likelihood ratio test statistics) for the goodness of fit hypothesis and the equal relative fishing power hypothesis are also given.

	$p = 0.5$	$p =$ estimated
# length classes	24	
# fish in total	1526	
a	-36.3	-27.7
b	1.23	0.92
p	0.5	0.57 (0.02)
l_{25}	28.5	29.0 (0.3)
l_{50}	29.4	30.2 (0.4)
l_{75}	30.3	31.4 (0.6)
H_0: model		
Deviance	36.0	14.8
d.o.f.	22	21
p-value	0.03	0.83
$H_0: p = 0.5$		
Deviance		21.2
d.o.f.		1
p-value		<0.001

Recall that the model of Section 6.3.2 defined the relative fishing power p to quantify the effect of possible differences in the fishing power of the two codends. It is assumed that the difference is the same over all sizes of fish.

With p fixed at 0.5 and a logistic selection curve, the model deviance (Table 6.5.3b) indicates a problem with the model and the deviance residuals (Figure 6.5.3, upper case) show that it is lack of fit. It is evident that the proportion of large fish retained in the test codend exceeds 0.5. Allowing the model to estimate p provides a major improvement and the model deviance is no longer significant and the deviance residuals show no obvious remaining structure (Figure 6.5.3, lower case). It is appropriate to choose this model and complete the analysis by calculation of the standard errors of the selectivity parameters.

6.6 Historical methods

For completeness, a very brief mention of some historical methodology is given here. These methods are solely numerical recipes for obtaining a fit to data. They are not based on a statistical model and the statistical properties of the resulting estimates are therefore largely unknown.

Pope *et al.*, (1975) method for "paired gears"

The premise of this method is that a covered codend type analysis can be used if the number of length l fish entering the test codend is assumed to be given by the number of fish that entered the control codend. This assumption is untenable whenever the test codend catch of a length class exceeds that of the control - an event which happens frequently for larger fish and particularly if the test codend is fishing more efficiently. Data manipulation is required, including an adjustment for unequal fishing powers. Simpson (1989) used a slight variation of this approach involving smoothing of the data and a statistical test for equal fishing powers.

Cadigan and Millar (1992) performed a simulation study in which it was seen that these methods exhibited considerable bias and consistently overestimated l_{50} and *SR*. The SELECT methodology of Section 6.3.2 was seen to be preferable.

Kimura (1978) method for "paired gears"
This method was offered for analysis of "paired gear" data in which both codends were test codends. However, it applies equally to the test and control codend situation. (Similarly, the SELECT methodology of Section 6.3.2 applies equally to the situation with two test codends.)

The fit is achieved by nonlinear least squares to the ratio of catches. There does not appear to be any evaluation of this approach, but it is felt that a major weakness arises because the ratios are not weighted to reflect their variability. (Appropriately weighted least squares fits are sometimes used as approximations to the maximum likelihood fit (e.g. McCullagh and Nelder, 1989, pg. 130)).

6.7 Sampled catches

When the catches are large it may not be practicable to measure each fish (see Section 5.2.1). When sampling it is extremely important to take a representative sample of the entire catch and to determine the sampling fractions of the codends with as much accuracy as possible. Here, p_1 and p_2 will denote the fraction of the catch in the codend and cover that was sampled (i.e. length measured), respectively.

The analyst has two choices - modifying the analysis or modifying the data. Modifying the analysis permits use of the raw data and retains statistical rigour. However, to many, modifying the data may be more intuitive because a usual analysis is then performed on the estimated total catches as calculated by scaling the counts by the inverse of the sampling fractions.

6.7.1 Analysis of scaled data from single hauls

A difficulty arises upon attempting to determine the reliability of the fit obtained from using estimated total catch numbers. If p_1 and p_2 are not too different then it may be reasonable to divide all estimated standard errors by the square root of some overall sampling fraction such as

$$\min(p_1,p_2) \text{ or } \frac{p_1+p_2}{2}.$$

(The former choice is the more conservative, giving higher standard errors.) This will inflate the estimated standard errors to reflect the true "sample size". The model deviance should be reduced by multiplying by this overall sampling fraction.

6.7.2 Analysis of raw data from single hauls

In "paired gear" studies the SELECT methodology requires no modification because parameter p (Section 6.3.2) can include the effects of sampling and as such can be considered a measure of both relative fishing power and relative sampling effort. That is, one simply analyses the raw (unscaled) data using the model with p estimated. (This assumes that the sampling fractions are not length dependent, i.e. that large fish are not preferentially sampled. Otherwise, straightforward modification to the model would be required.) Xu and Millar (1993) give an analogous analysis from a study in which gears are fished with unequal effort. In principle there is no difference between fishing with unequal effort and sampling with unequal effort.

Analysis of sampled catches from covered codend hauls is considered in Millar (1994). The maximum likelihood model can be easily modified and for logistic selection curves it is shown that the modification is entirely transparent. The logistic selection curve is determined by fitting a logistic curve to the raw (unscaled) data. This fitted logistic curve is not the selection curve, but if the estimated parameters of this curve are denoted a^* and b^* then the parameters a and b of the logistic selection curve are $a = a^* - \log_e(q)$ and $b = b^*$, where $q = p_1/p_2$ is the ratio of sampling fractions (Millar, 1994). This procedure can be generalised to allow the sampling fractions to be length dependent by the use of offsets (Millar 1994).

6.7.3 Sampling strategies and comparison of analyses

For covered codend studies, Millar (1994) showed that sampling similar numbers or similar fraction (i.e. $p_1 \approx p_2$) from the codend and cover was preferable to sampling equal weight. The latter will always yield more fish in the cover sample.

It was also found (Millar 1994) that the raw data and scaled data fits of a logistic selection curve were very similar except when the ratio of sampling fractions, q, was quite different from unity. Using simulation, correlations between the l_{50}'s estimated by the two methods were 0.936, 0.999, 0.999, 0.966 and 0.898 when the sampling fraction ratio was 0.17, 0.56, 1.47, 3.49 and 7.97, respectively. Similarly, the precision of l_{50}'s estimated by the two methods were similar when q was not too extreme, otherwise the raw data fit was more precise.

The results of Millar (1994) suggest that existing analyses that have been performed on scaled data would, in most cases, have provided good point estimates of the selectivity parameters. However, it is recommended that the raw data approach be used in future analyses of individual haul data because the statistical properties (e.g. standard errors) of the estimates can then be reliably estimated. Also, when taking the sample it is recommended that q should be at least ⅓ and no more than 3.

6.8 Multiple gear and replicate hauls data

In practice, a selection experiment will involve replicate hauls with one or more gears.

First, we show how the model can accommodate the deployment of different gears. Then, in Section 6.8.2 the issue of between-haul variation in replicate hauls is addressed. Section 6.8.3 outlines a method for jointly modelling both multiple gear and replicate hauls data. The concluding example in Section 6.8.4 demonstrates this method and two alternative approaches.

6.8.1 Parameterising multiple gears studies

Some selection studies will be interested in the difference in selectivity between different test gears, or in the change arising due to different deployment or controlled changes in a single gear. For example, test codends of several different mesh sizes may be used and/or tows of differing duration may be undertaken. One might also be interested in potential influences outside of the test design, such as the effect of the total catch weight in the codend.

Assume that the selectivity of each haul is adequately described by an r parameter selection curve (Section 6.2.1) and let $v_h = (v_{h1}, \ldots, v_{hr})^T$ be the selectivity parameters for haul h. (In a "paired gear" study one may wish to consider whether the relative fishing power parameter should also be modelled.) To model the selectivity parameters for haul h one might specify a linear relationship

$$v_h = X_h \alpha \tag{5}$$

where X_h is a known r x q design matrix depending on the net used for haul h, and α is a q x 1 vector of unknown parameters to be estimated.

The choice of an appropriate form for X_h is a crucial part of the model building process. This is a problem common to many regression modelling situations and, unfortunately, no guidelines can be given to cover all eventualities. Usually, the nature of the experiment will suggest likely candidate models; see for example, Fryer (1991) who compares the selectivities of two different codends and Reeves *et al.*, (1992) who investigate changes in selectivity with varying mesh size, codend diameter and extension length. Inspection of the data and residual plots are helpful in checking whether such models are appropriate and for suggesting alternative models that can be tried.

Sometimes, there are a number of "competing" models which provide adequate descriptions of the data and between which it is virtually impossible to discriminate. Whether this is important or not depends on the purpose of the experiment. For example, experience suggests that the choice of model is often not critical when identifying main effects, such as the "broad" effect of mesh size. However, if the data are to be used for predictive purposes -in particular, for the undesirable, but sometimes unavoidable, purpose of extrapolating outside the range of the data, then a close scrutiny of the behaviour of each competing model is required. See Fryer and Shepherd (1995) for a discussion of the issues involved.

6.8.1.1 Direct approach

The <u>direct approach</u> uses a simultaneous fit to the selectivity data from all of the gears. The selection curve parameters are specified to be of some assumed form, as in equation (5) say. For example, suppose that two different codend mesh sizes are used and that a logistic selection curve is to be fitted. It may be desired to formulate that the l_{50}'s and selection ranges of the selection curves be proportional to mesh size. If the mesh sizes are m_1 and m_2 respectively, with l_{50}'s denoted $l_{50,1}$ and $l_{50,2}$ respectively and selection ranges SR_1 and SR_2 respectively then this requirement gives

$$l_{50,2} = \frac{m_2}{m_1} l_{50,1} \quad and \quad SR_2 = \frac{m_2}{m_1} SR_1$$

In terms of the parameters a_1, b_1 and a_2, b_2 of the two logistic selection curves, this can be achieved by formulating

$$a_2 = a_1 \quad and \quad b_2 = \frac{m_1}{m_2} b_1$$

If we let $\alpha = (a_1, b_1)$ then, in terms of equation (5),

$$\begin{pmatrix} a_1 \\ b_1 \end{pmatrix} = v_1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} a_1 \\ b_1 \end{pmatrix}$$

and

$$\begin{pmatrix} a_2 \\ b_2 \end{pmatrix} = v_2 = \begin{pmatrix} 1 & 0 \\ 0 & \frac{m_1}{m_2} \end{pmatrix} \begin{pmatrix} a_1 \\ b_1 \end{pmatrix}$$

If this were a "paired gear" study then one could consider modelling the relative fishing power of the two codends.

This might just amount to considering whether the small mesh codend has the same relative fishing power as the large mesh codend.

6.8.1.2 Indirect approach

The <u>indirect approach</u> fits unrelated selection curves to the data from individual hauls. Then, one examines the individual fits to see if they can be explained by the differences in the gears. To implement the linear model in equation (6) one might assume that the individually estimated selection curve parameters are normally distributed. That is,

$$\hat{v}_h \sim N_r\left(X_h \alpha, R_h\right) \qquad (6)$$

where $\hat{v}_h$ is an r dimensional vector containing the estimated parameters for the individual fit to haul h. Here, R_h is the covariance matrix of $\hat{v}_h$, and can be estimated using the formulae in Section 6.3.3. The assumption of normality should be appropriate provided that a reasonable number of fish from the gear are measured.

One can greatly simplify this approach by restricting attention to just one parameter of the selection curves, l_{50} say. For example, in a non-rigorous analysis by Clark, (1957), selection curves fitted by eye to data from tows of 20, 40, 60 and 80 min. duration suggested that the l_{50} of the gear increased with tow duration. Suuronen et al., (1991) investigated the effect of catch weight on the l_{50} of pelagic herring trawls and, in one of the three selection trials performed, found a statistically significant (p-value<0.01) decrease in l_{50} with increasing catch weight.

6.8.2 Replicate hauls data

The analysis of replicate hauls data is complicated by the widely accepted view that, in practice, the selectivity of a net changes from haul to haul even though the net has not been altered in any way (Fryer, 1991). The causes of between-haul variation are unclear, but could be due to changes in uncontrolled variables such as towing direction, wind speed, water depth etc. or to changes in stock composition, density etc. Although between-haul variation is often not of direct interest to the gear technologist, it must be accounted for in the analysis of selectivity data to avoid making misleading statistical statements about the effects of controlled changes to the nets. Fryer (1991) demonstrates some of the inferential problems incurred by ignoring between-haul variation.

6.8.2.1 Individual hauls analysis

This approach can be considered a special case of equation (5) in which X_h is the same for each replicate haul. Either the indirect or direct analysis approach can be taken. The example in Section 6.8.4 shows how the individual $\hat{l}_{50}$'s from an indirect analysis are combined and used to estimate and incorporate between-haul variation.

6.8.2.2 Combined hauls analysis

With this approach the catch data combined over all replicate hauls is analysed as though it were a single haul. In addition to the consideration of between-haul variability, one must be aware that an analysis of the catch data combined over all hauls can be viewed as estimation of the mean selection curve for the test gear. (The mean selection curve can be defined as the selection curve describing the performance of the gear over the entire fishery.) Consequently, if catches are sampled it is necessary to calculate the estimated total catches from each haul before combining. This ensures that large catches contribute more to the mean selection curve than small catches.

In a combined hauls analysis the statistical inferences of Sections 6.3.3, 6.3.4, (or Section 6.7 if catches were sampled) do not accommodate between-haul variation and one of the approaches given below should be used.

<u>Replication estimate of dispersion (REP)</u>
Suppose that r tows are performed under the same conditions. For tows $i = 1,\ldots,r$ let n^i_{l1} be the number of length l fish in the test codend and let n^i_{l+} be the total number of length l fish for the tow. (These numbers will be estimated if the catch was sampled.) The proportion of length l fish taken by the codend over the r replicate tows will be denoted by

$$y_l = \frac{\sum_i n^i_{l1}}{\sum_i n^i_{l+}}$$

The replication estimate of dispersion (REP) is defined to be (McCullagh and Nelder, 1989),

$$\text{REP} = \frac{Q}{\text{d.o.f.}} \quad where$$

$$Q = \sum_l \sum_i \frac{(n^i_{l1} - n^i_{l+}\, y_l)^2}{n^i_{l+}\, y_l\,(1 - y_l)}$$

where d.o.f. is the degrees of freedom. This is given by the number of terms in the double summation less the number of length classes. In practice, the summation over length classes would be restricted to length classes for which $\sum_I n^i_{I+}$ is reasonably large, or length classes for which y_l is not too close to 0 or 1. Under the null hypothesis of no between-haul variation, Q has an approximate chi-squared distribution with d.o.f. degrees of freedom. If this null hypothesis is rejected then REP provides an estimate of the Over dispersion (caused by between -haul variation) present in a combined hauls analysis.

For example, the individual haul haddock data from Clark (1957) (Table 6.8.2.2) were used to determine if it is necessary to adjust the standard errors from the combined haul analysis (Table 6.5.2b). Only length classes such that $0.1 \leq y_l \leq 0.9$ were used. For the 20 min. hauls, Q was 15.9 on 18 d.o.f., and no between-haul variation is indicated. Q was 48.1 on 27 d.o.f for the 60 min. hauls. This is significant (p-value < 0.01) and gives REP = 48.1/27 ≈ 1.78. The standard errors (Table 6.5.2b) for the analysis of these data should be multiplied by $\sqrt{1.78} \approx 1.33$.

Table 6.8.2.2 Individual haul catch data for haddock in three 2O min. and three 6O min. covered codend hauls with 113 mm mesh. Data from Clark (1957).

	20 min. hauls						60 min. hauls					
length (cm)	c.e	cov	c.e	cov	c.e	cov	c.e	cov	c.e	cov	c.e	cov
18.5	0	0	0	0	0	0	0	0	0	0	0	0
19.5	0	0	0	0	0	2	0	3	0	1	1	0
20.5	0	0	0	1	0	4	0	9	0	4	1	12
21.5	0	0	0	0	0	11	2	25	0	6	0	38
22.5	0	0	0	9	0	19	7	50	2	23	1	78
23.5	0	1	0	10	1	42	9	80	2	41	2	69
24.5	0	0	0	4	5	42	7	78	0	40	3	74
25.5	0	0	1	5	0	30	9	59	1	39	4	48
26.5	0	1	0	2	3	24	5	51	1	23	1	28
27.5	0	0	0	0	1	5	1	30	0	21	0	11
28.5	0	0	0	0	0	3	0	17	0	3	1	4
29.5	0	0	0	0	1	2	0	2	0	1	0	1
30.5	0	0	0	0	0	0	1	7	0	0	0	1
31.5	0	0	0	0	0	2	2	7	0	1	0	4
32.5	0	0	1	0	2	2	4	8	1	2	0	9
33.5	0	1	0	0	4	3	0	7	1	1	1	8
34.5	2	3	1	4	2	5	11	17	3	2	2	8
35.5	3	3	0	0	5	6	13	16	2	4	3	11
36.5	2	2	4	3	7	9	13	20	3	3	7	14
37.5	8	4	7	3	14	8	10	21	14	4	12	7
38.5	10	1	4	0	15	7	23	21	12	5	22	8
39.5	12	1	5	5	17	3	21	9	7	2	18	13
40.5	8	0	5	1	17	2	19	12	14	1	22	4
41.5	11	0	5	0	13	3	11	4	10	1	21	3
42.5	3	0	3	0	12	2	12	1	4	0	10	0
43.5	2	0	2	0	12	1	6	2	7	0	5	0
44.5	1	0	2	0	8	0	13	0	5	1	4	1
45.5	3	0	3	0	6	0	5	0	0	0	1	0
46.5	2	0	2	0	5	0	4	0	0	0	2	0
47.5	1	0	0	0	2	0	4	0	1	0	3	0
48.5	3	0	0	0	2	1	0	0	3	0	0	0
49.5	2	0	0	0	1	0	0	0	0	0	0	0
50.5	2	0	0	0	3	0	4	0	2	0	2	0
51.5	0	0	0	0	2	0	2	0	1	0	1	0
52.5	2	0	0	0	0	0	2	0	0	0	1	0
53.5	0	0	1	0	0	0	0	0	0	0	0	0
54.5	1	0	0	0	0	0	0	0	0	0	2	0
55.5+	1	0	0	0	3	0	5	0	4	0	4	0

<u>Bootstrapping</u>
Bootstrapping is a computer intensive Monte-Carlo technique that aims to emulate the variability (including between-haul variability) that was present when the selectivity data were obtained. It makes minimal assumptions and would be expected to work reasonably well in this application if sufficient computer power is available. Millar, (1993b) applied this approach to a combined haul selectivity analysis for data from a scallop dredge.

6.8.3 Fixed and Random effects model

The fixed and random effects selectivity model of Fryer (1991) is a reasonably flexible approach for jointly modelling both the effects of controlled changes to the net (fixed effects) and between-haul variation (random effect). The between-haul variation is modelled by assuming that the selectivity of a net varies randomly between hauls about a mean selection curve with a certain probability distribution. Controlled changes in the net are incorporated by allowing the mean selection curve to change with the net (as in Section 6.8.1.).

Assume that the selectivity of each haul is adequately described by an r parameter selection curve (Section 6.2.1) and let $v_h = (v_{h1},\ldots,v_{hr})^T$ be the selectivity parameters for haul h. (In a "paired gear" study, relative fishing power could be included as an additional parameter.) Assume that the selectivity parameters vary from haul to haul according to the model

$$v_h = X_h \alpha + b_h$$

where

- X_h is a known r x q design matrix depending on the net used for haul h,
- α is a q x 1 vector of unknown parameters to be estimated,
- b_h is an r x 1 error vector, representing the random variation in selectivity for haul h.

The b_h are assumed to be independent and multivariate normally distributed with zero mean and constant, but unknown, r x r covariance matrix D. Thus v_h has a multivariate normal distribution with mean $X_h\alpha$ and variance D; i.e.,

$$v_h \sim N_r\left(X_h \alpha,\ D\right) \tag{7}$$

Thus, selectivity is specified by

- the parameters α, which determine how the mean selection curve $X_h\alpha$ changes with controlled changes to the net,
- the covariance matrix D, which measures the extent of the between-haul variation. When $D = 0$, there is no between-haul variation and the model reduces to that described in Section 6.8.1.

It is then necessary to estimate the parameters α and D.

Model (7) is a special case of the Laird-Ware model for longitudinal data (Laird and Ware, 1982; see also Jones, 1993). Other types of fixed and random effects models are feasible - particularly ones in which the covariance matrix changes with the controlled changes to the net, but these are not considered here.

Parameter estimation

The observations consist of the numbers of fish measured at length in each haul and are assumed to be binomially distributed with probabilities which depend on the selectivity parameters (including the relative fishing power parameter of a "paired gear" study) for that haul (see Sections 6.3.1 and 6.3.2). Thus, two types of random variation must be accounted for when estimating α and D: the variation in the selectivity parameters v_h given by model (7) and the binomial variation in the numbers of fish at length retained. In principle, α and D can be estimated by the direct approach (Section 6.8.1.1), that is, by maximising the marginal likelihood of the numbers of fish retained (Stiratelli *et al.* 1984). However, the direct approach is complicated and computationally intensive. The indirect approach, based on individual haul analyses, is usually adequate and is given below (Korn and Whittimore, 1979; Laird and Ware, 1982; Stiratelli *et al.*, 1984).

Let $\hat{v}_h$ be the maximum likelihood estimator of v_h and let R_h of equation (6) be replaced by the estimated r x r covariance matrix of $\hat{v}_h$ (Section 6.3.3). Assume that a sufficient number of fish at length were measured so that $\hat{v}_h$ is approximately multivariate normally distributed with mean v_h and covariance matrix R_h. That is, conditional on v_h,

$$\hat{v}_h \sim N_r(v_h, R_h) \tag{8}$$

Combining this with equation (7) includes the randomness in v_h, giving

$$\hat{v}_h \sim N_r(X_h\alpha, R_h + D) \tag{9}$$

In (9), the covariance matrix D measures the between-haul variation in the selectivity parameters v_h and the covariance matrices R_h measure the "known" binomial variation in estimating $\hat{v}_h$ due to the randomness in the numbers of fish observed.

Model (9) can now be used to estimate α and D by either maximum likelihood (ML) or residual maximum likelihood (REML) (e.g. Robinson, 1987). Both sets of estimates can be obtained either directly using a numerical maximisation routine or by the EM algorithm (Dempster *et al.*, 1977).

Software

Two pieces of software are currently available for fitting the fixed and random effects model: CC Selectivity (ConStat 1995) and a FORTRAN subroutine available on request from SOAEFD Marine Laboratory, Aberdeen (Rob Fryer). Both implementations are presently restricted to 2-parameter selection curves (i.e. any but the Richards curve.) The FORTRAN subroutine requires subroutines F01ABF and F03ABF of the Numerical Algorithms Group (1991) Library.

Remarks

Advantages

- Explicitly models both controlled changes in the net and between-haul variation.
- Uses individual haul fits, allowing rigorous statistical analysis of sampled catch data (Section 6.7.2)
- Permits valid statistical statements about the effects of controlled changes in the net.
- In principle, the modelling framework can be extended to incorporate a wide variety of responses.

Disadvantages

- Requires that a single parametric model adequately describes the selectivity of each haul.
- Requires that sufficient fish are measured in each haul so that the maximum likelihood estimates of the selectivity parameters are approximately multivariate normal. Hauls for which this is not so must be discarded. This poses problems if many hauls have to be discarded. In particular, the model is unlikely to be useful for data sets in which few fish are caught.
- Easy fitting procedures are only available provided simplifying assumptions can be made about the distribution of the between-haul variation.

6.8.4 Example 2 revisited: Analysis of a multiple gear replicated hauls study

Three analyses of these data are given

1. Indirect analysis of individual haul data
2. Direct analysis of combined haul data
3. Indirect fixed and random effects analysis of individual haul data

In principle, other combinations (e.g. direct analysis of individual haul data) could have been considered. The indirect combined analysis is essentially given in Table 6.5.2b.

