

THE BEHAVIOURAL BASIS OF FISH EXCLUSION FROM COASTAL
POWER STATION COOLING WATER INTAKES

by

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SUMMARY

Much has been written on the subject of fish protection at water intakes and engineers responsible for intake design are confronted with a diversity of approaches to the problem. Some of the information in the literature is site specific. Some of the approaches recommended may work well in a laboratory environment, but fail to make the transition to a full-scale system operating in the natural environment. In others, the cost of the facility simply outweighs the benefit to fisheries.

This Report goes back to first principles of fish behaviour in flow fields, to consider why fish enter water intakes and how they can best be excluded. It is shown that there are three vital elements to fish exclusion:

(1) the fish must be able to detect its approach to an intake before it can attempt to escape; (2) the direction of water flow must be horizontal, since fish are ill-equipped to react to vertical flow components; (3) the water velocity must be within the fish's swimming performance range. All three requirements must be met simultaneously; it is futile, for example, to reduce intake current velocities where waters are perpetually turbid, since fish would be unlikely to detect their approach to the intake.

There has been confusion in the literature over the particular characteristics of fish swimming performance that are important for fish to escape from water intakes. In this Report it is shown that velocity criteria based on maximum 'burst' swimming speeds are inappropriate, since the steady hydraulic conditions at water intakes do not stimulate 'burst' swimming. Instead, criteria based on maximum sustainable swimming must be adopted. A synopsis of swimming speed data applicable to the common groups of fish present in coastal waters in Britain is presented, and it is shown how these can be used to determine appropriate intake velocities for fish exclusion. Reference is made also to the problem of asymmetrical velocity distributions around offshore intakes located in tidal crossflows, and the correct application of velocity criteria in these situations.

Possible solutions are discussed where fish exclusion is a priority but the ability of fish to detect intakes is likely to be poor due to high turbidity. These involve the use of sound, light or hydraulic stimuli. However, results are likely to be site-specific and field trials would be required.

The fish-attractant properties of offshore intake structures are considered. Designers of many existing intake structures have unwittingly incorporated features which are now recognized as fish attractants, in particular, open steelwork superstructures and boulder rip-rap. Such features can be expected to add to the problem of fish ingress.

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1. INTRODUCTION

Large, direct-cooled power stations inevitably draw in quantities of fish and other aquatic organisms with the cooling water (CW) supply, which from any point of view is undesirable. Environmentally, the presence of dead and dying fish in screenwash 'trash' creates a bad public impression, even though it has been demonstrated repeatedly that the numbers of fish involved are unlikely to harm stocks as a whole (Turnpenny, Utting, Millner and Riley, 1983; Henderson, Turnpenny and Bamber, 1984; Henderson and Holmes, 1985). From a power-plant operational aspect, fish ingress adds to the daily problem of screenwash 'trash' disposal. At worst it can lead to screen blockage and reductions in generating load or even a complete shutdown, often with the possibility of physical damage to screening plant. In Britain, screen blockage by fish has occurred on several occasions at power stations operating on the south and east coasts (Dungeness, Isle of Grain, Sizewell, Kincardine) involving costs estimated at millions of pounds sterling in lost generation and repairs (Mawer and Harris, 1975; Langford, 1983).

There is no shortage of scientific literature on the subject of excluding fish from CW intakes. Techniques range from the bizarre (underwater rock music: Schuler and Larson, 1975) to costly systems involving ultra-fine screens or filters or fish return systems (Langford, 1983). Some ideas work well under laboratory conditions but fail to make a satisfactory transition to an engineering design; others seem good as engineering solutions but fail to work for biological reasons. A common fault throughout the literature is the failure to recognize the fundamental biological principles which lead to fish capture, and a subsequent failure to recognize the limitations imposed by a hostile aquatic environment and by engineering constraints.

This Report describes the biological reasons underlying fish entry into CW intakes, and attempts to establish basic principles of intake design for fish protection. This is based upon review of published literature, and the results both of 10 years of study of fish impingement at the CEGB's major coastal power stations, and of fish behavioural studies carried out at the CERL Marine Biology Unit, Fawley. It is hoped that the information presented will help to make engineers aware of how and why fish become drawn into water intakes, and how this problem may be alleviated.