6.8.4.1 Indirect analysis of individual hauls

Here, we revisit the covered codend data used in Example 2, applying the indirect analysis approach discussed in Section 6.8.1.2 to the individual hauls (Table 6.8.2.2). Although the gear used is the same, this can be considered a multiple gear study because of the controlled difference in tow duration. This example requires some familiarity with (weighted) one-way ANOVA and hierarchial modelling. The details are not discussed here and may be found in most regression texts.

Logistic selection curves were assumed and the fit to the 60 min. tow data was restricted to lengths above 27 cm (as per Example 2).

Table 6.8.4.1 Individual haul fits to the data of Table 6.8.2.2.

Haul	Duration	$\hat{a}$	$\hat{b}$	$\hat{l}_{50}$ (s.e.)	$\hat{SR}$ (s.e.)
1	20 min.	-26.4	0.735	35.9 (0.58)	2.99 (0.78)
2	20 min.	-11.5	0.325	35.6 (1.01)	6.77 (1.49)
3	20 min.	-9.8	0.279	35.3 (0.55)	7.89 (0.71)
4	60 min.	-11.6	0.307	37.6 (0.40)	7.15 (0.82)
5	60 min.	-15.3	0.427	35.7 (0.63)	5.14 (0.92)
6	60 min.	-17.8	0.476	37.4 (0.36)	4.62 (0.64)

A one-way ANOVA of haul duration (explanatory factor) on $\hat{l}_{50}$ (response) estimated the l_{50}'s of 20 min. tows and 60 min. tows to be 35.6 cm and 37.3 cm respectively. The ANOVA was weighted using the inverse of the estimated variance of each $\hat{l}_{50}$. With these weights the variance estimated from the ANOVA should be close to unity. In fact, it was 1.94, providing modest evidence (p-value=0.1) of between-haul variation. This is not convincing evidence of between-haul variation. However, taking the between-haul variation into account gives a conservative analysis, in this case resulting in the two estimated l_{50}'s having standard errors of 0.5 and 0.3, respectively, and haul duration having a marginally statistically significant (p-value=0.05) effect on l_{50}. Ignoring between-haul variation would reduce these standard errors and the effect of haul duration would have a smaller p-value, and hence remain significant.

A weighted one-way ANOVA using selection range as the response did not find an effect (p-value>0.1) of haul duration.

6.8.4.2 Direct analysis of combined hauls

Let (a_1, b_1) and (a_2, b_2) be the selection curve parameters for the 20 min. tow and 60 min. tow hauls respectively. Four models were fitted.

1. Equal *a*'s and *b*'s: No difference in selection curves.

2. Equal *a*'s: $a_1 = a_2$. This forces the relative difference between the l_{50}'s and *SR*'s of the two selection curves to be the same.

3. Equal *b*'s: This forces the two curves to have the same *SR*, but possibly different l_{50}'s.

4. Full model: No relationship assumed between (a_1, b_1) and (a_2, b_2). This fits two separate logistic curves, reproducing the fits of Example 2.

Table 6.8.4.2 Direct fits to combined hauls data.

Model		d.o.f	Model deviance	$\hat{a}_1$	$\hat{b}_1$	$\hat{a}_2$	$\hat{b}_2$
1.	$a_1 = a_2$, $b_1 = b_2$	61	55.2	-11.9	0.328	-11.9	0.328
2.	$a_1 = a_2$	60	38.9	-12.0	0.341	-12.0	0.324
3.	$b_1 = b_2$	60	37.1	-11.7	0.333	-12.4	0.333
4.		59	34.0	-10.6	0.304	-13.7	0.369

Table 6.8.4.3

Model		d.o.f	Log-likelihood	$\hat{a}_1$	$\hat{b}_1$	$\hat{a}_2$	$\hat{b}_2$
1.	$a_1 = a_2,\ b_1 = b_2$	7	1.85	-12.7	0.352	-12.7	0.352
2.	$a_1 = a_2$	6	4.64	-13.2	0.374	-13.2	0.355
3.	$b_1 = b_2$	6	4.89	-12.6	0.360	-13.3	0.360
4.		5	5.41	-11.0	0.314	-14.0	0.381

One would assume any between-haul variation to be of common magnitude in both the 20 min. and 60 min. hauls. Combining the Q values and d.o.f.'s given in Section 6.8.2.2 gives 64.0 on 45 d.o.f. This is statistically significant (p-value ≈ 0.03) and suggests that in the deviance analysis the differences in deviance should be divided by REP = $64.0/45 \approx 1.42$ and that standard errors should be multiplied by $\sqrt{64.0/45} \approx 1.19$.

The model deviance values show that model 2 and model 3 (common *SR*) are both significantly better than model 1. Models 2 and 3 have the same number of parameters, but model 3 is the preferred intermediate model because it has smaller model deviance. This model suggests that the selection range (estimated to be 6.6 cm) did not change due to increased haul duration, but that l_{50} increased from 35.1 cm to 37.1 cm. In this example, examination of Table 6.5.2b (the indirect combined analysis) leads to similar conclusions.

6.8.4.3 Indirect analysis with fixed and random effects

Individual haul fits (Table 6.8.4.1) were used in the indirect analysis in which the estimated l_{50}'s were modelled as functions of haul duration. Here, we model the individual haul parameter estimates $\hat{v}_h = (\hat{a}_h, \hat{b}_h)$ of Table 6.8.4.1 using equation (9).

Using the maximum likelihood method, the fits of the four models to the $\hat{a}$ and $\hat{b}$ values of Table 6.8.4.1 give, Model 2 and model 3 (common *SR*) have the same number of parameters, but model 3 is the preferred intermediate model because it has higher log-likelihood. The log-likelihood for model 1 (same selection curve) is 1.85, compared to the value of 4.89 for model 3. The likelihood ratio test statistic of $2(4.89 - 1.85) = 6.08$ (p-value<0.02) shows model 3 to be significantly better. The full model (no assumed relationship between curves for 20 min. and 60 min. hauls), has log-likelihood 5.41 and is not significantly better than model 3. Similar results were obtained from the restricted maximum likelihood method.

Model 3 estimates a common *SR* of 6.1 cm and l_{50}'s of 35.0 cm and 36.9 cm for the 20 min. and 60 min. hauls respectively. This compares closely with the combined hauls direct fit (Table 6.8.4.2) where model 3 was also preferred and produced an estimated common *SR* of 6.6 cm and estimated l_{50}'s of 35.1 cm and 37.1 cm.

From model 3, the between haul variation of parameters a and b was estimated to have covariance matrix

$$D = \begin{pmatrix} 4.89 & -0.144 \\ -0.144 & 0.0042 \end{pmatrix}$$

Other applications of the fixed and random effects model that have appeared in the selectivity literature are Reeves *et al.*, (1992) and Galbraith *et al.*, (1994).

7 Reporting of results

7.1 Minimum recommended report content

The author of a report on a selectivity experiment will wish to give a short concise account of the work carried out and the results obtained. He will often be faced with severe restrictions on the length of text and quantity of tables and figures if it is to be published in a journal. The amount of data generated in a selectivity experiment is large and it is impractical to attempt to include a hard copy of all the raw data particularly as any incorporation of the data in a later wider analysis would require haul by haul data. It is recommended that raw data be stored on computer database files as described in 5.1.3.

The report should aim to summarise the results giving the reader clear information on

- the vessel type, gear type and fish species concerned,
- the selectivity parameters found for the different gears tested,
- whether there was statistically significant difference between the selectivity parameters for the different gear configurations tested.

Furthermore it is particularly important that the reader should be able to assess the quality of the results presented

- are the fishing conditions representative of normal commercial fishing operations for the species considered?
- how good is the experimental technique?
- were there problems in conducting the experiments at sea?
- how good is the data analysis?
- can the results or raw data be used for other purposes or incorporated into data banks?

The minimum required information is

MATERIALS AND METHODS

Vessel

- engine power,
- fishery that the vessel normally takes part in,
- vessel type (research or commercial).

Gear

- gear type and name,
- mouth circumference in meshes and mesh size e.g. 500 meshes in 120mm full mesh; beam length for beam trawling.

Codends under test

- nominal mesh opening,
- number of open meshes between selvedges,
- length in m of the codend and any straight extension pieces located in front of it,
- twine material e.g. PA or PE, single or double, knotted or knotless, twisted or braided,
- any available measurement of twine diameter mm or runnage m/kg plus details of how the information was obtained (measurement or manufacturers specification),
- corresponding details of any windows together with details of where they are located,
- brief details of any strengthening bags or chafers attached.

Experimental method

- method used e.g. hooped covered codend and reasons for selecting it,
- design and specifications of small mesh codends-/covers - mesh size, number of open meshes round, stretched length, details of how and where they are attached to the main trawl, circumference and point of attachment of hoops,
- design and specification of trouser trawl if used including sketch showing how and where the trawl is divided. Comments on how this alters the trawls dimensions compared to standard commercial trawls.

Conducting the experiment

- technique for sampling and measuring catches, average sampling rates for the main species,
- details of gauge used to measure mesh sizes,
- account of the fishing conditions during the trip - area fished, depths, weather, average catch rates in test codends and comparison with normal commercial catch rates,
- practical problems encountered during the trip which may affect the quality of the data.

Analysis of the data

- selectivity model used (author and reference if using a standard model, detailed description if a new model is developed within the project),
- method of estimating selectivity parameters,
- methods for testing for significant differences between different codends.

RESULTS

For each codend tested:

Total catch weight per haul	Mean, standard deviation, minimum, maximum
Towing time	Mean, standard deviation, minimum, maximum
Sea state	Mean, standard deviation, minimum, maximum
Codend mesh opening	Mean

For each species:

Number of hauls
25% retention length, standard error and confidence limits
50% retention length, standard error and confidence limits
75% retention length, standard error and confidence limits
Selection factor and confidence limits
Selection range and confidence limits

Total number of fish within selection range	Test codend Total population

7.2 Suggested report format

Appendix 3 is a suggested outline for a report describing experiments measuring and comparing the selectivity parameters obtained for the same fish species in different codends.

The table at the end of Appendix 3 is a recommended one page format for the presentation of an overall results table. The vessel type should specify whether it is a research vessel or a commercial fishing vessel. Test date should be month and year. If the twine material was double twine or if the netting was knotless material then this should be recorded together with the basic chemical composition (PA, PET etc).

7.3 Format for storage and distribution of complete data sets

Complete data sets should be stored for possible future research and further analysis within or outside the institute. This requires standardisation of the format for storage and distribution of the data sets. The experimental data are covered by the standardised formats discussed in Section 5.1.3 and given in Tables 1-13 of Appendix 1.

A complete data set should also contain files with the selectivity results. The main contents are the estimates and variability of l_{25}, l_{50}, l_{75}, the selection factor and the selection range and also the number of fish in the selection range. The format is given in Table 14 which is also included in Appendix 1. A separate file should be made for each haul or each group of combined hauls as appropriate.

8 The use of selectivity data in fish stock assessment

8.1 Introduction

If fisheries are to be managed then there must be some quantity which managers can control. Since most fish stocks are highly variable due to large unpredictable annual changes in recruitment, the only factor which can be easily controlled is the exploitation rate. Selectivity plays a major part in the exploitation rate of fish stocks and is therefore and important tool for managers.

Fishing gears are selective in the fish they retain. They may select by species and by size. This chapter concentrates on size selectivity, principally codend selectivity of towed gears such as trawls, and how this relates to conventional fish stock assessment.

8.2 Selectivity and fishing mortality rate

Fishing mortality rate is a measure of the proportion of fish removed by fishing over a given time (usually a year). For simplicity we may write the catch of fish, C, as proportional to the number of fish in the sea, N;

$$C = EN \qquad (1)$$

where the proportionality constant, E, represents the exploitation rate. It can be shown that the exploitation rate comprises the fishing mortality rate, F, and the natural mortality rate, M, according to the expression;

$$E = \frac{F}{F+M}(1 - e^{-(F+M)}) \qquad (2)$$

If we assume that natural mortality is more or less constant then we can see that the exploitation rate is determined largely by F. In addition, it is worth noting that the fishing mortality rate can be crudely represented by a simple multiple of "selectivity", s, and fishing effort, f;

$$F = sf \qquad (3)$$

The definition of s in equation (3) is rather broad. It includes all factors which affect the "catchability" of fish and really represents the susceptibility of the fish to capture. Clearly codend selectivity will be a major component of this catchability. Fishing effort, as used here, simply means the time over which the target population is exposed to exploitation. It is important to note that if we wish to control fishing mortality then it can be done either by controlling effort or by controlling selectivity.

Since fish generally grow throughout their lives, size is related to age. Thus we may loosely think of a size selectivity ogive as an age selectivity ogive. In other words, the proportion of fish retained in the gear is age dependent. Fishing mortality rate can now be written as;

$$F_a = s_a f \qquad (4)$$

Since s_a lies on an ogive, for any value of f, F_a will lie on a similar ogive. It shows that for a typical towed gear fishery, fishing mortality is expected to be age dependent and this age dependency will be directly related to the selectivity ogive of the gear. Figure 8.1 shows the fishing mortality by age for North Sea whiting. The expected sigmoid relationship can be seen. It is important to appreciate, however, that selectivity as quantified by *s* incorporates other factors such as the spatial distribution of the fish population which may affect the observed selection pattern in such a way that typical codend size selection is obscured.

The fact that age dependent fishing mortality may be directly related to gear selectivity means that it can be managed by altering the selectivity ogive. However, it is important to realise that the extent of the change in the fishing mortality rate will vary across the age range depending on how much the ogive is altered. Figure 8.2 illustrates this property. Fishing mortality rates which remain in the fully selected size range are little affected while those at the younger ages are substantially reduced. By contrast, if effort (f) was altered, the effect would be the same for all age groups. Thus, in general, selectivity properties are most useful for improving the exploitation pattern (i.e. age dependent mortality) of the fishery while effort controls are most useful for controlling the overall exploitation rate.

8.3 Properties of selectivity ogives

It is commonly argued that it is desirable to shift selectivity ogives to the right (i.e. increase L_{50}) in order to protect juvenile fish. It is true that in heavily exploited fish stocks, where juveniles comprise a large part of the catch, there are large gains to be made by allowing more small fish to escape to grow bigger and so augment future catches. For fisheries in this condition, the problem is that too many small fish are caught. However, it is also possible to have a mesh size which is too large. In these circumstances, too many fish escape and die naturally instead of being caught. It is often possible to calculate an optimum mesh size for a particular stock. Figure 8.3 shows the results of a steady state calculation for North Sea whiting which suggests that a mesh size of about 110 mm would be an optimum.

Gears which possess a steep selectivity ogive are sometimes claimed to have "better" selectivity properties than those with a wide selection range. This need not be the case. Steepening the selection curve but retaining the same L_{50} will give more protection to small fish but increases the potential mortality on larger fish which may be undesirable if the spawning stock is already depleted. In addition, steep selectivity curves will tend to exploit a reduced size (and hence age) range of fish which means the catch will be comprised of fewer year classes. This can mean that catches will show greater inter-annual variability.

8.4 Technical and biological interactions

Stock assessment scientists generally make a distinction between technical and biological interactions. Technical interactions are those effects which arise through the use of different gears exploiting the same stock(s). Biological interactions occur through effects such as the predation of one stock on another. Altering gear selectivity can have an effect on both types of interaction.

8.4.1 Technical interactions

Fleets of vessels exploiting the same stock are likely to have differing selectivity properties. Consider the example in Figure 8.4 which shows two different gear types exploiting a cod stock. The two curves to the left show the selectivity for the same mesh size (90 mm) for each gear. Although the curves are similar there is a tendency for gear A to retain a larger proportion of fish at any given length in the selection range. This means that if the effort in fleet A was to increase, fleet B would lose. This is because fleet A effectively catches more of the smaller fish before fleet B has had a chance to catch them. For the same reason, if the effort of fleet B was reduced, the fleet A would benefit in the long run, not fleet B. This a classical technical interaction where there is "sequential" competition between gears.

Also shown in Figure 8.4 is the change in the selectivity if the mesh size was increased to 110 mm. The difference in selectivity between the two gears is now even larger. This means that fleet A will gain from the mesh increase at the expense of fleet B because it retains a lower size range of fish.

8.4.2 Biological interactions

Classical single species theory suggests that if a mesh size is increased in an over-fished stock, there will be long terms gains in yield from the fishery. This is because the smaller fish released by the increased mesh size will grow larger so that more large fish will be retained in the net in future years. This conclusion makes the assumption that the natural mortality of fish is fairly constant and independent of the population of potential predators. Many exploited fish stocks are not only predatory by are also cannibalistic. If a mesh size is increased it will tend to increase the number of larger fish. These are effectively larger predators and they generate a heavier predation effect not only on other fish stocks but on the juveniles of the same stock. This effect tends to counteract the effect of increasing the mesh size by at the same time increasing the natural mortality of the stock. It means the longer term gains of increasing a mesh size are often much smaller than single species analyses would suggest. The mesh change would still, however, result in a change in the size structure of the stock.

8.5 Minimum landing sizes

Many fisheries are subject minimum landing size (MLS) regulations. The intention of an MLS is to discourage fishers from exploiting small fish. Clearly the MLS should in some way relate to the selectivity of a gear (or, of course, vice versa). The choice of MLS is not all that obvious. Figure 8.5 shows a theoretical ogive with the L_{25} and L_{95} retention lengths indicated. If the MLS is set at the L_{95} point then it is clear that a large number of small fish will be retained in the gear which will probably have to be discarded. If the MLS is set at the lower retention length then fishers will lose a large number of fish above the legal size which they could otherwise have sold. This offers a strong incentive to fishers to modify their gear so that the selectivity ogive is shifted to the left and the MLS corresponds to a higher percentage retention length. This would undermine any minimum mesh size regulation.

8.6 The use of selectivity data

In the preceding sections the relationship between fishing mortality and selectivity has been described and the potential conservation properties of improved selectivity discussed. There is a practical question of how to best obtain and use selectivity data in assessments. First of all it is worth briefly considering one of the most common methods for evaluating the effect of a mesh size change on an exploited stock. In essence all that is done is to re-calculate a new set of age dependent fishing mortalities based on the new mesh size using the formula;

$$F_{new}=F_{old}\left(\frac{s_{new}}{s_{old}}\right) \qquad (5)$$

where "old" and "new" refer to the old and new mesh sizes. The parameters, s, are calculated directly from selectivity ogives derived from experiments. The new fishing mortalities can then be used in any assessment model. It is clear that in equation (5) there is an implicit assumption that the observed fishing mortalities correspond to the mesh size quantified by s. If the ratio of selectivity parameters in (5) is not representative of the true operational selectivities in the fishery then subsequent estimates of fishing mortality and the assessment will be in error.

Noting the calculation procedure above, it is of less concern here how best to conduct a selectivity experiment, such as whether a covered codend technique is preferable to a parallel haul method. The main issue is how best to quantify the selectivity characteristics of a fleet. Any fishing fleet will be heterogenous to a greater or lesser degree and even given the same nominal mesh size, the selectivity of the gear will be vessel dependent. Most selectivity experiments are conducted on a very small number of vessels under "ideal" conditions. It is important to know the extent to which measurements made under these conditions are good predictors of selectivity by commercial vessels using the same nominal mesh size. Unfortunately this is a major practical problem. In an ideal world an experimental approach would be to conduct selectivity experiments on a representative sample of each vessel type under a range of conditions. This is clearly impractical and would be vastly expensive. Nevertheless there is a need to bridge the gap between measurements made under controlled conditions and the selectivity of operational fleets. Solving the problem will require ingenuity and will almost certainly need recourse to indirect measurements of selectivity based on the passive dimensions of gears and the size range of fish retained in them. An exploratory analysis is required in order to identify the most promising way forward.

8.7 Selectivity of research vessel sampling gears

Most selectivity experiments concentrate on commercial gears for very obvious reasons. However, there is an important need for selectivity data relating to sampling gears used on research vessels. Many commonly used stock assessment methods rely on research vessel data as a means of calibrating stock size and potentially could be used to estimate mortality rates. The data are used in the form of abundance estimates based on catch per unit effort. It is assumed that an abundance index, u, is proportional to the number of fish in the sea, N, such that;

$$u_a=q_aN_a \qquad (6)$$

where q is a proportionality constant representing the catchability of the fish and a is a subscript for age. Catchability, q, will be size and hence age dependent, and for the reasons discussed above, will be related to the selectivity of the sampling gear. This means that the age dependent abundance estimates are all scaled to a different q which is unknown. Thus using u_a to estimate mortality rates will result in bias because the total mortality over a year, Z, is given by the formula;

$$Z=\ln\left(\frac{N_a}{N_{a+1}}\right) \qquad (7)$$

which on substitution yields;

$$Z = \ln\left(\frac{u_a}{u_{a+1}}\right) + \ln\left(\frac{q_{a+1}}{q_a}\right) \qquad (8)$$

Given that q is unknown, using u to estimate Z will clearly lead to bias unless the log q ratio is zero. This illustrates the importance of estimating the q ratio and could be done with appropriate selectivity data.

8.8 Conclusions

Gear selectivity is a major factor determining the exploitation of a fish stock. Since fish grow throughout their lives modifying the selectivity of the gear will alter the exploitation pattern of the fishery and can lead to improvements in the equilibrium yield expected from the fishery. Managing gear selectivity is therefore an important means of fully exploiting the growth potential of fish. However, because fishing mortality is a product of both fishing effort and selectivity, controlling gear selectivity alone is insufficient to manage a stock at a target exploitation rate.

It is important in fish stock assessment to be able to quantify the expected changes resulting from the implementation of a new gear or mesh size. This requires knowledge of the selectivity characteristics of both the existing gear and the new gear. By necessity most gear selectivity experiments are conducted in somewhat artificial conditions compared to routine fishing operations. There is a need to establish the link between experimental selectivity data and the effective selectivity of commercial fleets.

The degradation of catch data from official statistics as a result of mis-reporting has caused an increasing reliance on research vessels survey data. These data need to be corrected for the effects of size specific selection by the sampling gear. Selectivity information for these gears would be a valuable contribution to the correction of potential bias.

9 References

Anon. 1964. Report of the Mesh Selection Working Group 1959-60. ICES Coop. Res. Rep. 2.

Anon. 1986. Council Regulation (EEC) No. 3094/86 laying down certain technical measures for the conservation of fishery resources. Official Journal of the European Communities No. L288/1.

Anon. 1992a. Report from FTFB Subgroup : Evaluation of source of variability in the fishing power of the GOV trawl. Int. Coun. Explor. Sea CM 1992/B:39.

Anon. 1992b. Manual for the International Bottom Trawl Surveys. Rev. IV. Addendum to ICES CM 1992/H:3.

Anon. 1992c. Multilingual Dictionary of Fishing Gear. 2nd ed. Fishing News Books, Oxford and Office for Official Publications of the European Communities, Luxembourg, 333 pp.

Anon. 1992d. Multilingual Dictionary of Fishing Vessels and Safety on Board. 2nd ed. Fishing News Books, Oxford and Office for Official Publications of the European Communities, Luxembourg, 947 pp.

Anon. 1995. Admiralty List of Radio Signals. Vol. 3. NP 283. Hydrographer of the Navy, Taunton, UK.

Barlow, R.E.D., Bartholomew, J., Bremner, J.M. and Brunk, H.D. 1972. Statistical inference under order restrictions. Wiley. 388 p.

Beverton, R.J.H., and Holt, S.J. 1957. On the dynamics of exploited fish populations. Fish. Invest. London Ser. 2, 19:533 pp.

Brandt, A. von, and Carrothers, P.J.G. 1964. Test methods for fishing gear materials (twines and netting). In: H. Kristjonsson (Ed), Modern Fishing Gear of the World. Vol. 2. Fishing News Books, Farnham.

Bridger, J. P., Foster, J. J., Margetts, A. R., and Strange, E. S. 1981. Glossary of United Kingdom Fishing Gear Terms. Fishing News Books Ltd, Farnham, 115 pp.

Buja, A., Hastie, T., and Tibshirani, R. 1989. Linear smoothers and additive models (with discussion). Ann. Statist. 17: 453-555.

Cadigan, N.G., and Millar, R.B. 1992. The reliability of selection curves obtained from trouser trawl or alternate haul studies. Can. J. Fish. Aquat. Sci. 49: 1624-1632.

Chopin, F. 1988. The design and testing of two 1:3 scale commercial trawls fitted with separator panels. Final Report on contract FP111-7-0585/01-OSC to Fisheries Development and Fishermen's Services Division, PO Box 550, Halifax, Nova Scotia, Canada, B3J 2S7.

Clark, J.R. 1957. Effect of length of haul on codend escapement. ICNAF/ICES/FAO workshop on selectivity, Lisbon. Paper S25.

Cleveland, W.S., and Devlin, S.J. 1988. Locally-weighted regression: an approach to regression analysis by local fitting. J. Amer. Stat. Ass. 83: 596-610.

Collet, D. 1991. Modelling binary data. Chapman and Hall, London. 369 pp.

ConStat, 1995. CC selectivity. Grønspættevej 10, DK-9800 Hjørring, Denmark.

Cooper, C.G. 1993. Experiments with different grate designs in a silver hake trawl. DFO, Industry Services and Native Fisheries, Scotia-Fundy Region, Nova Scotia, Can. Project Summary No 45/1993.

Cooper, C.G., and Hickey, W.M. 1989. Selectivity experiments with square mesh codends of 130, 140 and 155 mm. Fisheries Development and Fishermen's Services Division, PO Box 550, Halifax, Nova Scotia, Canada, B3J 2S7, Project Report 154:154p.

Dahm, E. 1974. Zur Messung der Biegesteifigkeit schwerer Trawlnetzgarne. (On the measurement of the flexural stiffness of heavy trawlnet twines). Protokolle Fischereitechnik, XIII, 62:289-302. Also Scot. Fish. Res. Trans. 151.

Davies, F. M. 1934. Size limits and mesh regulations for sea fish: Appendix B - report on the results of experiments with savings gear. Appendix C - a mesh experiment indicating that small fish escape while the trawl is being towed. Appendix D - Preliminary note on a commercial mesh experiment. Rapports et Proces-verbaux des reunions, Conseil Permanent International pour l'Exploration de la Mer. 90(5) 14-31.

Dempster, A.P., Laird, N.M., and Rubin, D.B. 1977. Maximum likelihood from incomplete data via the EM algorithm. J. R. Stat. Soc. B39: 1-38.

Feller, W. 1968. An introduction to probability theory and its applications, volume I, 3rd edition. Wiley, New York.

Ferro, R.S.T. 1989. Objective measurement of the thickness of netting twine used in the fishing industry. Fish.Res., 8:103-112.

Ferro, R.S.T., and O'Neill, F.G. 1994a. An overview of the characteristics of twines and netting that may change selectivity. ICES CM 1994/B:35.

Ferro, R.S.T., and O'Neill, F.G. 1994b. An overview of methods of measuring twine and netting characteristics and mesh size. ICES CM 1994/B:36.

Ferro, R.S.T., and Stewart, P.A.M. 1990. The analysis of catch comparison data. ICES CM 1990/B:34.

Ferro, R.S.T., and Xu, L. 1996. An investigation of three methods of mesh size measurement. *Fisheries Research*, 25(2), 171-190.

Fryer, R.J. 1991. A model of between-haul variation in selectivity. ICES J. Mar. Sci. 48: 281-290.

Fryer, R.J. 1996. The power of codend selectivity trials (in prep.)

Fryer, R.J., and Shepherd, J.G. 1995. Models of codend size selection. J. Northw. Atl. Fish. Sci. (in press).

Galbraith, D.K., Fryer, R.J., and Maitland, K.M.S., 1994. Demersal pair trawl codend selectivity models. Fish. Res. 20: 13-27.

Glass, C.W., and Wardle, C.S. 1989. Comparison of the reactions of fish to a trawl gear, at high and low light intensities. Fisheries Research, 7:249-266.

Glass, C.W., and Wardle, C.S. 1995. Studies on the use of visual stimuli to control fish escape from codends II The effect of a black tunnel on the reaction behaviour of fish in otter trawl codends. Fisheries Research, 23 165-174.

Glass, C.W., Wardle, C.S., and Gosden, S.J. 1993. Behavioural studies of the principles underlying mesh penetration by fish. ICES mar. Sci. Symp., 196:92-97.

Hamley, J.M. 1975. Review of gillnet selectivity. J. Fish. Res. Bd. Can. 32:1943-1969.

Hastie, T., and Tibshirani, R. 1990. Generalised additive models. Chapman and Hall, London.

Hillis, J.P., and Early, J.J. 1982. Selectivity in the *Nephrops* trawl. ICES CM1982/B:19.

HMSO, 1969. Marine Observer's Handbook. 9th edition. Met.0.522, HMSO, London.

Hodder, V.M., and May, A.W. 1964. The effect of catch size on the selectivity of otter trawls. ICNAF Res. Bull. 1.

Hughes, S.E. 1976. System for sampling large trawl catches of research vessels. J. Fish. Res. Board Can. 33:833-839.

Hunter, C.J., and Wheeler, C.O. 1972. Device for measuring length and girth of fish. J. Fish. Res. Board Can. 29 (12):1784-1785.

International Standards Organisation, 1974. Fishing nets - Netting - Basic terms and definitions. ISO 1107.

International Standards Organisation, 1976. Determination of elongation of netting yarns. ISO 3790.

Isaksen, B. 1995. Report of the study group on unaccounted mortality in fisheries. ICES CM 1995/B:1.

Isaksen, B., and Valdemarsen, J.W. 1987. Selectivity of codends with shortened top panels. Institute of Fishery Technology Research, Bergen. Unpublished typescript in Norwegian.

Isaksen, B., and Valdemarsen, J.W. 1990. Selectivity in codends with short lastridge ropes. ICES CM 1990/B:46

Isaksen, B., Olsen, S., and Valdemarsen, J .W. 1989. How does a round fish experience a given scientific mesh size? Summary in ICES CM 1989/B:42.

Isaksen, B., Valdemarsen, J.W., Larsen, R.B., and Karlsen, L. 1992. Reduction of fish bycatch in shrimp trawl using a rigid separator grid in the aft belly. Fish. Res. 13:335-352.

John, P.W.M. 1971. Statistical design and analysis of experiments. Macmillan Co, New York.

Jones, R.H. 1993. Longitudinal data with serial correlation: a state-space approach. Chapman and Hall, London.

Kimura, D.K. 1978. Logistic model for estimating selection ogives from catches of codends whose ogives overlap. J. Cons. int. Explor. Mer, 38: 116-119.

Kirkwood, G.P., and Walker, T.I. 1986. Gill net mesh selectivities for Gummy Shark, *Mustelus antarticus* Günther, taken in south-eastern Australian waters. Aust. J. Mar. Fresh. Res. 37: 689-697.

Klust, G. 1982. Netting materials for fishing gear. 2nd ed. Fishing News Books Ltd, Farnham, 175 pp.

Korn, E.L., and Whittimore, A.S. 1979. Methods for analyzing panel studies of acute health effects of air pollution. Biometrics, 35: 795-802.

Laird, N. M., and Ware, J.H. 1982. Random-effects models for longitudinal data. Biometrics, 38: 963-974.

Larsen, R.B., and Isaksen, B. 1993. Size selectivity of rigid sorting grids in bottom trawls for Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). ICES Mar. Sci. Symp. 196:178-182.

Lehmann, E.L. 1983. Theory of point estimation. Wiley, New York.

Lowry, N., and Robertson, J.H.B. 1995. The effect of twine thickness on codend selectivity of trawls for haddock in the North Sea. Fisheries Research (In press).

Madsen, N., and Moth-Poulsen, T. 1994. Measurement of the selectivity of *Nephrops* and demersal roundfish species in conventional and square mesh panel codends in the northern North Sea. ICES CM 1994/B:14.

Manly, B.F.J., McDonald, L.L., and Thomas, D.L. 1993. Resource selection by animals: statistical design and analysis for field studies. Chapman and Hall, London.

McCullagh, P., and Nelder, J.A. 1989. Generalised linear models, 2nd edition. Chapman and Hall, London. 511 p.

Millar, R.B. 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. JASA 87: 962-968.

Millar, R.B. 1993a. Analysis of trawl selectivity studies (addendum): implementation in SAS. Fish. Res. 17: 373-377.

Millar, R.B. 1993b. Incorporation of between-haul variation using bootstrapping and nonpara-metric estimation of selection curves. Fish. Bull. 91: 564-572.

Millar, R.B. 1994. Sampling from trawl gears used in size selectivity experiments. ICES J. mar. Sci. 51: 293-298.

Millar, R.B. 1995. The functional form of hook and gillnet selection curves can not be determined from comparative catch data alone. Can. J. Fish. Aquat. Sci. In press.

Millar, R.B., and Cardigan, N.G. 1991. A FORTRAN program for fitting selectivity curves to trouser trawl data. Can. Tech. Rep. Fish. Aquat. Sci. 1783: iii + 19 p.

Millar, R.B., and Walsh, S.J. 1990. Analysis of trawl selectivity studies with an application to trouser trawls. ICES C.M. 1990/B:14

Millar, R.B., and Walsh, S.J. 1992. Analysis of trawl selectivity studies with an application to trouser trawls. Fish. Res. 13: 205-220.

Numerical Algorithms Group. 1991. NAG library manual, mark 15. Numerical Algorithms Group, Oxford.

O'Neill, F.G., and Xu, L. 1994. Twine flexural rigidity and mesh resistance to opening. ICES CM 1994/B:31.

Polet, H., and Redant, F. 1994. Selectivity experiments in the Belgian Norway lobster (*Nephrops norvegicus*) fishery. ICES CM 1994/B:39.

Pope, J.A., Margetts, A.R., Hamley, J.M., and Akyuz, E.F. 1975. Manual of methods for fish stock assessment Part III Selectivity of fishing gear. FAO Fish. Tech. Pap. (41) Rev. 1.

Reeves, S.A., Armstrong, D.W., Fryer, R. J., and Coull, K. A. 1992. The effects of mesh size, codend extension length and codend diameter on the selectivity of Scottish trawls and seines. ICES J. Mar. Sci. 49:279-288.

Robertson, J.H.B. 1993. Design and fitting of square mesh windows in whitefish and prawn trawls and seine nets. Scot. Fish. Inf. Pamph. 20.

Robertson, J.H.B., and Stewart, P.A.M. 1988. A comparison of size selection of haddock and whiting by square and diamond mesh codends. J. Cons. int. Expl. Mer 44:148-161.

Robinson, D.L. 1987. Estimation and the use of variance components. Statistician, 36: 3-14.

Sangster, G.I. 1994. Report of the sub-group on methodology of fish survival experiments. ICES CM 1994/B:8.

Sangster, G.I., Lehmann, K., and Breen, M. 1996. Commercial fishing experiments to assess the survival of haddock and whiting after escape from four size of diamond mesh codends. *Fisheries Research,* FISO 25/3-4, pp 323-346, March 1996.

Schmoyer, R.L. 1984. Sigmoidally constrained maximum likelihood estimation in quantal bioassay. JASA 79: 448-453.

Shevtsov, S.E. 1979. The effect of twine thickness and the size of the catch on the selectivity of trawl codends. Ryb. Khoz. Issled. Bass. Balt. Morya, 14:140-154.

Simpson, D.G. 1989. Codend selection of winter flounder *Pseudopleuronectes americanus.* NOAA technical report NMFS 75. 10 p.

Skalski, J.R., and Perez-Comas, J.A. 1993. Non-parametric maximum likelihood estimation of mesh size selectivity. Fish. Res., 18: 321-334.

Soldal, A.V., and Isaksen, B. 1993. Survival of gadoids that escape from a demersal trawl. ICES Mar. Sci. Sym., 196, 122-127.

Stewart, P.A.M., and Robertson, J.H.B. 1985. Small mesh covers. Scot.Fish. Res. Rep. 32.

Stiratelli, R., Laird, N.M., and Ware, J.H. 1984. Random-effects models for serial observations with binary response. Biometrics, 40: 961-971.

Suuronen, P., and Millar, R.B. 1992. Size selectivity of diamond and square mesh codends in pelagic herring trawls: only small herring will notice the difference. Can. J. Fish. Aquat. Sci, 49: 2104-2117.

Suuronen, P., Lehtonen, E., and Tschernij, V. 1993. Possibilities to increase the size selectivity of a herring trawl by using a rigid sorting grid. NAFO SCR Doc 93/119, serial no N2313.

Suuronen, P., Millar, R.B., and Jarvik, A. 1991. Selectivity of diamond and hexagonal mesh codends in pelagic herring trawls: evidence of a catch size effect. Finnish Fish. Res., 12:143-156.

Templeman, W. 1963. Otter trawl covered codend and alternative haul mesh selection experiments on redfish, haddock, cod, American plaice and witch flounder: Girth measurements of haddock, cod and redfish and meshing of redfish in the Newfoundland area. ICNAF Special publication 5, 2 The selectivity of fishing gear: 201-217.

Walsh, S.J., Koeller, P.A., and McKone, W.D. 1993. Proceedings of the International Workshop on Survey Trawl Mensuration, Northwest Atlantic Fisheries Centre, St John's, Newfoundland, March 18-19,1991. Can. Tech. Rep. Fish. Aq. Sci., No 1911.

Wardle, C.S. 1989. Understanding fish behaviour can lead to more selective fishing gears. In proceedings, World Symposium on fishing gear and fishing vessel design, 1988:12-18. Published by The Newfoundland and Labrador Institute of Fisheries and Marine Technology, St Johns, Canada.

Wardle, C.S. 1993. Fish behaviour and fishing gear. Behaviour of Teleost Fishes. Chapman and Hall.

Watson, J.W., Mitchell, J.F., and Shah, A.K. 1986 Trawling efficiency device: a new concept for selective shrimp trawling gear. Mar. Fish. Rev. 48:9pp.

Westhoff, C.J.W., Pope, J.A., and Beverton, R.J.H. 1962. The ICES mesh gauge, ICES.

Wileman, D.A. 1992. Codend selectivity: Updated review of available data. Final Report under Study Contract 1991/15 for Commission of the European Communities, Directorate General for Fisheries. DIFTA, North Sea Centre, P.O. Box 59, DK-9850 Hirtshals, Denmark.

Wydoski, R.S., and Wolfert, D.R. 1968. An improved girthometer for studies of gillnet selection. The Progressive Fish Culturist. Jan. 1968.

Xu, X., and Millar, R.B. 1993. Estimation of trap selectivity for male snow crab *(Chionoecetes opilio)* using the SELECT modelling approach with unequal sampling effort. Can. J. Fish. Aquat. Sci. 50: 2485-2490.

10 Glossary

10.1 Gear and vessel terms

backstrop	The short rope system, usually of wire or chain, permanently attached to the rear of the otter board and connecting it to the sweep or bridles.
beam length	According to latest EU regulations to be measured from inner edge of starboard shoe to inner edge of port shoe.
belly	Series of sections of the trawl between lower wings and extension piece.
belly length	Length of that part of the trawl between the centre of the footrope and the start of the extension or codend.
bollard pull	Maximum towing force of a ship displayed under static conditions.
braided twine	Netting twine obtained by interlacing three or more strands in such a way that they cross each other in diagonal direction to the edge of the fabric.
bridle	The ropes (two or more per side) usually of wire, linking the trawl or seine wingends to the sweep or backstrops.
bycatch	That part of the catch which is not the targeted species.
carapace length	For Crustaceans the distance between base of eye socket and mid dorsal distal edge of carapace.
chafer	Replaceable material (hides, old netting etc.) fixed to the codend for protection against chafing on the sea bed.
codend	The rearmost part of the trawl, having either a cylindrical shape, i.e. the same circumference throughout, or a taper-ing shape. Made up of one or more panels (pieces of netting) of the same mesh size attached to one another along their sides in the axis of the trawl by a seam where a side rope may be attached.
codline	A rope making it possible to close the rear of the codend and/or strengthening bags by means of either a knot which can be easily loosened or a mechanical device.
Danish (anchor) seine	A seine incorporating a funnel-shaped net (with wings and

codend) and very long ropes set out on the sea bed and hauled to an anchored vessel in the open sea.

diamond mesh	Normal rhomboid shape of meshes in sheet netting.
discard rate	That fraction of the catch that consists of species and/or sizes that is not retained for sale but rejected at sea.
engine power	Mechanical power (engine break power) of the ship's engine usually expressed in hp or kW.
extension (or codend extension or extension piece)	Sections of netting between belly and codend. May be tapered but the taper should be much lower than that of the belly (see Figure 10.1).
fishing circle	Stretched circumference of a trawl or seine expressed as the number of meshes round at the centre of the front edge of the belly multiplied by the mesh length.
fishing line	In a trawl or seine the main frame rope along the leading edge of the lower panel.
fishing power	The ability of a gear to catch fish of given species and length class. Usually a relative measure comparing different gears (to a standard).
flapper	A piece of netting with a mesh size at least equal to that of the codend, fastened inside a trawl in such a way that it allows catches to pass from the front to the rear of the trawl but limits their possible return.
flexural stiffness	Resistance of a twine to lateral or bending deformation. It may be defined as the force required to cause a unit of bending deflection.
grid	Structure made of parallel bars used to separate fish of different size.
groundrope	Connected sections of rope, usually of wire or chain, protected with rope rounding or rubber discs or various types of bobbins, attached to and in front of the fishing line, to shield the lower leading margin of a bottom trawl from ground damage whilst maintaining ground contact.
GRT	Gross register tonnage (measure of the overall size of a ship determined in accordance with the provisions of the International Convention on Tonnage Measurement of Ships).
hauling time	Time when the ship starts hauling the gear e.g. at the first move of the warp winch.
headline	The principal upper frame rope of a net to which the netting is attached.
knotless netting	Netting made by machine from yarns which are interlaced at intervals to form meshes.
length overall	The total length from the foremost to the aftermost points of a vessel's hull.
lifting strop	A piece of rope or wire loosely encircling the circumference of the codend or the strengthening bag, if any, and attached to it by means of loops or rings. More than one lifting strop may be used at any time. Its purpose is to make it possible to close off the codend in order to facilitate its loading aboard.
linear density	Mass per unit length of a twine. Expressed in tex (mass in grams per 1000 m)
mesh length	a) For knotted netting, the distance between the centres of two opposite knots in the same mesh fully extended in the N-direction. The N-direction is the direction at right angles (Normal) to the general course of the netting. b) For knotless netting, the distance between the centres of two opposite joints in the same mesh when fully extended along its longest possible axis.

mesh opening	a) For knotted netting, the inside distance between two opposite knots in the same mesh fully extended in the N-direction. The N-direction is the direction at right angles (Normal) to the general course of the netting. b) For knotless netting, the inside distance between two opposite joints in the same mesh when fully extended along its longest possible axis.
monofilament	A coarse filament with larger diameter and stiffness and a wiry character. Mostly with a circular cross section and diameters between 0.1 and 1.0 mm or more. A number of filaments may be twisted together to form a twine.
multifilament	Twine consisting of a number of continuous filaments. Continuous filaments are fibres of indefinite, practically infinite length. Continuous filaments have a silky like appearance and are produced in different degrees of fineness, generally much thinner than 0.05 mm diameter.
nozzle	Circular device enclosing the propeller of a ship to increase thrust at low speeds.
otterboards	Shearing devices, two of which hold open horizontally the wings and mouth of a trawl.
pair seine	A seine towed between 2 vessels in a similar way to a pair trawl but using long seine ropes instead of warps between the vessel and the sweep or bridles.
power block	A mechanized pulley to haul in nets, purse seine, etc.
propeller pitch	The distance a propeller will advance during one revolution when revolving in any unyielding medium. With a variable pitch propeller the blades can be controlled to vary the pitch.
Scottish seine	A type of seine net which is set from a free-floating marker buoy. When the vessel has reached the buoy again, it is lifted aboard, the two ends of the seine ropes are connected to the winch and dragging and hauling begins from the forward-moving vessel (fly dragging).
selvedge	The bulky seam formed by gathering together adjacent side margins, several meshes wide, of two panels of a net and lacing them together.
selvedge rope	Load-bearing rope fixed down the length of selvedge.
shooting hatch	An opening, generally rectangular, in the stern of a fully shelter-decked vessel affording shooting of the gear.
shooting time	Time when the fishing gear is shot. Ideally this is the time when the gear is fully operational on the sea bottom or in its final shape in pelagic fishing. For simplicity reasons often the time is recorded when the full warp length required has been shot and when the winch stops turning.
split fibre	Fibre originating from oriented plastic tapes (films) which are stretched during manufacture by such a high draw-ratio that the tapes split longitudinally when twisted under tension. May also be obtained by mechanically fibrillating film tapes.
square	Section of top panel between headline and upper belly.
square mesh	Mesh shape originating from mounting netting with 45° deviation from the N-direction such that the bars run parallel and at 90° to the trawl axis.
square mesh window	Rectangular piece of netting with square meshes, inserted into a codend or net of rhomboid meshes, usually into the upper panel in order to increase the release of fish.
staple fibre	Discontinuous fibres, usually prepared by cutting filaments into

lengths suitable for the yarn spinning process. Their fineness is similar to that of continuous filaments, their length generally ranges from 40 mm to 120 mm, or more.

strengthening bag	A cylindrical piece of netting completely surrounding the codend of a trawl and which may be attached to the codend at intervals. It shall have at least the same dimensions (length and width) as that part of the codend to which it is attached. Its purpose is to strengthen the codend and to prevent it from bursting when filled with fish and when the trawl is hauled on board.
sweep	The single rope, usually of wire, designed to sweep the sea bed. Located between the otterboard backstrops or towing warps (pair trawling) or seine rope and the bridles of a trawl or seine. If there are no bridles the sweep connects to a pole/dan leno system or directly to the trawl wingends.
twisted twine	Twine resulting from a twisting process of two or more yarns or strands.
warp	Long flexible steel rope connecting vessel (trawler) to the otterboards or in the case of pair trawling to the sweeps or bridles.
window	Rectangular piece of netting (usually in square meshes) inserted into a codend or net of diamond meshes, usually into the upper panel to increase the release of fish. See also "square mesh window".

Further explanations and definitions of terms can be found in Anon., 1992c, Anon., 1992d, Bridger *et al.,* 1981 and Klust 1982.