Reference is made also to research into the design of fishing gear since the behavioural basis of fish capture is similar for both water intakes and towed fishing gears, although the aims regarding fish are diametrically opposed. It is quite valid in many instances simply to reverse the sense in which the principles are applied.

2. FISH BEHAVIOUR IN FLOW FIELDS

Water currents are a natural feature of the aquatic environment and fish react to them in a number of ways. This subject has been reviewed comprehensively by Arnold (1974). The response to currents varies between species, and within species according to the time of day, tidal currents and stage of the life cycle. Three main categories of response can be distinguished:

- (i) random movement or passive drift (i.e. no response);

- (ii) positive or negative rheotropism (i.e. swimming with or against currents);
- (iii) selective tidal stream transport/modulated drift.

At low current speeds ($<1-3 \text{ cm s}^{-1}$), the current has no effect on the direction in which the fish swims. At higher current speeds, a common response is for the fish to head into the current (positive rheotropism) and to maintain station relative to the background (i.e. sea bed, fixed structures, etc.). Most often this response is mediated visually by the optomotor reflex. The optomotor reflex is a behavioural response whereby the fish attempts to stabilize its visual field by maintaining station with reference to the most prominent components of the visual field. The optomotor reflex is also important in maintaining school structure in pelagic species (Blaxter, 1975).

The optomotor reflex breaks down in low visibility. This can be caused by turbidity, or by the light intensity falling below a threshold level. This light threshold is surprisingly low, e.g. down to 10^{-7} lux (Arnold, 1974). It has been shown recently on the west coast of Scotland that even on the darkest night in midsummer there is sufficient light for mackerel to school (Glass, Wardle and Mosjiewicz, 1986).

In the absence of light, either passive drift occurs (predominantly in pelagic species such as herring and sprat) or else fish must rely upon cues derived from tactile contact with the sea bed (demersal fish only). It is possible also that fish can detect currents by means of velocity gradients or rotational currents, but the extent to which these mechanisms are used is not clear (Arnold, 1974).

Exceptions to positive rheotropism do occur. Fish inhabiting intertidal areas must follow the ebb and flow of the tide, though this may be due to a combination of negative rheotropism and response to depth change (i.e. hydrostatic pressure). More obvious exceptions are migrating diadromous fish (e.g. eels, shad, salmonids), moving from river to sea or vice versa. Salmonid smolts are negatively rheotropic when leaving the rivers and positively rheotropic when returning.

The final category is not directly relevant to flow fields around CW intakes but will be described for the sake of completeness. Within the sea, many species use selective tidal-stream transport to reduce energy costs of migration (Harden Jones, 1968). The mechanism involves moving with the tide in the direction of the destination, but remaining stationary on or near the sea bed during the reverse tidal phase. An analogous mechanism, known as 'modulated drift', is used by some freshwater species (notably salmonids) to effect downstream dispersal (as fry, parr, smolts). Their movement is modulated by light intensity, the fish remaining stationary in the light and drifting in the dark (Arnold, 1974).

Within this framework of natural behaviour, it is possible to predict how fish will respond to man-made currents at CW intakes. It is evident that fish which are attempting to follow currents will be particularly susceptible to impingement, which may be why salmonid smolts, for example, tend to be attracted towards cooling water intakes sited in the path of their seawards migration. Fish leaving inter-tidal feeding

areas on a falling tide are similarly vulnerable. For all fish, the natural response to a strong current in daylight conditions will be to turn into the current and to maintain station relative to the background, (e.g. the sea bed, sea wall or components of the intake structure) or else to swim away, but this will depend on the ability of the fish to detect the relative movement of the water. Escape at this stage will be possible only if the fish can swim fast enough.

Many older designs of offshore CW intake are open-topped and create a vertical drawdown of water which fish are ill-equipped to detect or escape from. Weight (1958) introduced the concept of a capped intake structure so that water is drawn in horizontally rather than vertically, offering fish a flow field more akin to the natural situation. The cap is known as a 'velocity cap' and can reduce fish ingress by as much as 90% (Downs and Meddock, 1974).