10.2 Statistical terms and symbols

a,b	parameters of a two-parameter selection curve
$\hat{a}$	estimate of parameter a
deviance	equivalent to the likelihood ratio test statistic and used for goodness of fit tests and hypothesis tests of competing models
d.o.f.	degrees of freedom
$\log_e(\cdot)$	natural log
logit$(\cdot)$	for any number ρ between 0 and 1, we define logit$(\rho) = \log_e \left(\frac{p}{1-p}\right)$
l_x	the length at which retention is x%. That is $r(l_x) = x/100$. In particular l_{50} is the length of 50% retention
n_{l1}	number of length l fish caught in the test codend
n_{l2}	number of length l fish caught in the control codend (cover or small mesh codend)
n_{l+}	total number of length l fish caught, $n_{l+} = n_{l1} + n_{l2}$
p	relative fishing power of the test codend, the probability that a fish entered the test codend given that it entered the combined (test and control) gear
p_1	sampling fraction in the test codend
p_2	sampling fraction in the control codend
q	ratio of sampling fractions, $q = p_1 / p_2$
probit$(\cdot)$	the inverse of the cumulative distribution function of a standard normal random variable
$r(\cdot)$	the selection curve, that is, $r(l)$ is the retention probability of a length l fish
s.e.	standard error
SR	selection range, $SR = l_{75} - l_{25}$
y_l	proportion of length l fish caught that were in the test codend, $y_l = n_{l1} / n_{l+}$

δ	asymmetry parameter in Richards selection curve
Σ_l	summation over all length classes
$\phi(\cdot)$	the curve fitted to "paired gear" data, that is, $\phi(l)$ is the probability that a length l fish will be in the test codend catch (given that it is in the combined catches of the pair of gears)
χ^2	chi-square

Figures

to

Manual of methods of measuring the selectivity of towed fishing gears

List of figures

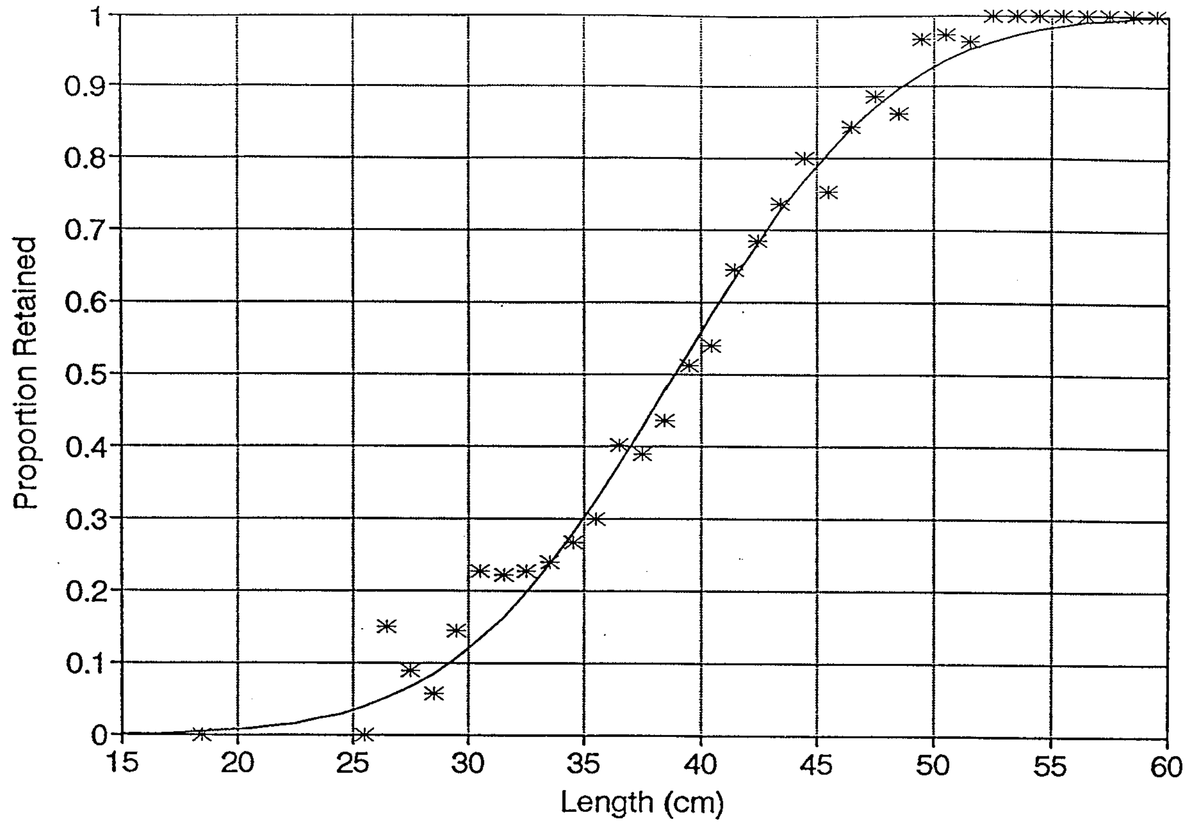


Figure 1.2.3. Example of a codend mesh selection curve.

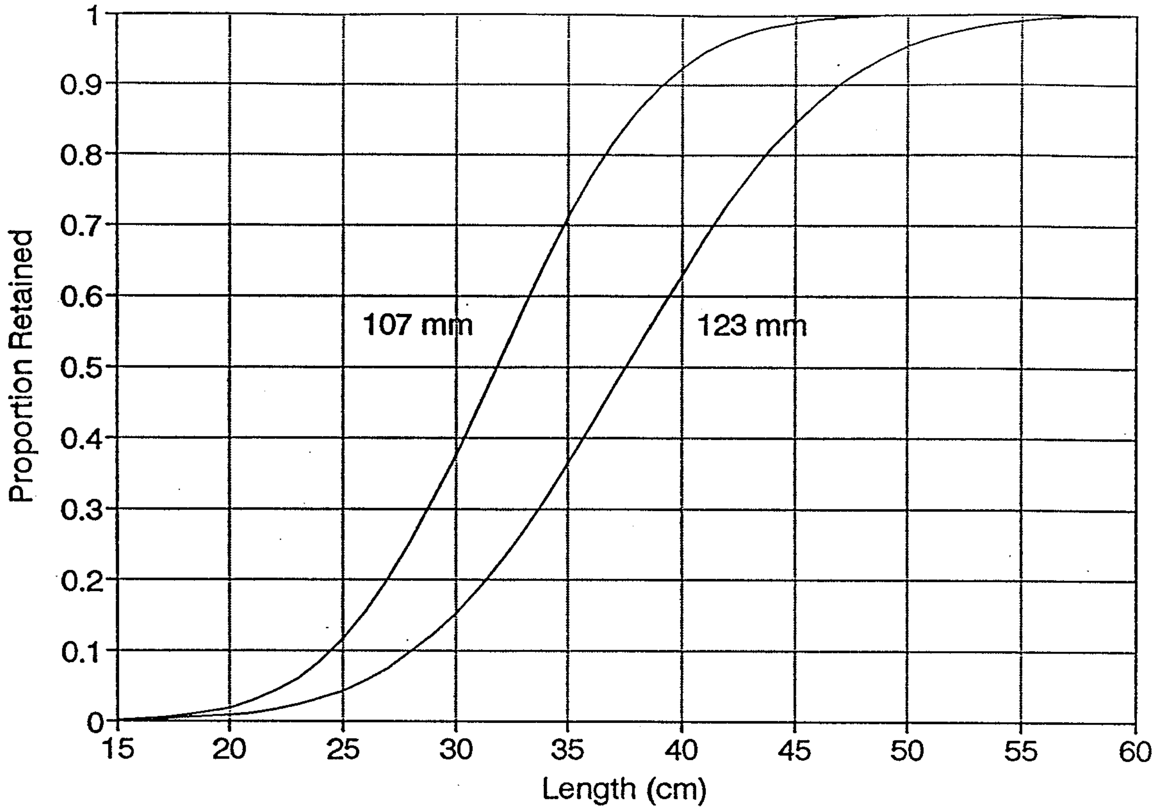


Figure 1.2.5. Example of change in codend mesh selection curve on increasing codend mesh size.

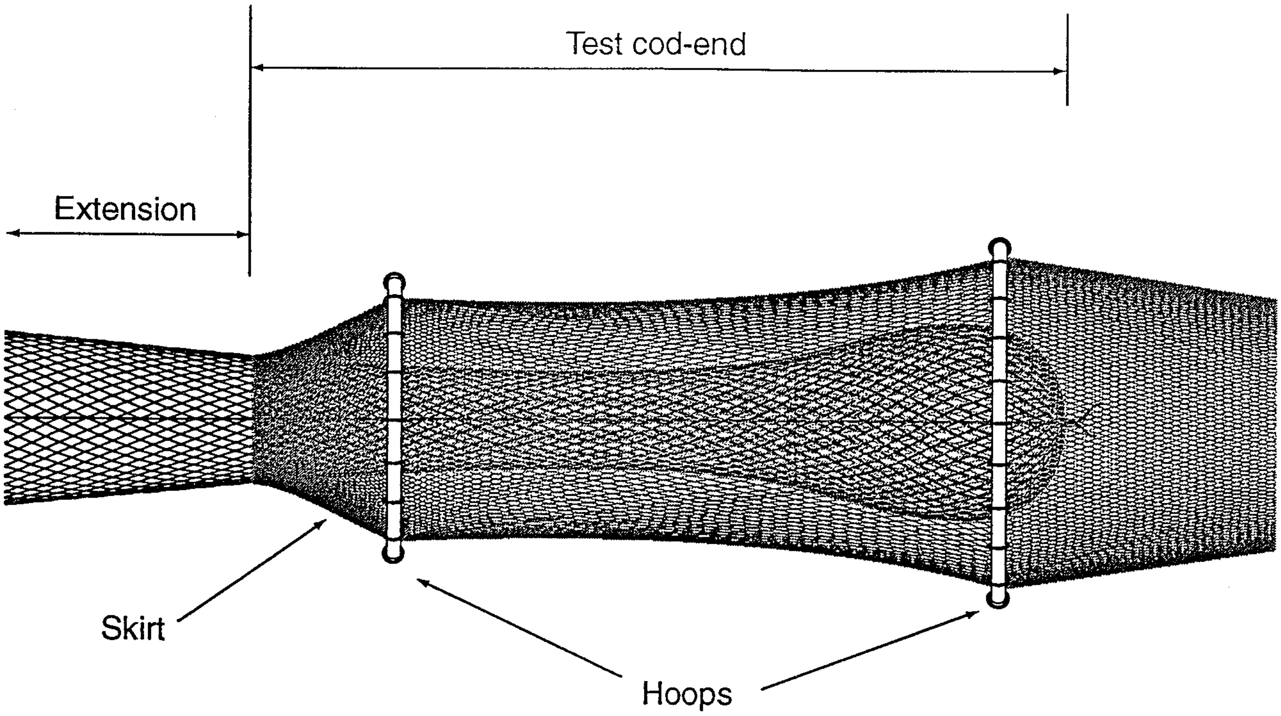


Figure 2.1.1. Schematic diagram of covered cod-end.

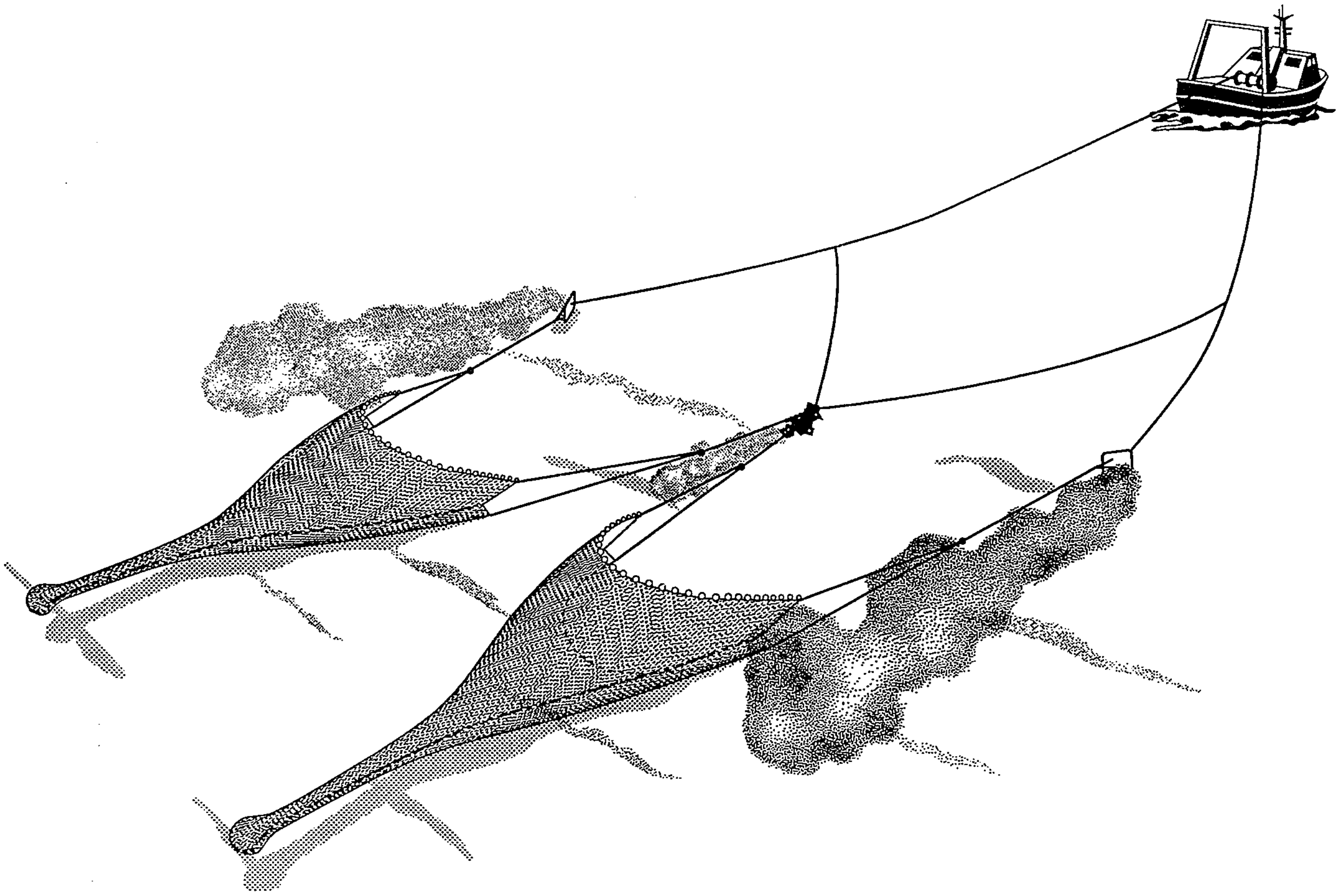


Figure 2.1.4 Schematic diagram of twin trawl

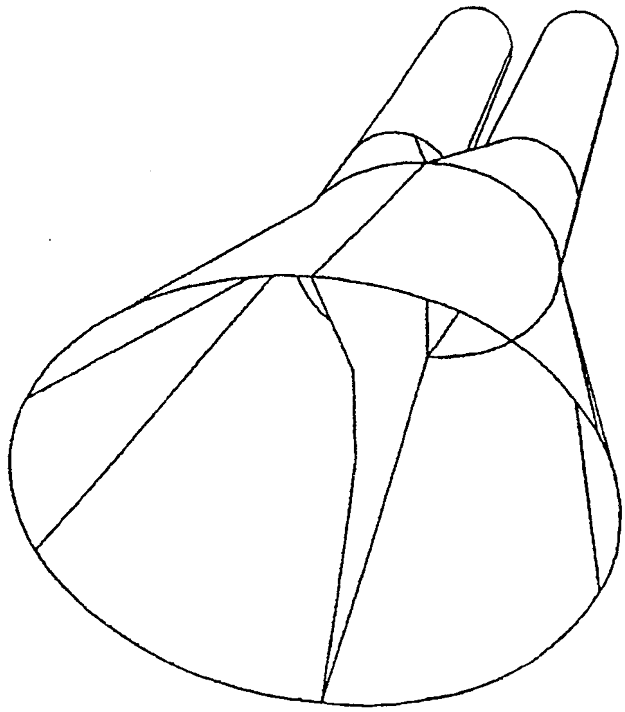


Figure 2.1.5a Schematic diagram of trouser trawl - a single net with a vertical dividing panel and two cod-ends

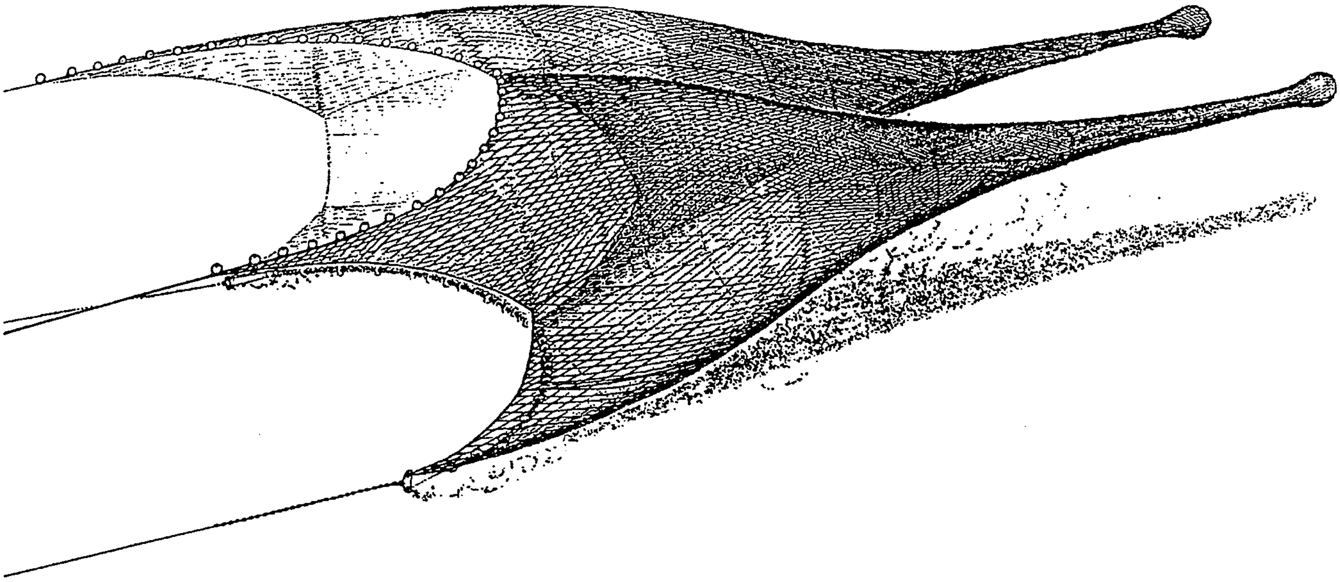


Figure 2.1.5b Schematic diagram of divided or siamese trawl - two nets hung on a single headline and groundrope

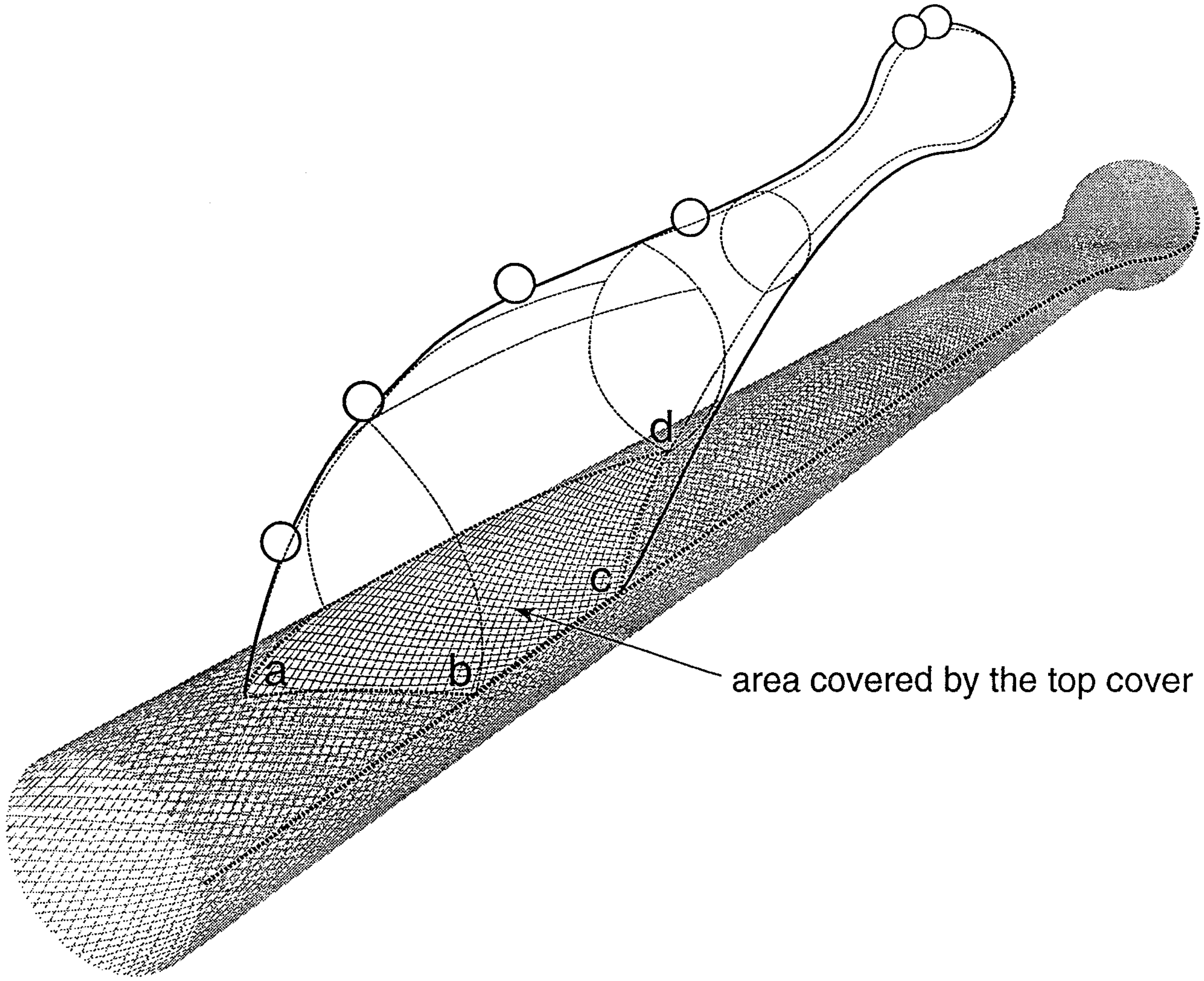
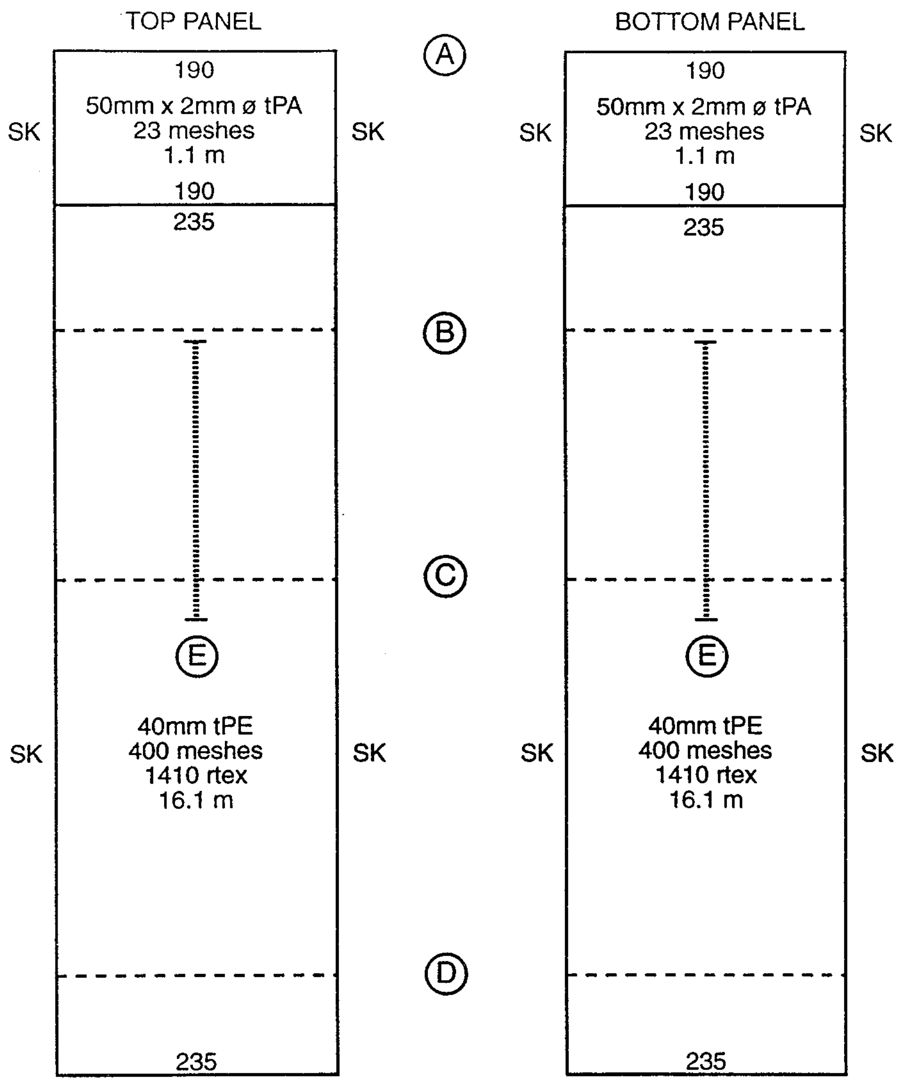


Figure 2.1.6 Schematic diagram of top cover over a window



NOTES

(A) 1 row deep of a larger mesh size to simplify joining to net

(B) Forward hoop is 1.76 m from forward end

(C) Aft hoop is 5.48 m from forward end. Both hoops held in position by 26 x 125 mm cod-end rings spaced evenly around the cover

(D) Lifting bag join (200 mm twisted nylon 6 mm ø x 17 rows x 89 meshes round)

(E) 6.1 m long zip starts 1.78 m down from forward end, positioned in the middle of each panel

There are 14 full meshes gathered into each selvedge (7 from each panel)

Figure 4.2.1.2 Design of 2 panel 40 mm small mesh cover used for 6 m long cod-end of 10 m stretched width (not to scale)

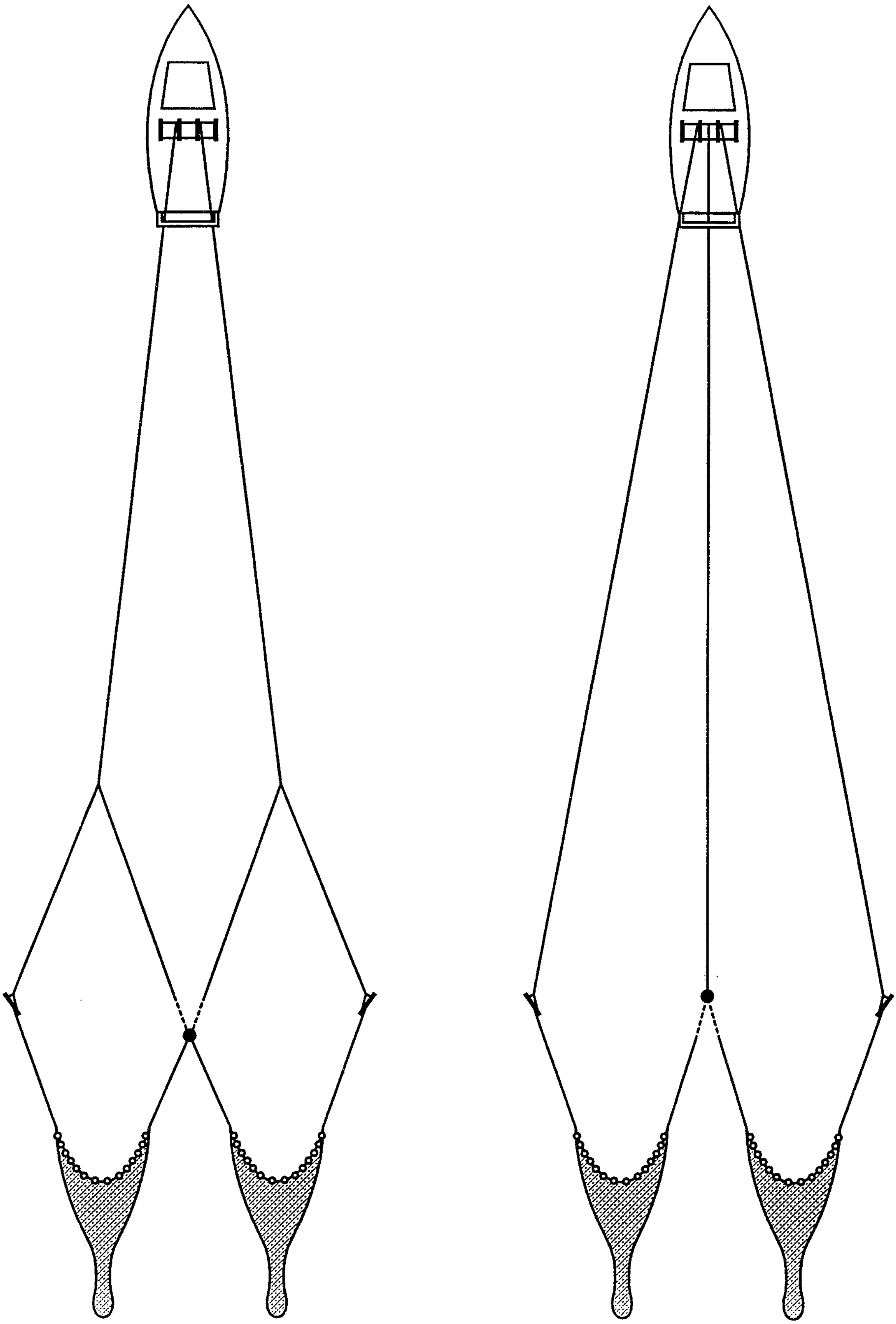


Figure 4.2.4.3a Two and three warp rigs for twin trawl

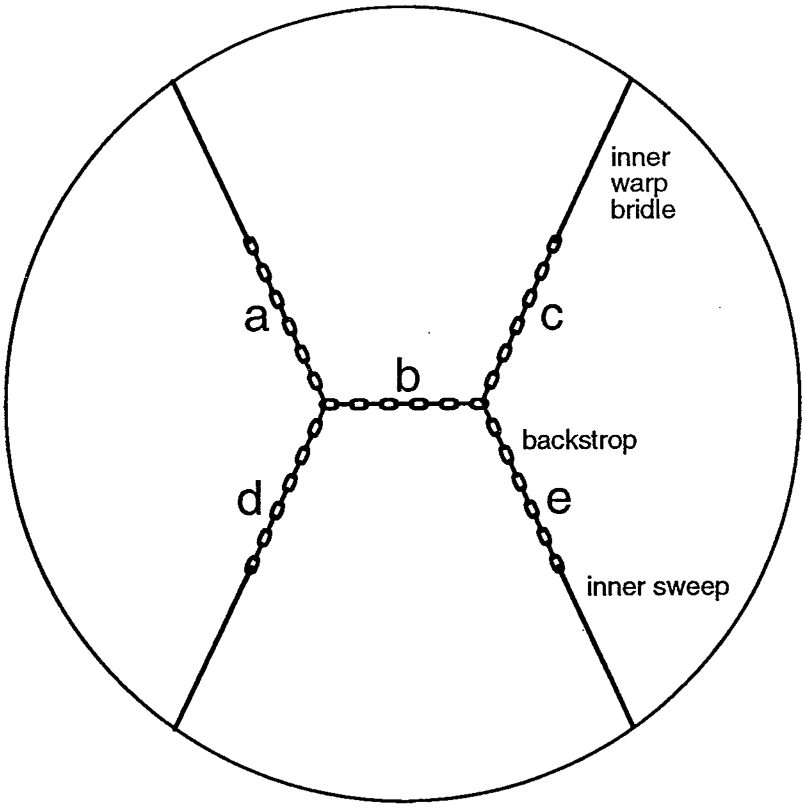


Figure 4.2.4.3b Alternative rig for chain weight in two warp twin trawl system

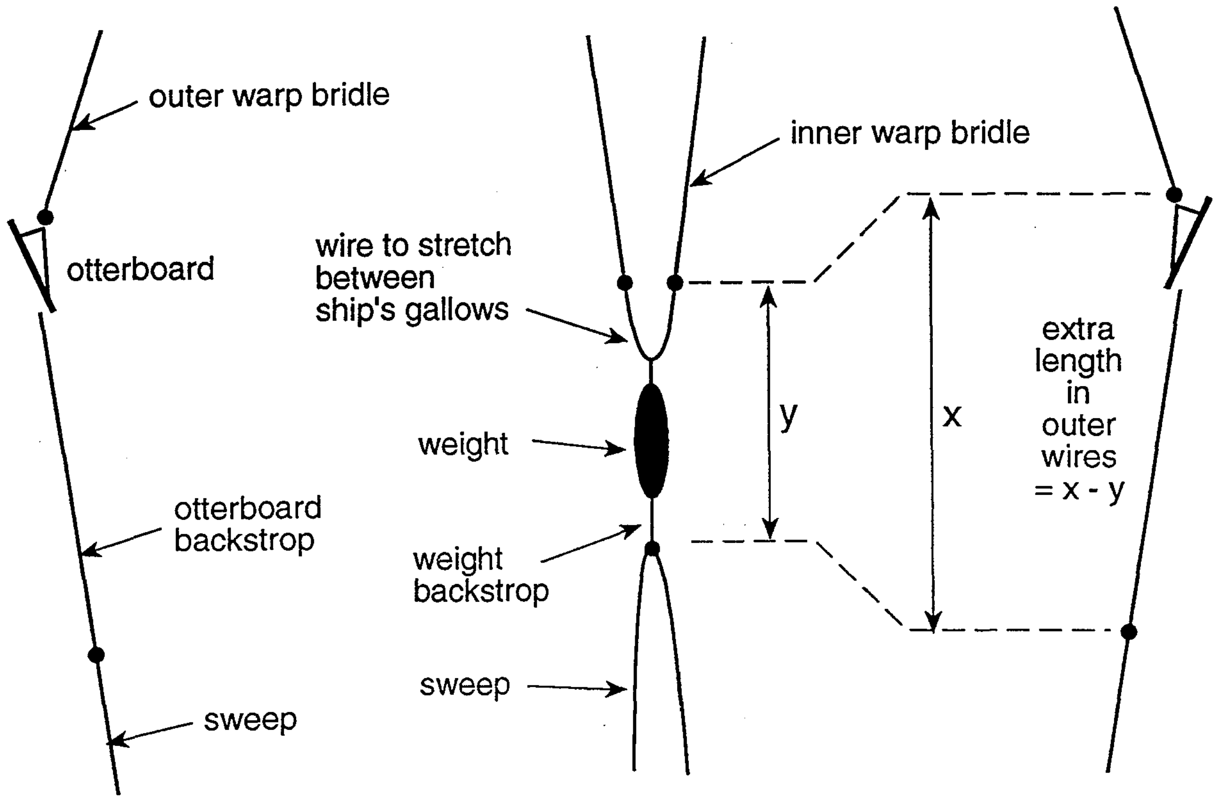


Figure 4.2.4.3c. Detail of otterboard and centre weight to show extra length needed in outer wires of a two warp twin trawl rig.

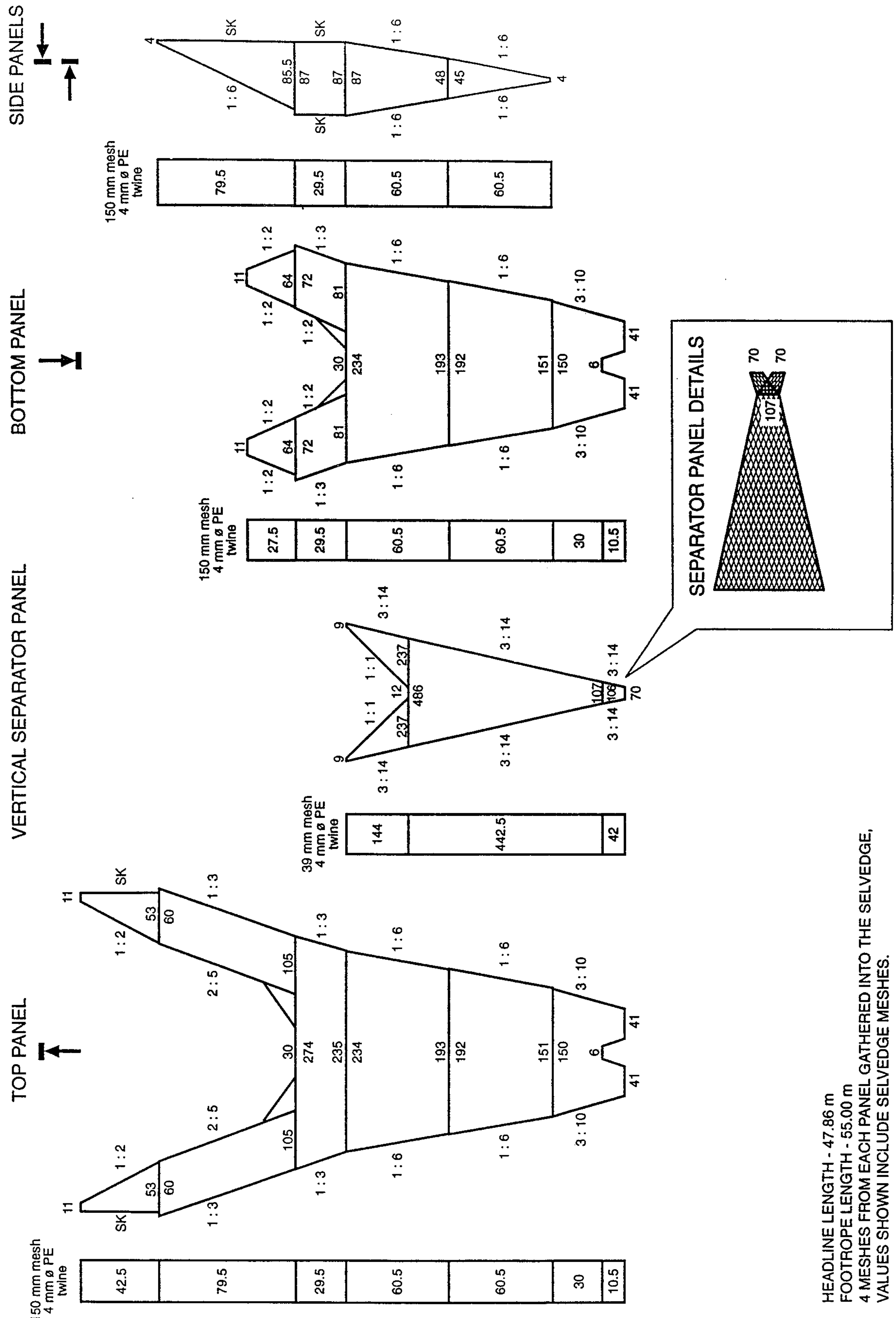


Figure 4.2.5.2 Example of a specification for a trouser trawl with vertical dividing panel