There are therefore three fundamental requirements for fish exclusion at water intakes. These can be summarized in the three key words, detection, velocity, and direction:

1. Detection: in order to escape, the fish must first be able to detect its approach to the intake, either visually or through mechanical cues (touch, noise, pressure changes, etc.). Poor visibility through low light or high turbidity may inhibit this, in which case alternative signals must be provided.
2. Velocity: the velocity along the line of escape must be within the fish's range of swimming performance.
3. Direction: the direction of water flow must be maintained in a horizontal plane for fish to resist being drawn in.

The following sections review aspects of fish reactions to water intakes and discuss how these requirements can be met by proper intake design.

3. SWIMMING PERFORMANCE OF FISH

3.1 'Burst' and Sustained Swimming

Fish locomotion has fascinated biologists and physicists for many years and there exists a vast literature dealing with the mechanics, physiology and biochemistry, as well as the speeds which fish can attain (see reviews by Blaxter, 1969; Wardle, 1976; Blake, 1983). Much of the work on swimming speeds has been carried out to determine optimum towing speed of trawling gears to maximize fish capture. The same data can, of course, be applied to intake design so that velocities at water intakes can be kept within the swimming speed capabilities of the fish. However, not all the data in the literature are relevant to this consideration and the findings require careful interpretation.

The swimming activity of fish is described by terms such as 'cruising speed', 'maximum sustainable speed', 'burst speed', 'critical swimming speed', 'voluntary swimming speed', and so on (Blaxter, 1969; Brett, 1967; Sonnichsen, Bentley, Bailey and Nakatani, 1973). From a

physiological standpoint, only two categories are justified, these usually being termed 'maximum sustainable swimming speed' and 'burst speed'. Blake (1983) refers to this as a 'two-gear' system. The basis for this distinction is the fact that most fish possess two types of propulsive musculature, known as 'red' and 'white' muscle, respectively. The smaller component is the red muscle, normally comprising 10-20% of the total muscle volume. The red coloration is due to a high content of the oxygen-storing pigment myoglobin. Also, the muscle is heavily infiltrated with blood capillaries to maintain a good oxygen supply which the red muscle fibres require for contraction. For this reason, red muscle is also commonly referred to as 'aerobic' muscle. In most fish, the red muscle is identifiable as a narrow band along the flanks of the fish, though deep red fibres are found in some species (Fig. 1). Despite the relatively smaller volume of the red muscle, it is responsible for most of the fish's activity, providing the 'low gear' for normal cruising and sustained swimming.

White muscle, on the other hand, represents up to 90% of muscle volume, and is used almost exclusively for rapid acceleration to achieve burst speeds, the so-called 'high gear'. White muscle fibres contract faster than red fibres and, because they function anaerobically, are not limited by the rate of arterial oxygen supply.

Typically, burst swimming is used by predatory fish when feeding, or by the prey fish when escaping. At normal cruising speeds the additional mass of unused white muscle is no great burden to the fish since it is approximately neutrally buoyant. However anaerobic muscle fatigues within a few minutes and studies have shown that repayment of the oxygen debt may take up to 24 hours (Batty and Wardle, 1979). During this recovery period the fish is unable to attain maximal performance and hence is at increased risk of predation.

The relevance of these facts to intake design centres on the question of which mode of swimming is likely to be employed by fish attempting to escape from an intake. Clearly, if they engage anaerobic swimming muscle they will achieve higher swimming speeds, typically 2-5 times higher (Wardle, 1976). Evidence does not point this way, and most investigators agree that fish which come into contact with intake currents adopt a steady sustained swimming posture and not the 'burst-drift' posture associated with anaerobic swimming (e.g. Schuler and Larson, 1975; Turnpenny, 1983). The pattern of behaviour observed for juvenile clupeid schools (sprat and herring) by Turnpenny (1983) at the intakes of Fawley Power Station, Hampshire, is almost exactly analogous to that described by Wardle (1976) on the basis of underwater filming of fish behaviour in front of towed fishing gears. From these observations, three stages can be distinguished: (1) the fish perceive the approach of the net or intake and turn to swim away from it; (2) the fish adopt a steady sustained swimming posture, maintaining a constant distance from the approaching structure for as long as possible; (3) finally, the fish either fatigue and drop back with current into the net or intake and are captured, or else they swim out ahead of the current and escape.