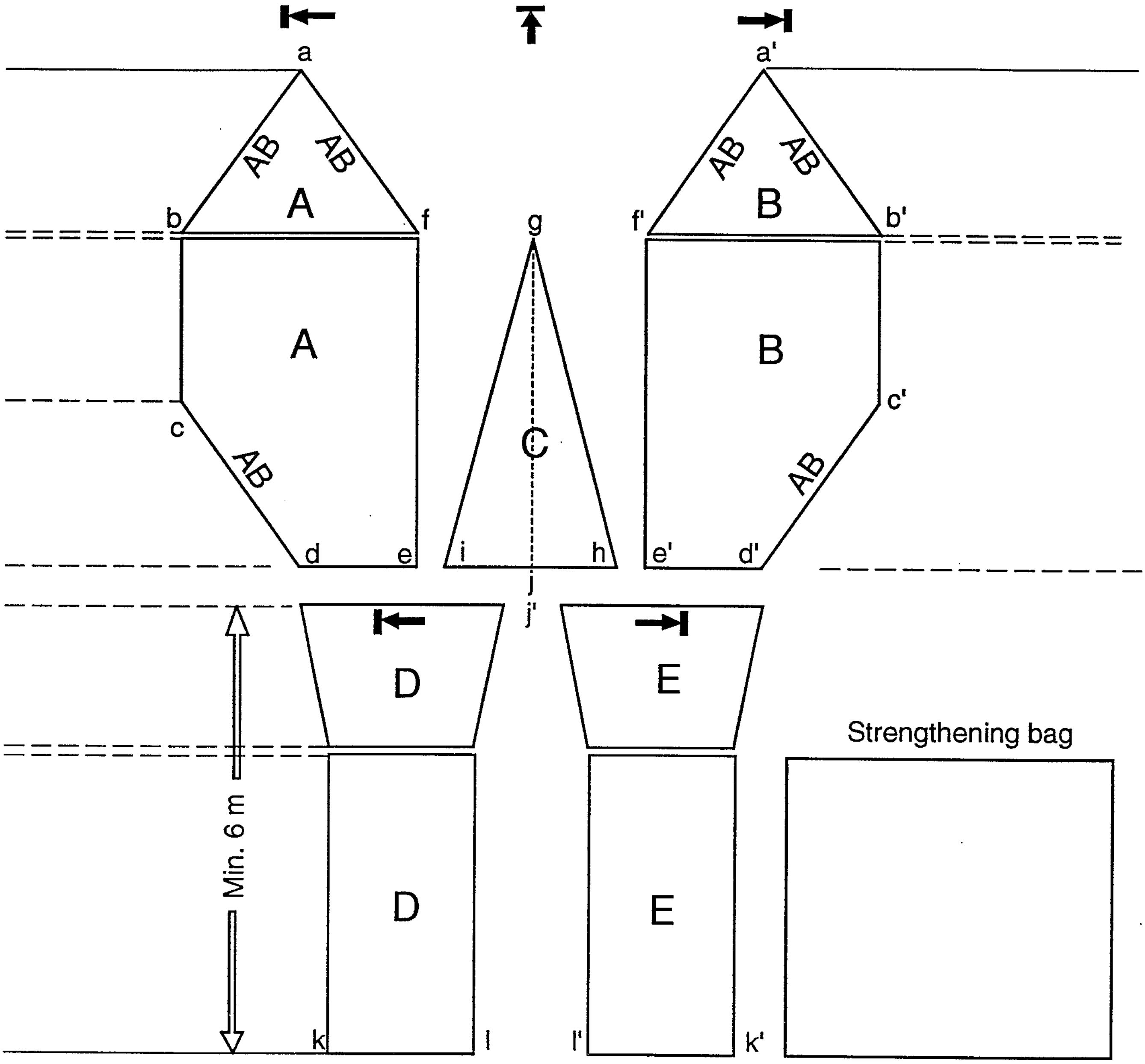


Figure 4.2.6.2 Design of a top cover

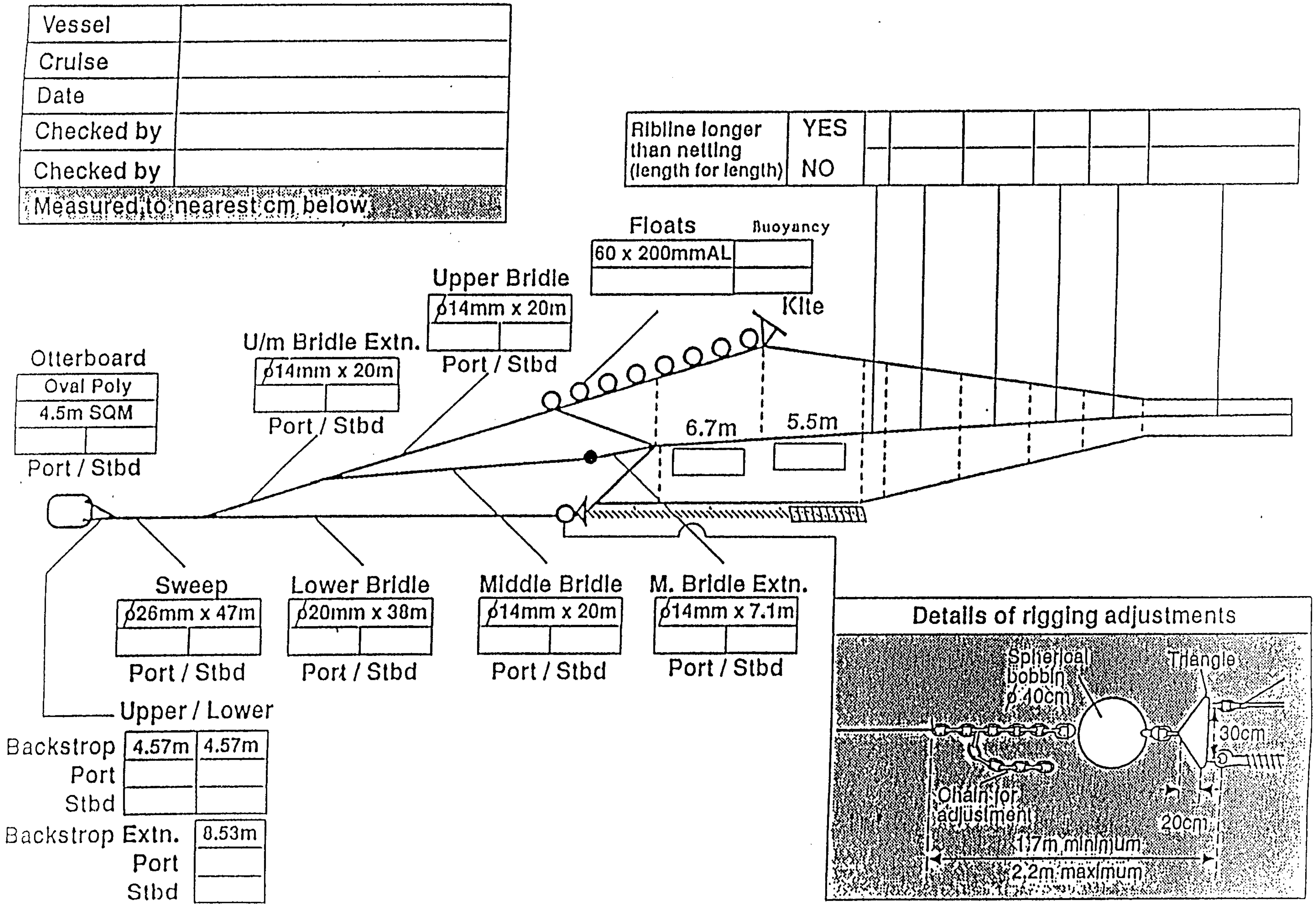


Figure 5.1.1.2a. Example of trawl rigging diagram

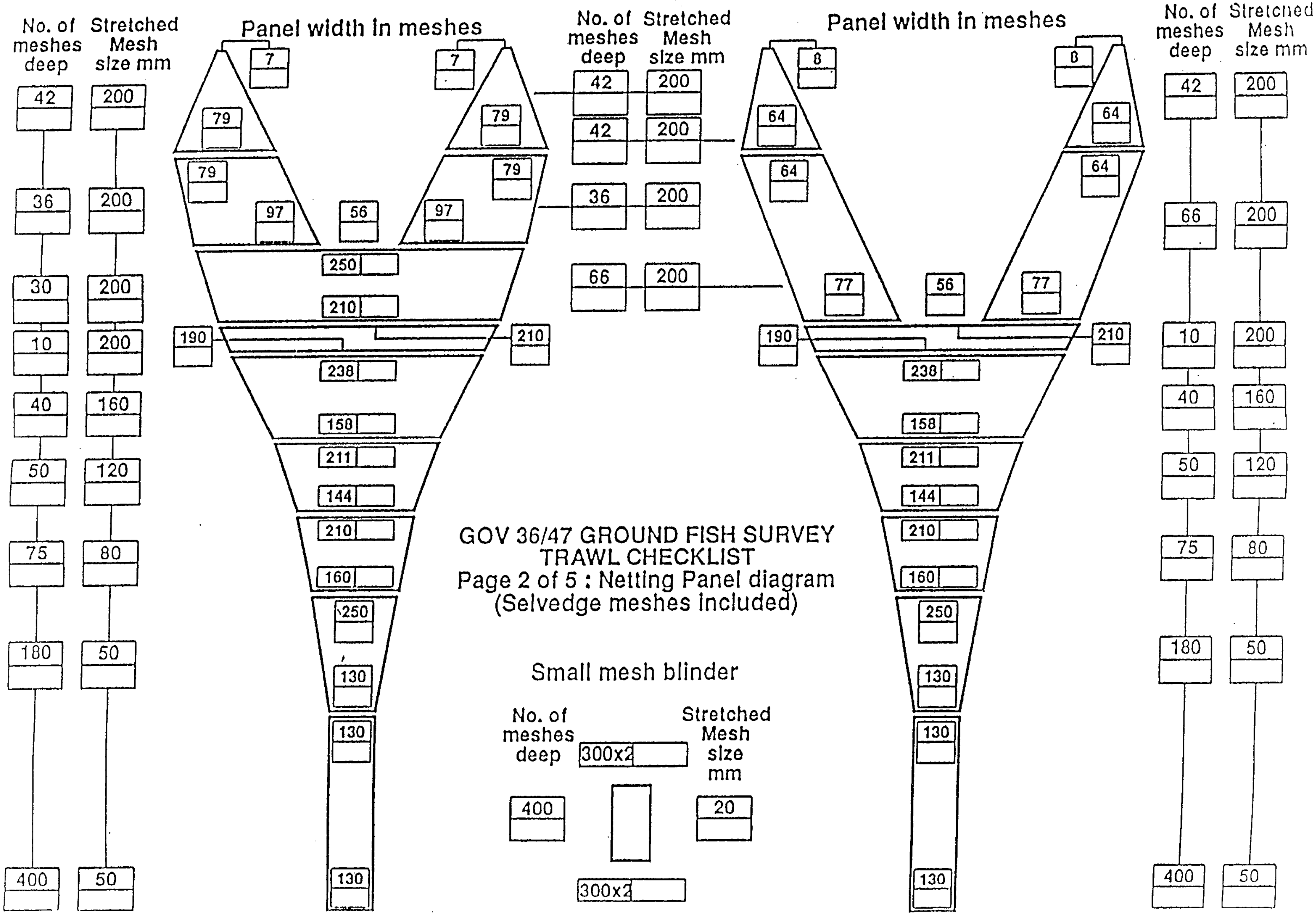


Figure 5.1.1.2b. Example of trawl netting specification

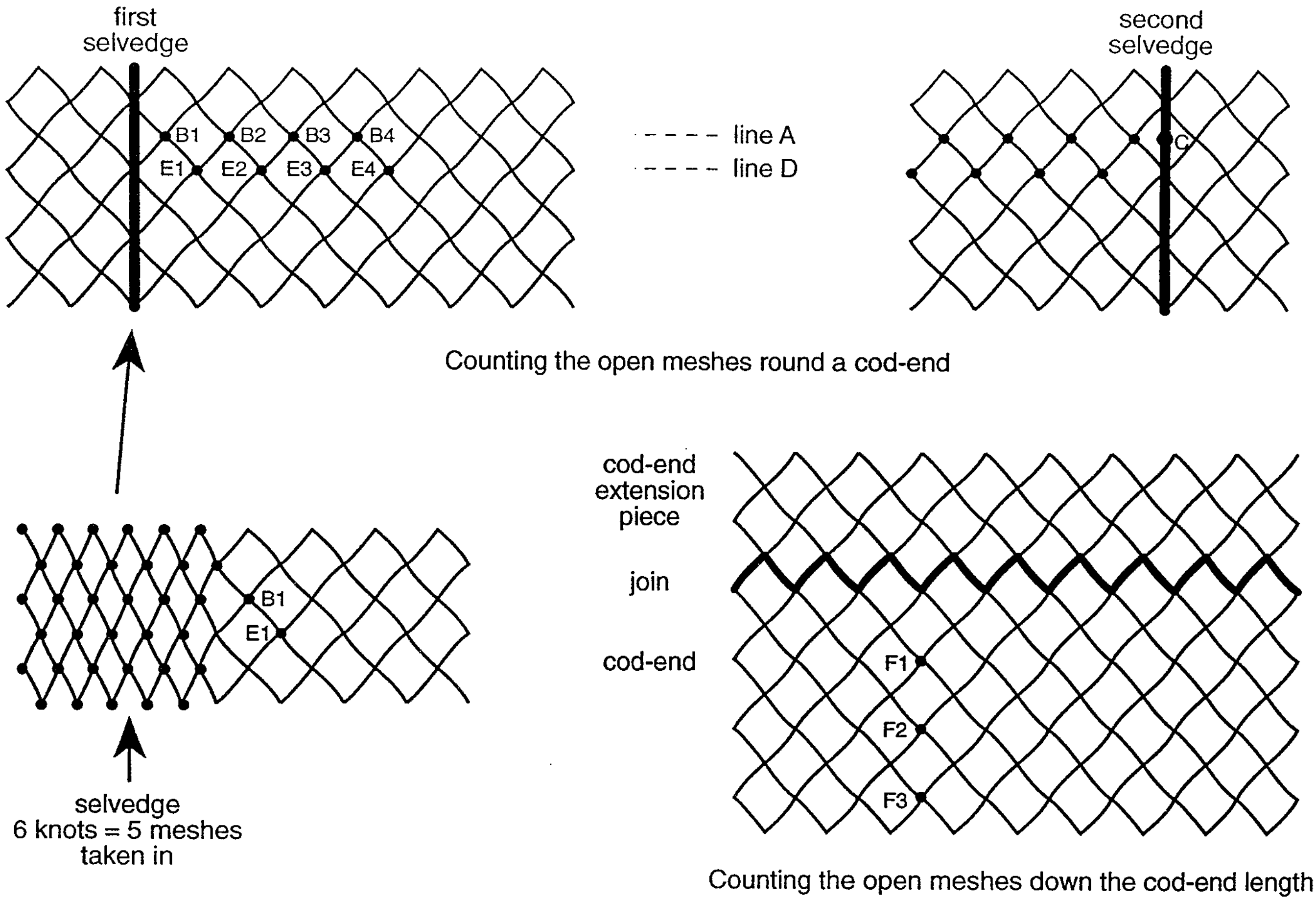


Figure 5.2.5.1 Counting diamond meshes

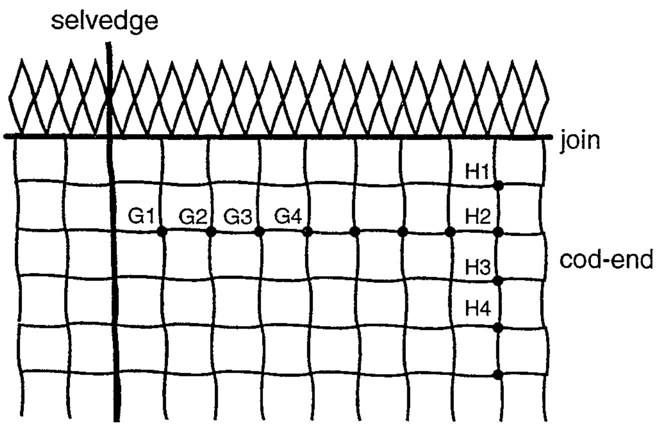


Figure 5.2.5.4
Counting square meshes

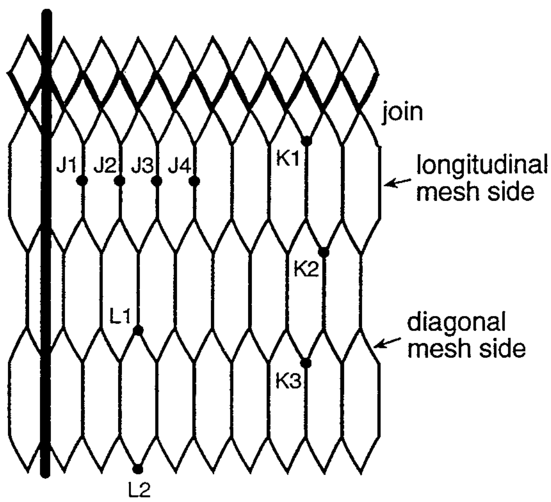


Figure 5.2.5.5
Counting hexagonal meshes

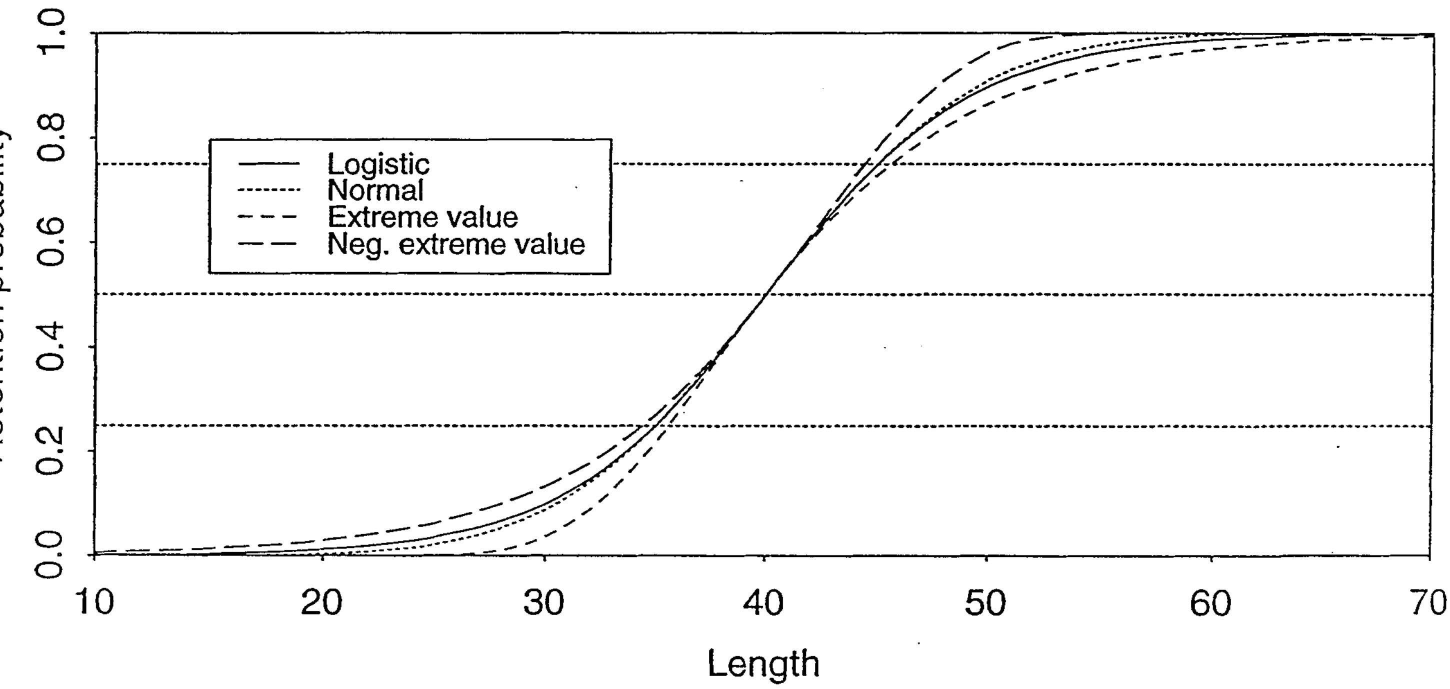


Figure 6.2.2a. Examples of the two parameter selection curves.
Parameters of the curves were chosen to give each one a 50% retention length of 40 and selection range of 10.

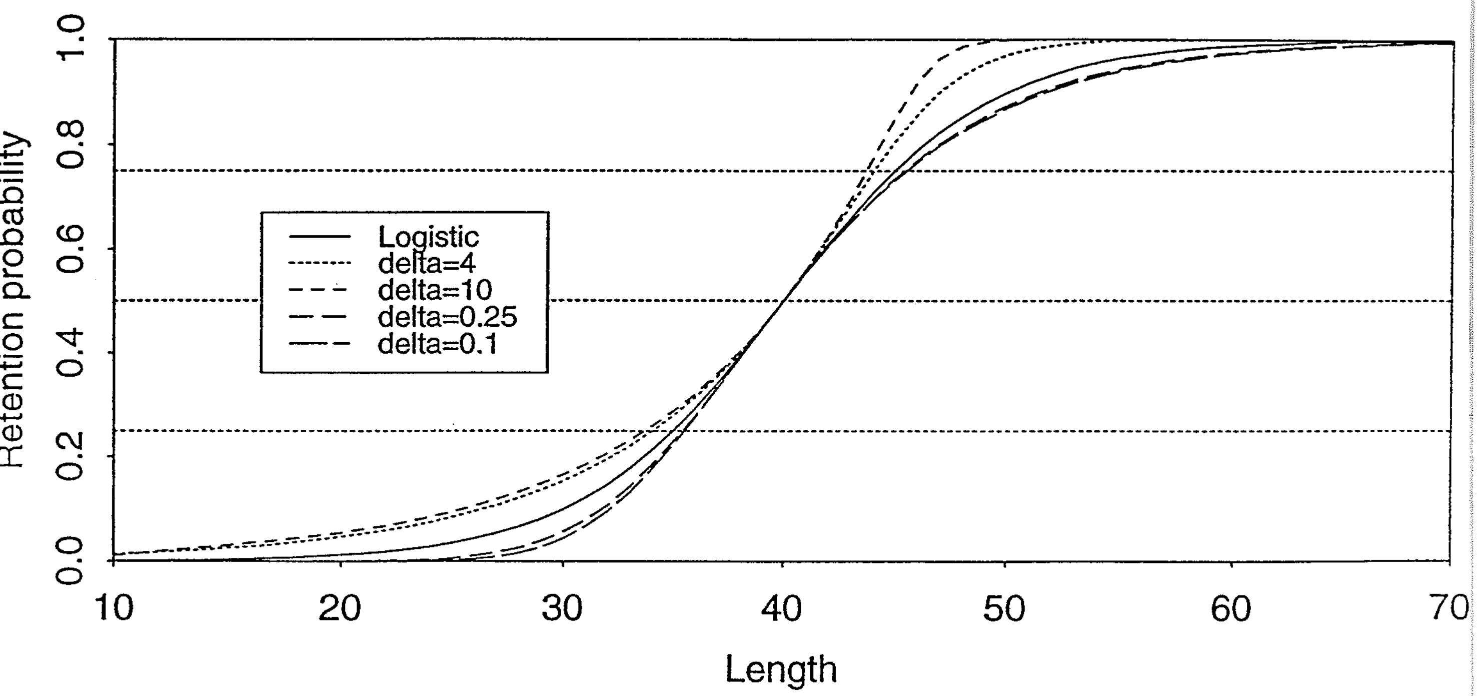


Figure 6.2.2b. Examples of Richards selection curves for differing values of the asymmetry parameter, δ.
The two remaining parameters of the curves were chosen to give each one a 50% retention length of 40 and selection range of 10.

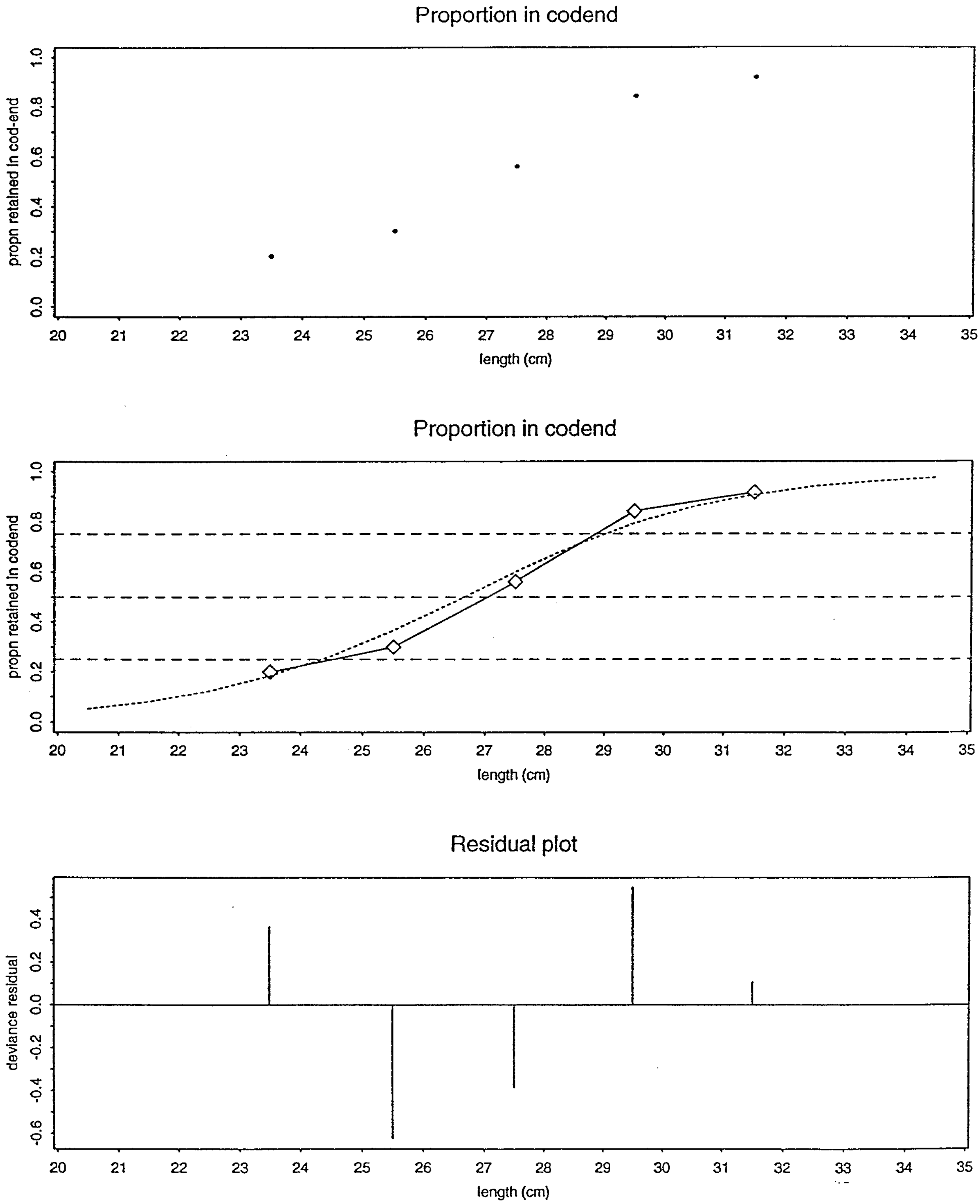


Figure 6.5.1 Example 1. Covered codend haddock data from Pope et al. (1975). Fitting logistic selection curve by (exact) maximum likelihood.

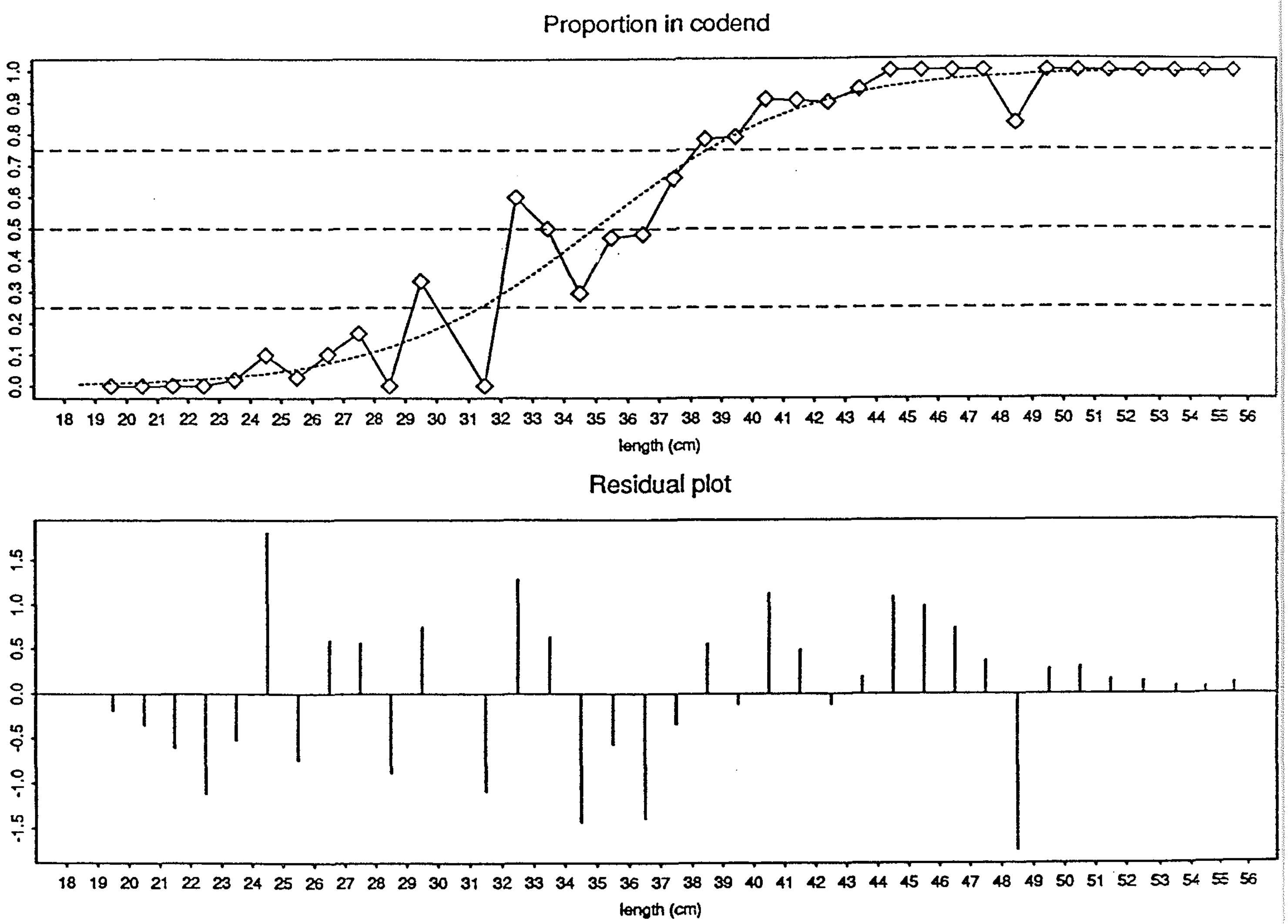


Figure 6.5.2a. Example 2. Covered codend haddock data from Clark (1957). 20 min. haul duration. Fitting logistic selection curve.