This pattern of behaviour leads one to question why many of the fish which are caught apparently do not bring into action the higher performance white muscle, thereby increasing their chance of escape. The

answer may lie in the high penalty to be paid by fish which make a wrong decision about the mode of swimming to adopt, by way of the risk at which they place themselves during the recovery period after anaerobic swimming. Fish may have evolved an escape response in answer to quite specific stimuli, criteria of which may not be met in front of a steadily moving trawl or in the steady current approaching a water intake. This explanation is supported by observations of fish behaviour in front of towed fishing gears. Wardle (1976) reports that "divers have shown that if they reach out and grab at a haddock swimming between the wings (of the net), this fish can easily burst away at great speed and swim out of the gear". With steady movements, however, they choose not to. Similarly, in front of the water intakes at Fawley Power Station (Turnpenny, 1983), clupeid schools are seen to be quite capable of escape when startled by a sudden movement or noise such as an object being dropped into the water nearby.

3.2 Measures of Sustained Swimming Performance

Sustained swimming performance has been measured in a number of ways. There are reports in the literature on swimming speeds of fish measured in the natural environment by sonar (e.g. Harden Jones, 1962), acoustic tagging (Greer Walker, Harden Jones and Arnold, 1978) and other such observational methods. Whilst these methods are unlikely to suffer from the disadvantage of stress induced by handling and confinement which may affect laboratory findings, there is no way of knowing whether the fish are swimming at the limits of their performance. It is these limits which are of interest in the context of intake design.

Experimental methods of measuring maximum sustainable swimming performance usually entail use of a flume. That used by CERL at Fawley has a 7 m (L) × 0.6-1.5 m (W) × 0.2-0.5 m (D) test section in which water velocities from 5-120 cm s⁻¹ can be achieved by means of a paddle wheel driving a water circuit (Turnpenny, 1982). Velocity across the test section is maintained to within ±1 cm s⁻¹ across the width of the flume, thus ensuring that all the fish are exposed to the same velocity.

There are two approaches to the measurement of sustained swimming performance (Turnpenny and Bamber, 1983). In one method, batches of fish are introduced into the flume at a range of velocities and the times to exhaustion are noted. From these, swimming speed/endurance plots, such as shown in Fig. 2, can be constructed. Maximum sustainable swimming speed is that speed at which endurance time drops from hours to minutes, e.g. at about five body lengths per second (L s⁻¹) for sand smelt (Fig. 2). The disadvantage of this method is that it requires a separate batch of fish for each velocity tested. Each group represents a single experiment, which makes the exercise time-consuming and costly in fish.

The second method devised by Brett (1967) uses a single batch of fish which are exposed to a stepwise increase in velocity each hour until they fall back and become impinged on a downstream grid. Brett then defines the Critical Swimming Speed (U_{crit}) as:-

$$U_{crit} = \text{Velocity at time step prior to impingement} + \left\{ \frac{\text{Minutes at impingement velocity}}{\text{Time step (minutes)}} \right\} \times \text{Velocity increment}$$

As can be seen from Fig. 2 the mean U_{crit} line for a group of fish corresponds closely with the estimate of maximum sustainable speed based on the more laborious incremental method. In both cases, the swimming speeds indicated represent the point at which white muscle is used to support swimming activity (i.e. the point of anaerobic swimming) and for practical purposes the critical swimming speed can therefore be regarded as the maximum sustainable swimming speed.

The U_{crit} method has been adopted for all routine measurements of fish swimming performance at CERL.

3.3 Factors Affecting Sustained Swimming Performance

3.3.1 Inter-specific differences

Sustained swimming performance varies widely between species as a result of variations in body form, proportion and disposition of red muscle and the mechanics of movement through the water. These differences reflect the various lifestyles to which different species have become adapted (Blake, 1983). In general, sustained swimming performance must be considered for individual species, though, as will be shown, within certain groups of fish performance characteristics may be similar.