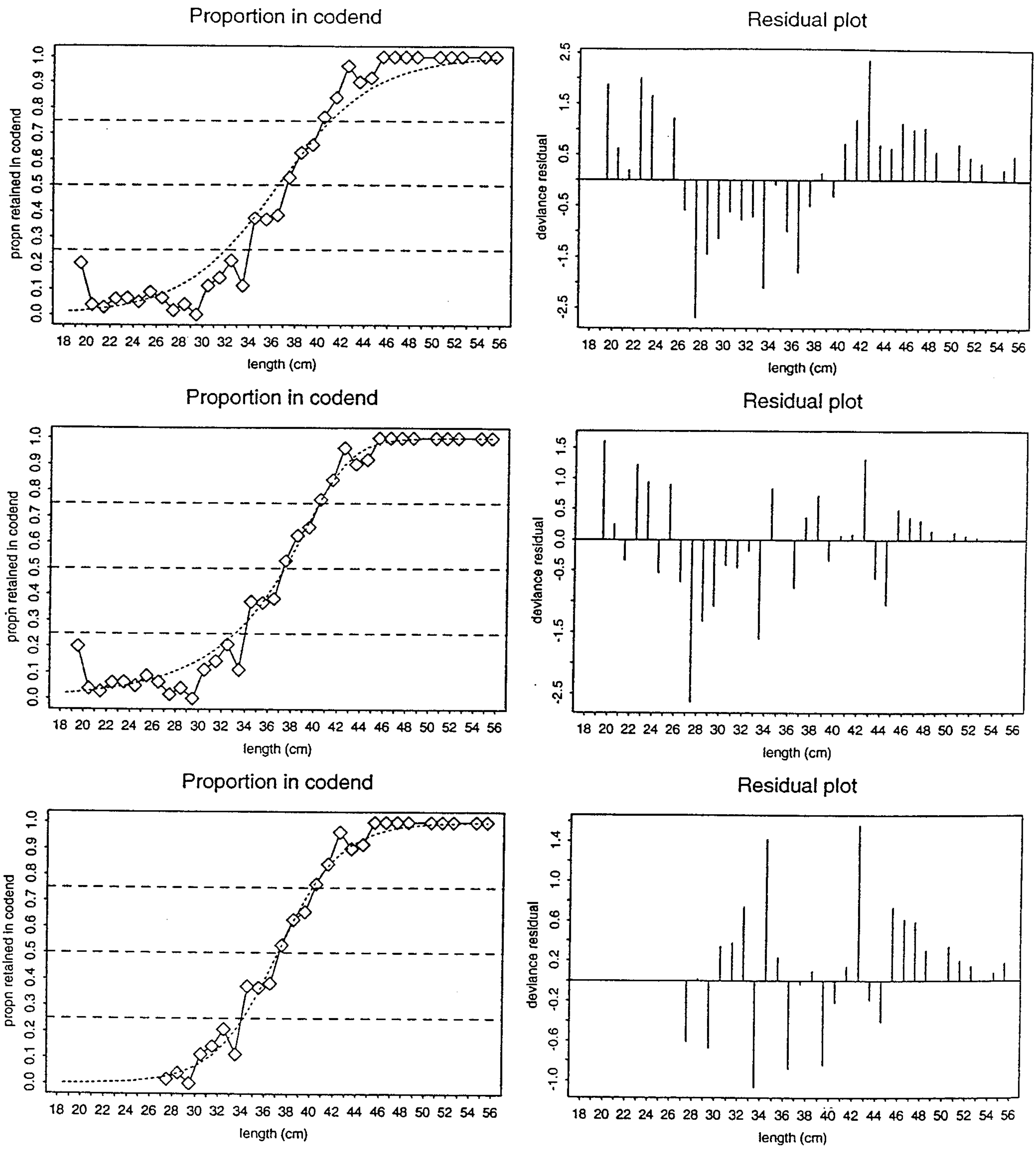


Figure 6.5.2b. Example 2. Covered codend haddock data from Clark (1957). 60 min. haul duration.

Upper plots:	Fitting logistic selection curve
Centre plots:	Fitting Richards selection curve
Lower plots:	Fitting logistic selection curve fish > 27 cm.

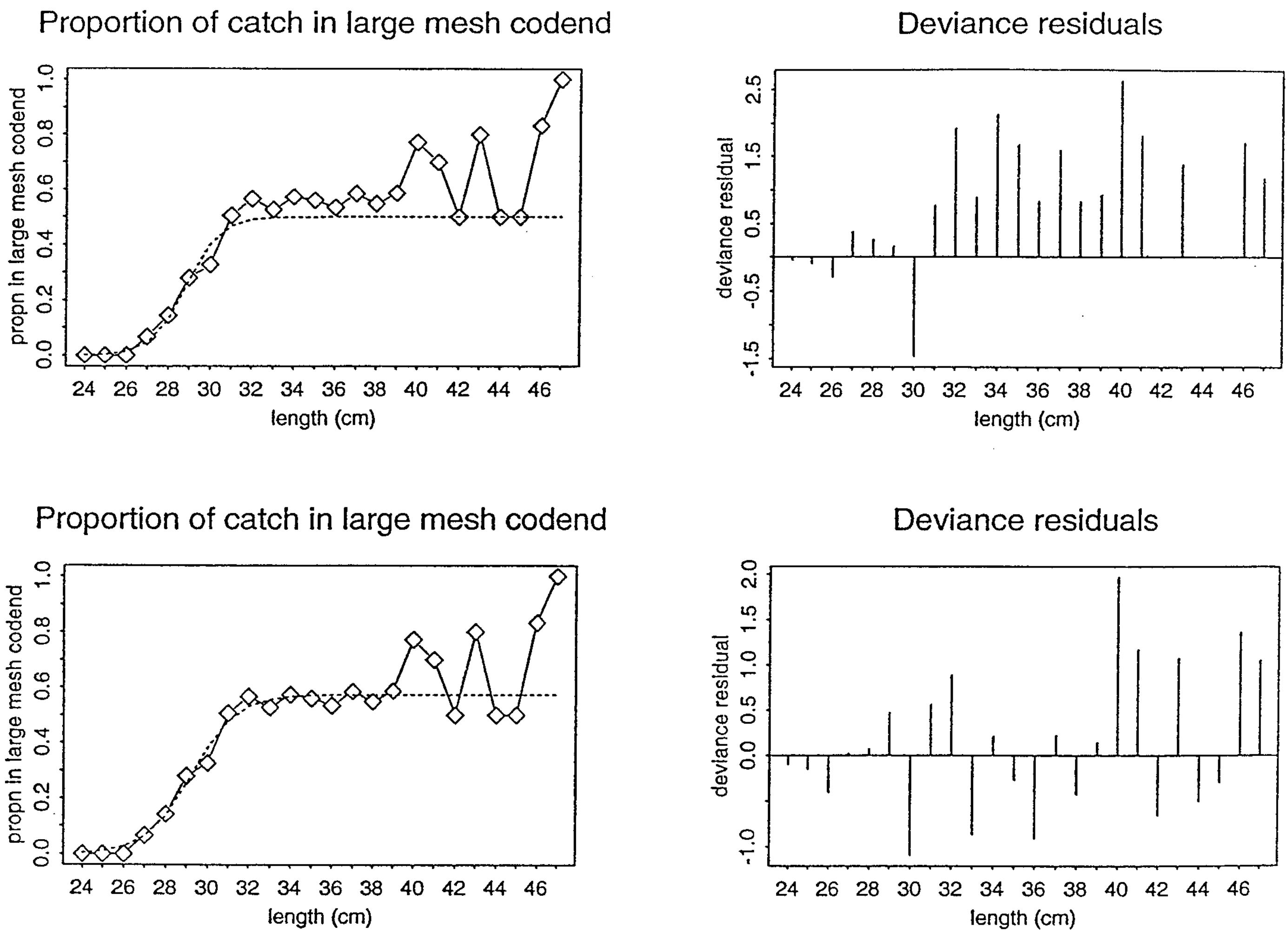


Figure 6.5.3. Maximum likelihood (SELECT) fits to alternate haul haddock data from Pope et al. (1975)

Upper plots: Fitting logistic selection curve. p fixed at 0.5 (equal codend fishing powers assumed)

Lower plots: Fitting logistic selection curve. p estimated (unequal codend fishing powers).

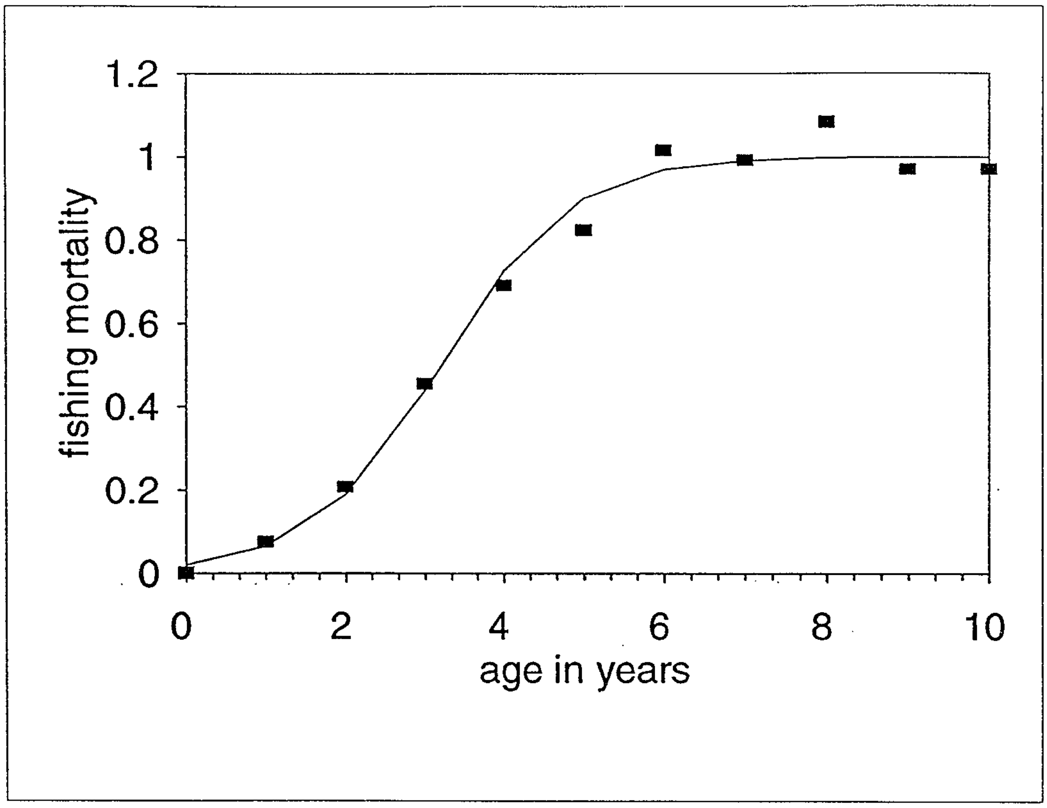


Fig. 8.1. Fishing mortality by age of North Sea whiting generated by the human consumption fishery. The age specific mortality rates follow a sigmoid curve.

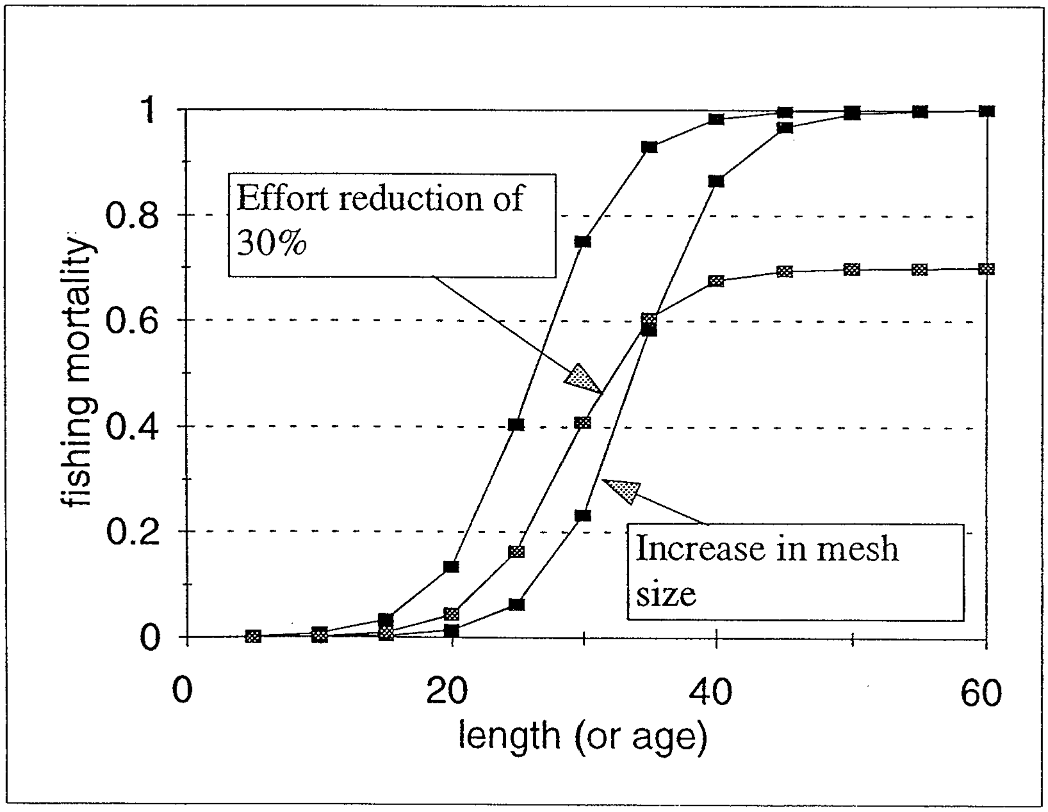


Fig. 8.2. The difference between increasing mesh size or reducing effort on fishing mortality rate.

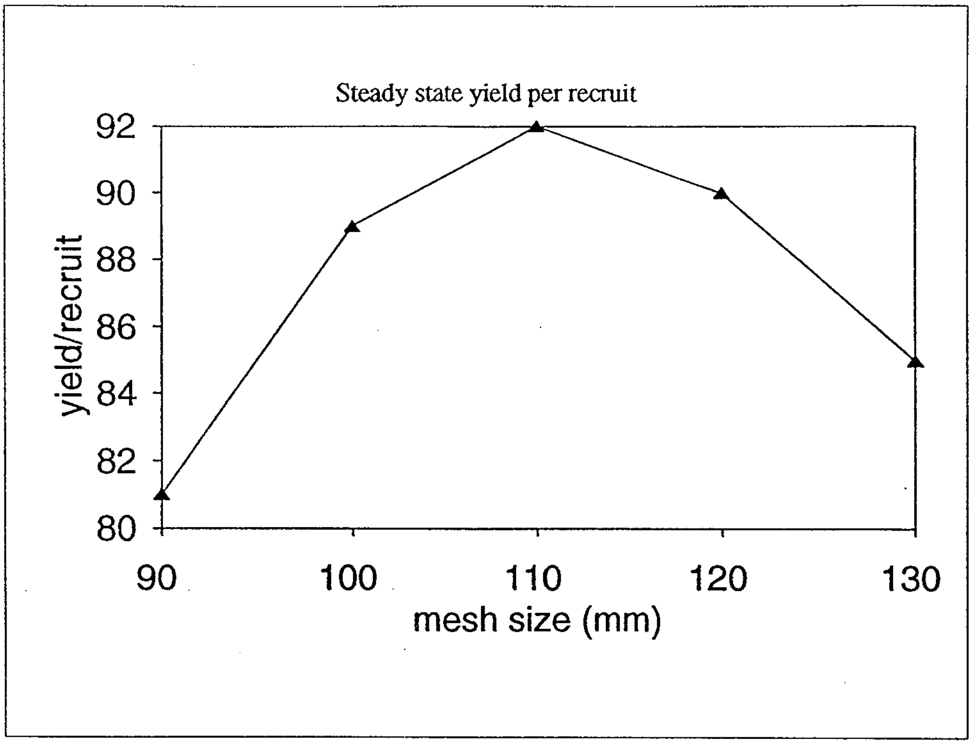


Fig 8.3. Theoretical optimum mesh size for a whiting stock assuming fixed recruitment and mortality rates.

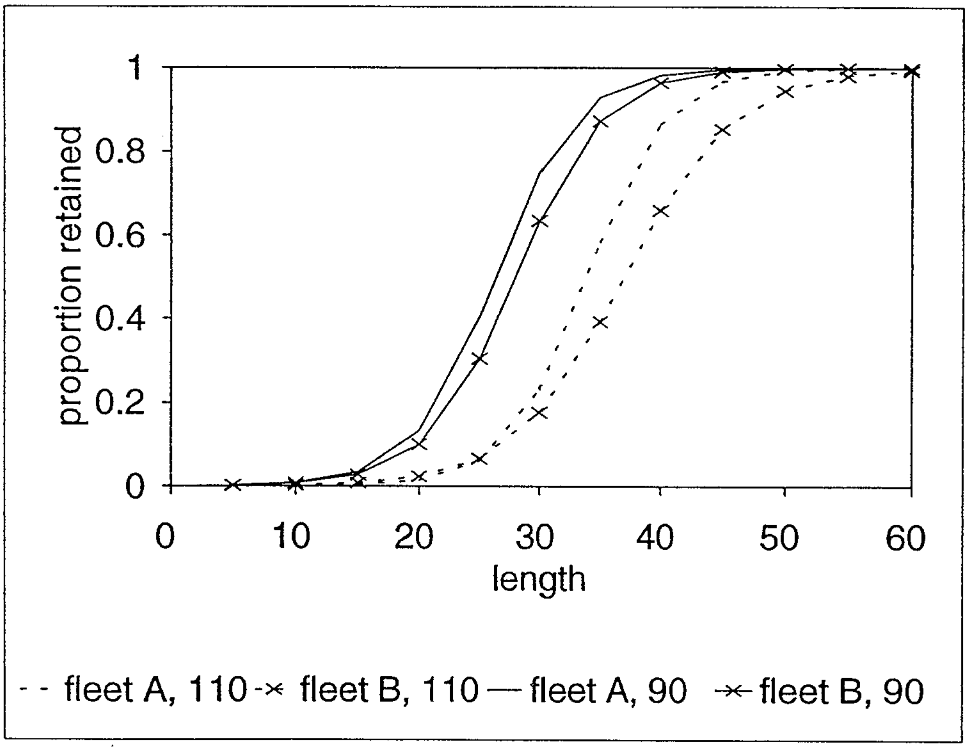


Fig 8.4. Selectivity ogives for two fleets using mesh sizes of 90mm or 100mm. Fleet A benefits from an increase in mesh size at the expense of fleet B.

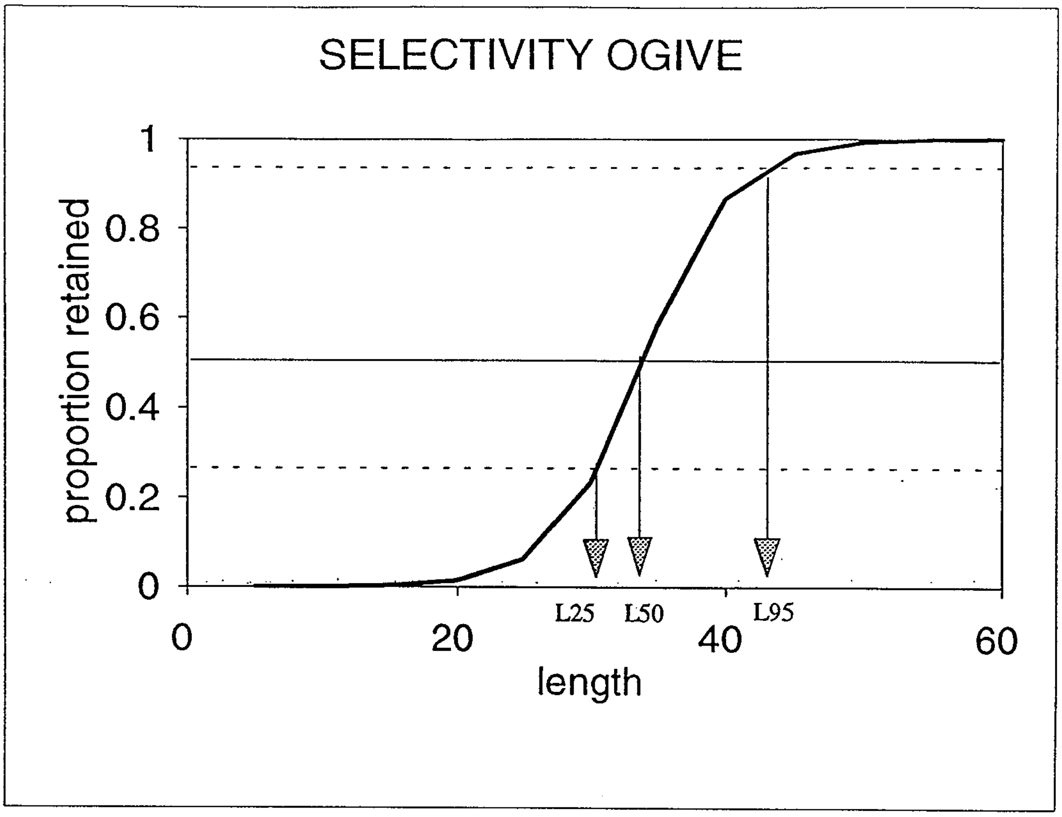


Fig. 8.5. The minimum landing size (MLS) problem. An MLS at the L95 point means many fish are discarded. An MLS at L25 leads to a loss of marketable fish.

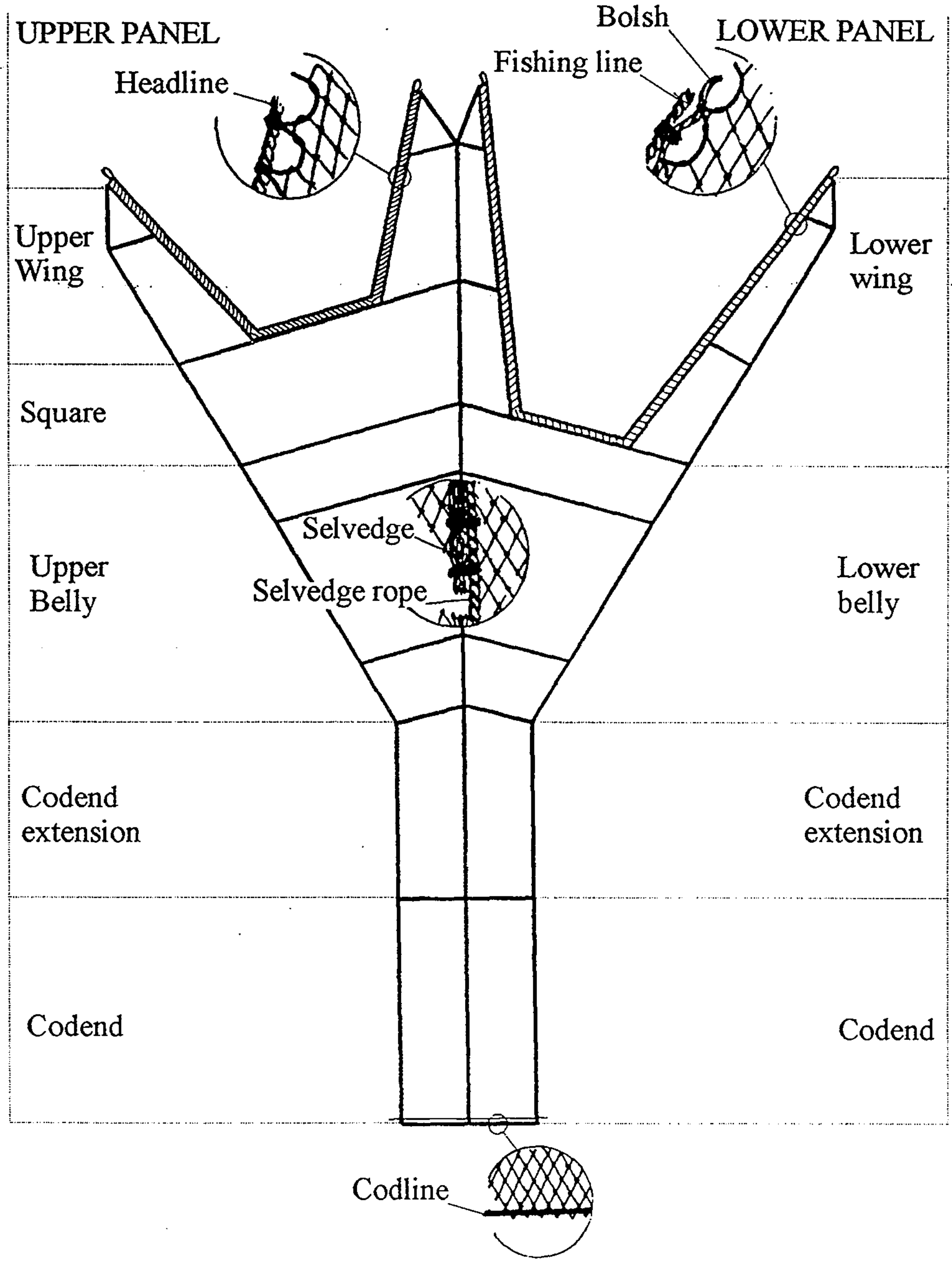


Figure 10.1 The principal net sections and ropes of a two panel bottom trawl.