As a rough guide, pelagic species such as the scombrids (tuna, mackerel) and clupeids (e.g. sprat, herring) are recognized as the fastest swimmers, followed by demersal species such as gadoids (cod, haddock, saithe, etc.) and flatfishes. Inshore benthic species (e.g. blennies, gobies, sea scorpions, dragonets, bullheads, pipefishes) on the other hand, have no recognizable sustained performance capability, since their mode of life involves either browsing or darting for food or cover if threatened.

The anadromous salmonids also have quite fast sustained performance, as befits their requirement for protracted migrations (Blaxter, 1969).

3.3.2 Intra-specific differences

Swimming performance within individual species is known to be affected by a number of factors including physiological condition, size, and water quality (Blaxter, 1969). The relationship between fish size and sustained swimming performance has been investigated by many authors (see reviews by Bainbridge, 1961, Blaxter, 1969, Wardle, 1977, Blake, 1983). It is frequently assumed that swimming speed is directly proportional to the length of the fish, and hence many accounts refer to swimming speeds in terms of body lengths swum per second ($L s^{-1}$). It is now well known that this relationship does not hold over a wide range of fish sizes, and that smaller fish can swim a larger number of $L s^{-1}$ than can bigger fish,

$$\text{i.e. } U \propto L^d \quad (d < 1) \quad \dots (1)$$

Where U is the distance swum in unit time, L is fish length. This finding is especially important in considering intake design, since most published

swimming performance data refer to mature commercial sized fish, whereas fish impinged at power station intakes are predominantly small species or juveniles of commercial species, and these may swim faster than published data would suggest. It is therefore necessary to obtain performance data directly for smaller sized fish, or else to re-scale values based on larger specimens by determining an appropriate value for the exponent.

Bainbridge (1961) examined reasons for the relative decrease in performance in larger fish by examining the relationship between power available from swimming muscles and the drag forces on the fish's body, based on the hydrodynamic theory of flow over a flat plate. His analysis, developed further by Turnpenny (1984), leads to the conclusion that increased drag limits the performance of larger fish such that for laminar and turbulent flow conditions respectively:

$$U_{\text{lam}} \propto L^{(b-1.5)0.40} \quad \dots (2)$$

and

$$U_{\text{turb}} \propto L^{(b-1.8)0.36} \quad \dots (3),$$

where b is the coefficient in the regression of fish weight (W) on length:

$$W = a L^b \quad \dots (4).$$

Assuming isometric growth, which is approximately true for many species, then $b = 3.0$ and expressions (2) and (3) simplify to:

$$U_{\text{lam}} \propto L^{0.60} \quad \dots (5)$$

$$U_{\text{turb}} \propto L^{0.43} \quad \dots (6)$$

Wardle (1977) has shown that during sustained swimming activity, fish tend to remain below critical Reynolds numbers (1×10^6) at which laminar flow becomes turbulent, and hence expression (5) can be adopted.

Turnpenny (1984) fitted this model to performance data for the gadoid species pout, in the length range 6.1-20.5 cm and showed that the resulting curves adequately accommodated data for other members of the gadoid family up to 40 cm in length. Both the oxygen content and the

temperature of the surrounding water have been shown to influence sustained swimming performance. A clear demonstration of these effects was given by Brett (1964) who studied performance of Pacific Salmon in a tunnel respirometer. Brett showed a logarithmic increase in oxygen demand with increased temperature over the range 5-15°C. At temperatures above 15°C swimming speed was reduced due to oxygen limitations which result from the combination of increased oxygen demand and decreased oxygen solubility at higher temperatures. These effects of temperature on sustained swimming performance have also been shown for some marine fish species (Turnpenny and Bamber, 1983; Turnpenny, 1984).

The influence of water temperature on fish catch at water intakes is widely reported (Langford, 1983). Catches tend to increase at low winter water temperatures, due to the decreased swimming performance and hence escape potential. Under these conditions oxygen is unlikely to become a limiting factor except where the oxygen level is greatly reduced by pollution. In general, therefore, consideration of metabolic effects can be confined to temperature effects.