Appendix 1:
Data base format for permanent records of raw data and selectivity results

to

Manual of methods of measuring the selectivity of towed fishing gears

Table 1 - PROJECT IDENTIFICATION

Field	Field Name	Type	Width	Dec	Rating	Comment
1	TITLE	Characte	25		**	Free text
2	PROJ_CODE	Characte	10		**	Project code

Table 2 - CRUISE IDENTIFICATION

Field	Field Name	Type	Width	Dec	Rating	Comment
1	CRUISE_CODE	Characte	4		**	Year + Cruise No
2	PROJ_CODE	Characte	10		**	Project code
3	INSTITUTE	Characte	10		**	Institute name
4	VESSEL_CODE	Characte	10		**	Vessel code

Table 3 - EXPERIMENT IDENTIFICATION

Field	Field Name	Type	Width	Dec	Rating	Comment
1	EXP_CODE	Characte	10		**	Experiment code
2	CRUISE_CODE	Characte	4		**	Year + Cruise No
3	PROJ_CODE	Characte	10		**	Project code
4	METHOD	Characte	15		**	Experimental method
5	GEAR_CODE	Characte	10		**	Gear code
6	TEST_DEVICE	Characte	10		**	Test device code
7	CONTROL_DEV	Characte	10		**	Control device code

Table 4 - VESSEL DATA

Field	Field Name	Type	Width	Dec	Rating	Comment
1	VESSELCODE	Characte	10		**	Vessel code
2	VESSELNAME	Characte	20		**	Vessel name
3	VESSELNO	Characte	10		**	Vessel registration number
4	VESSELTYPE	Characte	15		**	Free text
5	RES_COM	Characte	1		**	R=research vessel, C=commercial vessel
6	VESSEL_LOA	Numeric	4	2	*	Length Overall in meter
7	VESSEL_GRT	Numeric	4	2	*	Tonnage in register tons
8	ENG_POWER	Numeric	4		**	Engine power in kW (@)
9	PROP_PITCH	Characte	1			Propeller pitch: F=fixed, V=variable
10	NOZZLE	Logical	1			T=with nozzle, F=no nozzle
11	BOLLRDPULL	Numeric	5			Bollard pull in N (1kgf=9.81N)

(@) conversion from m-kgf-s-units : 1 hp = 0.735 kW
conversion from ft-lbf-s-units : 1 hp = 0.746 kW

Table 5 - GEAR DATA

Field	Field Name	Type	Width	Dec	Rating	Comment
1	GEAR CODE	Characte	10		**	gear code
2	GEARTYPE	Characte	3		**	use codes for gear type
3	NO_GEARS	Numeric	1		**	no of gears in multiple riggings
4	TICKL_MAT	Characte	1		**	T=tickler chains, M=chain mat (TBB only)
5	FISHCIRCLE	Numeric	4	2	**	circumference in m
6	HEADLINE	Numeric	4	2		headline length in m
7	BEAM LENGTH	Numeric	4	2	**	beam length in m (TBB only)
8	GROUNDROPE	Numeric	4	2		groundrope length in m
9	BELLY LNGTH	Numeric	3	1	*	belly length in m
10	EXTENSION	Numeric	4	2	**	extension length in m
11	GROUNDROPE	Characte	40		*	type/construction of footrope, free text
12	OTTER_TYPE	Characte	20		*	otter board type
13	OTTER_SIZE	Numeric	2	2	*	otter board area in m^2
14	NET_CODE	Characte	10		*	net drawing code
15	RIGGING_CODE	Characte	10		*	rigging plan code

Table 6 - CODEND DATA

Field	Field Name	Type	Width	Dec	Rating	Comment
1	TEST_DEVICE	Characte	10		**	test device code
2	CE_MESHLNG	Numeric	3		*	length of mesh in mm
3	CE_MESHROU	Numeric	3		**	number of open meshes round
4	CE_MESHSEL	Numeric	3			no of meshes round including selvedge meshes
5	CE_LENGTH	Numeric	3	1	**	codend length in m
6	CE_LENGTHM	Numeric	3			codend length in no of meshes
7	CE_MESHSTY	Characte	20		**	codend mesh type, free text
8	SELV_NO	Numeric	1			no of selvedges
9	SELROPE_NO	Characte	1		**	no of selvedge ropes
10	SELROPE_LN	Numeric	3	1	**	length of selvedge ropes
11	SELROPE_MA	Characte	10		**	selvedge rope material
12	CE_MAT	Characte	3		**	use codes for codend netting material
13	CE_KNOT	Characte	10		**	knotted or knotless netting, free text
14	CE_TWINETYP	Characte	15			twine type, free text
15	CE_TWINECON	Characte	1		*	twine construction, T=twisted, B=braided
16	CE_SINDOUB	Characte	1		**	S=single twine, D=double twine
17	CE_TWINETEX	Numeric	5		**	linear density in tex
18	CE_TWINEDIA	Numeric	2		*	twine diameter in mm
19	CE_TWINECOL	Characte	10		**	twine colour, free text
20	CE_STIFF	Numeric	2			flexural stiffness; force in N (@)
21	CE_ATTACH	Characte	25			type of codend attachments, free text

(@) flexural stiffness is defined as the force required to cause a unit of bending deflection (Klust, 1973)

Table 7 - WINDOW DATA

Field	Field Name	Type	Width	Dec	Rating	Comment
1	TEST_DEVICE	Characte	10		**	test device code
2	MESH_TYPE	Characte	40		**	mesh type in the window
3	WIN_POS	Characte	40		**	position of the window, free text
4	WIN_LENGTH	Numeric	4	2	**	length of window in m
5	WIN_BRDTH	Numeric	4	2	**	breadth of window in m
6	WINW_MSHSI	Numeric	3		**	mesh opening in mm
7	WIN_MAT	Characte	3		*	use codes for window netting material
8	WIN_KNOT	Characte	10		**	knotted or knotless netting, free text
9	WIN_TWETYP	Characte	15			twine type, free text
10	WIN_TWECON	Characte	1		*	twine construction, T=twisted, B=braided
11	WIN_SINDOU	Characte	1		**	S=single twine, D=double twine
12	WIN_TWETEX	Numeric	4		**	linear density in tex
13	WIN_TWEDIA	Numeric	2		*	twine diameter in mm
14	WIN_TWECOL	Characte	10		**	twine colour, free text
15	SAMECOLOUR	Logical	1			T=same colour as other netting F=different colour

Table 8 - GRID DATA

Field	Field Name	Type	Width	Dec	Rating	Comment
1	TEST_DEVICE	Characte	10		**	test device code
2	GRID_LNGTH	Numeric	4	2	**	length of grid in m
3	GRID_BRDTH	Numeric	4	2	**	breadth of grid in m
4	BAR_SIZE	Characte	25		*	grid bar shape and size, free text
5	ELEMENT_NO	Numeric	2		**	number of elements in the grid
6	GRID_MAT	Characte	20		*	grid material, free text
7	BAR_DISTAN	Numeric	3		**	distance between bars in mm
8	GRID_POS	Characte	40		**	position of the grid, free text
9	GRID_ANGLE	Characte	40		*	setting angle, free text

Table 9 - COVER DATA

Field	Field Name	Type	Width	Dec	Rating	Comment
1	CONTROL_DEV	Characte	10		**	control device code
2	COV_TYPE	Characte	40		**	type of cover, free text
3	COV_MESHSI	Numeric	3		**	mesh opening in mm
4	COV_MESHRO	Numeric	3		**	no of open meshes round
5	COV_LENGTH	Numeric	4	2	**	cover length in m
6	COV_MESHTY	Characte	20		**	cover mesh type, free text
7	COV_MAT	Characte	3			use codes for cover netting material
8	COV_KNOT	Characte	10			knotted or knotless netting, free text
9	COV_TWETYP	Characte	15			twine type, free text
10	COV_TWECON	Characte	1			twine construction, T=twisted, B=braided
11	COV_SINDOU	Characte	1			S=single twine, D=double twine
12	COV_TWETEX	Numeric	4			linear density in tex
13	COV_TWECOL	Characte	5			twine colour, free text
14	COV_HOOPNO	Numeric	1		**	no of hoops
15	COV_POS	Characte	40		**	position of hoops, free text
16	COV_HOOPDI	Numeric	4	2	**	diameter of hoops in m
17	COV_HOOPMA	Characte	10			hoop material
18	COV_OTHERD	Characte	40		**	other devices to open cover, free text
19	COV_OTHERPL	Characte	10		**	code of plan of covers for special devices
20	COV_ATTACH	Characte	40		*	cover attachment specifications, free text

Table 10 - SMALL MESH CODEND DATA

Field	Field Name	Type	Width	Dec	Rating	Comment
1	CONTROL_DEV	Characte	10		**	control device code
2	SM_MESHSI	Numeric	3		**	nominal inside mesh size in mm
3	SM_MESHROU	Numeric	3		**	no of open meshes round
4	SM_LENGTH	Numeric	4	2	**	small mesh codend length in m
5	SM_MESHTYP	Characte	20		**	mesh type, free text
6	SM_NETMAT	Characte	3			use codes for cover netting material
7	SM_KNOT	Characte	10			knotted or knotless netting, free text
8	SM_TWETYPE	Characte	15			twine type, free text
9	SM_TWECON	Characte	1			twine construction, T=twisted, B=braided
10	SM_SINDOUB	Characte	1			S=single twine, D=double twine
11	SM_TWETEX	Numeric	4			linear density in tex
12	SM_TWECOL	Characte	5			twine colour, free text

Table 11 - OPERATIONAL AND ENVIRONMENTAL DATA

Field	Field Name	Type	Width	Dec	Rating	Comment
1	PROJ_CODE	Characte	10		**	project code
2	CRUISE_NO	Characte	4		**	year + Cruise No
3	EXP_CODE	Characte	10		**	experiment code
4	DATE	Date	8		**	date
5	HAUL_NO	Characte	3		**	haul number
6	HAUL_START	Characte	6		**	shooting time
7	HAUL_STOP	Characte	6		**	hauling time
8	ICES_STREC	Characte	4		**	ICES statistical rectangle
9	LAT_START	Characte	6		**	latitude when shooting
10	LON_START	Characte	7		**	longitude when shooting
11	LAT_STOP	Characte	6		**	latitude when hauling
12	LON_STOP	Characte	7		**	longitude when hauling
13	DEPTH	Numeric	3		*	water depth in m
14	WARPLENGTH	Numeric	4			warp length in m
15	VERT_OPEN	Numeric	3	1	*	vertical net opening in m
16	WING_SPREAD	Numeric	2			wing spread in m
17	OT_SPREAD	Numeric	3			otter board spread in m
18	NET_DEPTH	Numeric	3		*	depth of pelagic net in m
19	SPEEDWATER	Numeric	3	1	**	vessel speed through the water in knots
20	SPEEDGROUN	Numeric	3	1	**	vessel speed over the ground in knots
21	NETSPEED	Numeric	3	1	*	net speed in knots
22	TOW_DIRECT	Numeric	3			towing direction in degrees
23	TIDE	Characte	1			towing direction in relation to tide (I=in/W=with/A=across)
24	WIND_DIREC	Numeric	3			wind direction in degrees
25	WIND_SPEED	Numeric	1			wind speed in Beaufort
26	SEA_STATE	Numeric	2		*	use sea state code
27	LIGHTLEVEL	Numeric	5			light level in lux
28	LIGHT_METH	Characte	25			light level measurement method, free text
29	DEFICIENCY	Characte	40		*	any deficiency from normal operation, free text
30	MESHGAUGE	Characte	25		**	mesh gauge type, free text
31	MEAS_FORCE	Numeric	1		**	mesh measuring force in kgf
32	CE_MESHOPE	Numeric	4	2	**	mesh opening in mm
33	CE_MESH_SD	Numeric	6	4	**	codend mesh opening standard deviation in mm
34	CE_MEAS_NO	Numeric	4	3	**	number of codend mesh measurements

Table 12 - TARGET SPECIES

Haul no:
Device (Test / Control):
Total catch weight:

	Species 1	Species 2			Species j
Sampling fraction					
Sample weight					
Total weight					
No of fishes					
length class 1 length class 2 length class 3 length class n					

Table 13 - BY-CATCH DATA

Haul no:
Device (Test / Control):

Species	Weight
Debris	

Table 14 - SELECTIVITY RESULTS

Field	Field Name	Type	Width	Dec	Rating	Comment
1	PROJ_CODE	Characte	10		**	project code
2	CRUISE_NO	Characte	4		**	year + Cruise No
3	EXP_CODE	Characte	10		**	experiment code
4	HAUL_NO	Characte	5		**	haul number(s)
5	SPECIES	Characte	25		**	species
6	SEL_MOD	Characte	40		**	selectivity model used
7	STAT_ANAL	Characte	40		**	statistical analysis technique used
8	L25	Numeric	4	2	**	25 % retention length in cm
9	L25_SE	Numeric	5	3	**	L25 standard error in cm
10	L25_CF_L	Numeric	4	2	**	L25 lower 95% confidence limit in cm
11	L25_CF_U	Numeric	4	2	**	L25 upper 95% confidence limit in cm
12	L50	Numeric	4	2	**	50 % retention length in cm
13	L50_SE	Numeric	5	3	**	L50 standard error in cm
14	L50_CF_L	Numeric	4	2	**	L50 lower 95% confidence limit in cm
15	L50_CF_U	Numeric	4	2	**	L50 upper 95% confidence limit in cm
16	L75	Numeric	4	2	**	75 % retention length in cm
17	L75_SE	Numeric	5	3	**	L75 standard error in cm
18	L75_CF_L	Numeric	4	2	**	L75 lower 95% confidence limit in cm
19	L75_CF_U	Numeric	4	2	**	L75 upper 95% confidence limit in cm
20	SF	Numeric	3	2	**	selection factor
21	SF_SE	Numeric	5	3	**	selection factor standard error
22	SF_CF_L	Numeric	4	2	**	selection factor lower 95% confidence limit
23	SF_CF_U	Numeric	4	2	**	selection factor upper 95% confidence limit
24	SR	Numeric	4	2	**	selection range
25	SR_SE	Numeric	5	3	**	selection range standard error
26	SR_CF_L	Numeric	4	2	**	selection range lower 95% confidence limit
27	SR_CF_U	Numeric	4	2	**	selection range upper 95% confidence limit
28	NO_SR	Numeric	5		**	no of fish in the selection range

Appendix 2:
Printed forms for data collection at sea

to

Manual of methods of measuring the selectivity of towed fishing gears

The level of importance of the data is indicated as follow:

(**)/heavy shading: must be recorded
- experimental data essential for data analysis
- parameters known to have an effect upon codend selectivity and which must be recorded

(*)/light shading: should be recorded
- parameters which are suspected to have an effect upon codend selectivity

()/no shading: optional
- other parameters which may be useful for future reference.

PROJECT IDENTIFICATION

Title	
Project code(**)	

CRUISE IDENTIFICATION

Cruise code (**)	
Project code (**)	
Institute (**)	
Vessel code (**)	

EXPERIMENT IDENTIFICATION

Experiment code (**)	
Cruise code (**)	
Project code (**)	
Experimental method (**)	
Gear code (**)	
Test device code (**)	
Control device code (**)	

VESSEL DATA

Code (**)	Name (**)	No (**)

Type (**)	
Research/Commercial (**)	

Length Overall m (*)	
GRT (*)	

Engine power (kW) (**)	

Propeller pitch (Fixed/Var)	
Nozzle (Y/N)	
Bollard pull (N)	

GEAR DATA

Code (**)	
Type (**)	
No of gears (**)	

Fishing circle (m) (**)	
Headline (m)	
Groundrope (m)	
Belly length (m) (*)	
Extension length (m) (**)	
Groundrope type	

Otter board type (*)	Otter board size (m^2) (*)

For beam trawls :

Beam length (m) (**)	Tickler chains/chain mat (**)

Net drawing code (*)	Rigging plan code (*)

CODEND DATA

Code (**)	

Length of mesh (mm) (*)	
No of open meshes round (**)	
Meshes round including selvedges	
Codend length in m (**)	
Codend length in no of meshes	
Mesh type (**)	
No of selvedges	

No of selvedge ropes (**)	
Length of selvedge ropes (m) (**)	
Selvedge rope material (**)	

Codend material (*)	
Knotted/knotless (**)	
Twine type	
Twisted/braided twine (*)	
Single/double twine (**)	
Linear density (tex) (**)	
Twine diameter (mm) (*)	
Twine colour (**)	
Flexural stiffness (N)	

Codend attachments (**)

WINDOW DATA

Code (**)	

Mesh type (**)	
Window positioning (**)	
Window length (**)	
Window breadth (**)	
Mesh opening (mm) (**)	

Netting material(*)	
Knotted/knotless (**)	
Twine type	
Twisted/braided twine (*)	
Single/double twine (**)	
Linear density (tex) (**)	
Twine diameter (mm) (*)	
Twine colour (**)	
Same colour as other netting?	

GRID DATA

Code (**)	

Grid length (**)	
Grid breadth (**)	
Grid bar shape and size (*)	
No of elements (**)	
Grid material (*)	
Bar distance (**)	

Grid position (**)	
Grid setting angle (*)	

COVER DATA

Code (**)	

Cover type (**)	

Mesh opening (mm) (**)	
No of open meshes round (**)	
Cover length in m (**)	
Mesh type (**)	

Cover material	
Knotted/knotless netting	
Twine type	
Twisted/braided twine	
Single/double twine	
Linear density (tex)	
Twine colour	

No of hoops (**)	
Positioning of hoops (**)	
Hoop diameter (**)	
Hoop material	

Other devices to open cover (**)	
Code of plan of other covers (**)	

Cover attachments (*)

SMALL MESH CODEND DATA

Code (**)	

Mesh opening (mm) (**)	
No of open meshes round (**)	
Small mesh codend length in m (**)	
Mesh type (**)	

Small mesh codend material	
Knotted/knotless netting	
Twine type	
Twisted/braided twine	
Single/double twine	
Linear density (tex)	
Twine colour	

HAUL BY HAUL DATA

Project(**)		Cruise (**)		Experiment(**)	

Date (**)		Haul no (**)		ICES stat (**) rectangle	

Shooting		Hauling	
Time (**)		Time (**)	
Latitude (**)		Latitude (**)	
Longitude (**)		Longitude (**)	

Water depth (m)(*)		Warp length (m)		Net depth (m) (*)	

Vert. net opening (m)(*)		Wing spread (m)		Otterboard spread (m)	

Vessel speed			
through the water (knots) (**)		over the ground (knots) (**)	
Net speed (knots) (*)			

Towing direction		Relative to the tide (against/with/across)	

Wind direction		Speed (Bft)	
Sea state (*)			

Light level	
Measurement method	

TEST CODEND MESH SIZE

Gauge (**)		Force (kgf) (**)	

Mean opening (mm) (**)	St. deviation (**)	Number (**) measurements

Appendix 3:
Suggested report format

to

Manual of methods of measuring the selectivity of towed fishing gears

Suggested outline for a report describing experiments to measure the selectivity of different codends

Abstract

1. **INTRODUCTION**
   Purpose of the experiments
   Relevance to commercial fishing and fisheries management problems

2. **MATERIALS AND METHODS**
   - **2.1 Vessel**
   - **2.2 Gear under test**
     Basic trawl/seine
     Codends under test
   - **2.3 Experimental design**
   - **2.4 Experimental technique**
     Design and operation of small mesh codends/covers/trouser trawl
     Codend mesh size measurement
     Catch measurement and sampling
   - **2.5 Trials narrative**
   - **2.6 Data analysis techniques**
     Selectivity model
     Parameter estimation
     Statistical tests for differences between codends

3. **RESULTS**
   - **3.1 Fishing conditions**
     Catch rates for target species
     Population length frequencies
     Other factors wind, weather, bycatches
   - **3.2 Gear selectivity**
     Selectivity by target species and codend
     Statistical significance of differences between codends

4. **DISCUSSION**
   - **4.1 Comparison of results with previous work**
     Difference in basic level of selectivity species by species compared with results of other selectivity experiments using same gear types
     Comparison with other tests investigating the same type of change in codend design
   - **4.2 Commercial fishing implications of the results**
   - **4.3 Fisheries management implications of the results**

5. **CONCLUSIONS**

References

Results summary

Gear type:
Vessel type:
Vessel name:
Vessel HP:
Experimental method:

Species:
ICES Area:
Test date:
Selectivity model:
Analysis technique:

Test codend specification

	Codend	Window
Mesh opening mm		
Number open meshes round		
Length m		
Extension length m		
Twine material description		
R-tex		
Twine diameter mm		

Fishing conditions

	Mean	Standard deviation	Min	Max
Total catch weight per haul test codend kg				
Towing time hours				
Sea state				

Selectivity results

Number valid hauls
Total numbers in selection range — Test codend
Total population

	Estimate	Standard error	95% confidence limits	
			Lower	Upper
25% length cm				
50% length cm				
75% length cm				
Selection factor				
Selection range cm				

Appendix 4:
Subgroup meetings and participants

to

Manual of methods of measuring the selectivity of towed fishing gears

Sub-Group meetings and participants

The Sub-Group held a first meeting in Gothenburg, Sweden, from 15-17 April 1993 to:

a) describe information to be recorded during selectivity trials, and specify its format;

b) review the recognised techniques for conducting selectivity experiments, including their application, advantages, and disadvantages, and make recommendations for further developing and testing;

c) review the recognised methods of analysis of selectivity data to be used for the techniques described in b) above and make recommendations for further development. (C.Res. 1992/2:9).

A second meeting was held in Montpelier, France, from 21-23 April 1994 to prepare a final version of the Manual on Recommended Methodology of Selectivity Experiments. (C.Res. 1993/2:8:1)

During 1995 the Sub-Group worked by correspondence to continue with the preparation of the Manual on Recommended Methodology of Selectivity Experiments. (C.Res.1994/2:7:11)

Participants to the Gothenburg meeting
Mr P Carrera, Spain
Mr C Cooper, Canada
Mr R Ferro, UK
Mr R Fonteyne, Belgium
Dr R Fryer, UK
Mr B Isaksen, Norway
Mr R Karlsson, Sweden
Dr E Pikitch, USA
Mr P Suuronen, Finland
Dr F Theret, France
Mr W Thiele, Germany
Mr B West, USA
Mr D Wileman, Denmark (Chairman)

Participants to the Montpelier meeting
Mr C Cooper, Canada
Mr D Erickson, USA
Mr R Ferro, UK
Mr R Fonteyne, Belgium
Mr R Karlsson, Sweden
Mr T Kreissel, Netherlands
Mr K Lange, Germany
Mr R Larsen, Norway
Mr B van Marlen, Netherlands
Mr G Sangster, UK
Mr P Suuronen, Finland
Dr F Theret, France
Mr D Wileman, Denmark (Chairman)