3.4 Swimming Performance Data for Representative British Species

Although several hundred species of fish have been recorded in British coastal waters (Wheeler, 1968), and typically 50-80 species occur in intake screen catches from any one power station, a sub-set of a dozen or so species (Table 1) has been found to account for 80-90% of the catch at coastal sites in Britain (P.A. Henderson, pers. comm.). It is therefore sensible to narrow the discussion to these species in order to establish criteria for fish exclusion. From time to time there will be additional species which deserve attention for ecological or socio-political reasons. A typical example is the Atlantic salmon and so the salmonid family is also included in the synopsis of swimming speed data contained in this section. Even for this subset of species, data are sparse, and only provisional estimates of performance can be made for some species, pending further experimental work.

Within the literature on swimming speed, a variety of different formulae has been used to express maximum sustainable swimming speeds. To facilitate comparison and further utilization, the data summarized here have been re-examined and fitted to a standard model of form:

$$U_{crit} = (a + k_t \cdot T)L^{0.6} \quad \dots (7)$$

In this formula, U_{crit} is the maximum sustainable swimming speed measured in units of distance swum per second and T is the water temperature, a and k_t being species-specific regression coefficients. Table 2 lists values of these coefficients for several different species.

As seen from Fig. 3 the slopes of the lines and hence the values of the temperature coefficient, k_t , are similar, especially for those species of fish where larger numbers of specimens have been tested. The mean value of the temperature coefficient, weighted for the number of specimens in each case tested, is 0.58. This value has therefore been

assumed in cases where adequate data covering a range of temperatures were not available.

Further assumptions are also made:

1. Performance of species within any one family is comparable. For practical purposes, this assumption appears to hold within the Gadidae (Turnpenny, 1984) and within the Clupeidae (Turnpenny, 1983) and, in view of the similar morphology should hold within the flatfish too (Pleuronectidae, Soleidae).
2. No data was available for the flatfish, species listed. Wardle (1976) locates plaice on a similar performance curve to cod. Also, Beamish (1966) gives data for the North American winter flounder, which indicate similar performance to gadoid species. Values of a and b derived from gadoid data have therefore been applied to flatfishes.
3. Finally, at high water temperatures oxygen will become limiting, and thus performance will decline. For Pacific Salmon (Brett, 1967) and pout (Turnpenny, 1984) this occurs at temperatures of 15-20°C, though in sand-smelt performance is linear up to 20°C (Turnpenny and Bamber, 1983). In polluted waters having a lower oxygen content, oxygen will become limiting at correspondingly lower temperatures. For the present purpose, a linear relationship up to 17.5°C has been assumed for all species.

4. SWIMMING SPEED DATA IN INTAKE DESIGN

4.1 Specification of Approach Velocities

The water velocity ahead of the primary (coarse) screening systems of a water intake structure is termed the 'approach velocity'. A more precise definition for the present purpose is the maximum velocity in an intake system against which fish must swim to escape. To ensure that fish can escape, the approach velocity must therefore be kept below the maximum sustainable swimming speeds of the fish.

The swimming speed required for escape depends on the orientation of the fish. If the screen is not aligned normal to the flow and the velocity is close to the maximum sustainable swimming speed, fish are often observed to swim ahead of the screen, in a direction perpendicular to the screen face (Sonnichsen *et al.*, 1973; Arnold, 1974). This indicates that the fish are orientating to the face of the screen rather than the hydraulic streamlines. A similar behaviour has been observed in fishing gear research amongst flatfish herded by the sweeps and bridles of a trawl (Main and Sangster, 1981). It is generally agreed, therefore, that the design velocity for fish escape should be computed as the velocity vector normal to the bars of an intake and not along the streamline, unless these happen to be perpendicular to the trash-rack face.

Design values for approach velocities have been adopted by various agencies with a view to fish exclusion. Schuler and Larson (1975) cite a design velocity of 76 cm s⁻¹ for the Southern California Edison Company's (SCEC) offshore) intake structures, but from their own

experimental trials recommended a modified design value of 46 cm s⁻¹ for SCEC's San Onofre Nuclear Generating Station. Other utilities in the USA have adopted design values as low as 15-30 cm s⁻¹ (Sonnichsen *et al.*, 1973). In Britain, the CEGB has no rigid policy on this matter, though for example for the proposed Sizewell 'B' Power Station design, Mawer (1982) specifies a peripheral velocity at the capped offshore structure 'in the order of 50 cm s⁻¹ to enable fish to escape.

It must be borne in mind that other factors influence the choice of approach velocity, for example the necessity to prevent sedimentation in waters with a high silt burden, and the higher cost of the larger structure required to maintain low approach velocities. The final design velocity must therefore reflect an optimization of all the salient factors, of which fish exclusion is only one; its importance will depend upon the significance of the locality to fisheries.

Fish Escape Model

To ascertain approach velocities from which fish can escape, it is necessary to consider first the species present in the locality and then the size distributions present. From this information, swimming performance data can be used to predict the proportion of fish vulnerable at any given water temperature. Where significant seasonal variations occur due to age-selective migrations or growth, separate length distribution and temperature values can be applied for each season.

For fish to escape an approach velocity V_a the condition is

$$V_{crit} > V_a \quad \dots (8)$$

The critical length L_{crit} , i.e. the smallest size of fish which can escape, is derived from expressions (7) and (8) as:

$$L_{crit} = [V_a / (a + k_t \cdot T)]^{1/0.6} \quad \dots (9)$$

The proportion of fish vulnerable is then the sum of fish smaller than L_{crit} divided by the total population size, or if the length - frequency distribution is described by n classes of width w , such that $\sum_{i=1}^n L(i) = 1$ then the proportion vulnerable, p , is given by

$$P = \sum_{i=1}^{L_{crit}/w} L(i) \quad \dots (10)$$

Examples of this model applied to a range of species are shown in Fig. 4 (a - n). Here, values of p have been calculated for approach velocities in the range 0-150 cm s⁻¹ at 5 cm s⁻¹ increments. Along with these are shown the length distributions on which the curves are based.

Swimming speed coefficients are those listed in Table 2. The length distributions are for illustrative purposes and will vary from one coastal location to another, but are taken from recorded observations at UK coastal sites and are fairly typical of the inshore waters around power stations. The main site to site differences are likely to be in the proportional representation of different age classes. For example sprats at estuarine sites tend to be dominated by the 0+ age group, whereas at open coastal sites, particularly on the east coast of Britain, older classes predominate in winter months. To simplify presentation in these plots, the bulk annual length distributions have been used, summated for each of the 12 months, and curves have been computed based on swimming performance at four temperature values covering a typical annual range of 2.5-17.5°C.

For all species, the probability of escape is lowest when waters are coldest and thus to design for the worst case the 2.5°C temperature curve is most appropriate. However, in cases where the inshore presence of the species is seasonal, a temperature value relevant to that season should be selected. For example, for salmon smolts having a spring migration past the intakes, a water temperature of around 12.5°C might be appropriate.

Table 3 lists the maximum approach velocities for total exclusion of each species corresponding to the four temperatures shown in Figs 4a-n. Two sets of figures are shown. The left hand columns represent maximum approach velocities to enable fish of all age groups to escape. The right hand columns represent values for fish of age one year and older which can be applied to locations where 0-group fish are not strongly represented and where values in the left hand columns would therefore be excessively stringent. The values for one group and older fish are calculated from equation (7) using the minimum length values for age one fish shown in Table 3.

To provide an example, consider the problem of sprat influxes at power stations on the south-east and east coast of Britain. Their exclusion requires that approach velocities should be kept low enough for the fish to escape (given the necessary stimulus to do so). As the fish involved are predominantly of age one and older, and as the problems occur only during the winter months (Turnpenny and Utting, 1980) when water temperatures are low, a design approach velocity of 50 cm s⁻¹ would be chosen for sprat exclusion.

To achieve successful exclusion, other criteria would have to be met, and these are discussed in the next sections.

4.2 Velocity Characteristics of Water Intakes

4.2.1 Onshore and shoreline intakes

An 'onshore' intake is defined as one where the water is abstracted without the need for an offshore pipeline and intake structure. Where the marginal water is shallow, water is normally taken via a deep canal, or directly through a sea wall where the marginal water is deep. The second type is known as a 'shoreline' intake.

A typical onshore intake layout is shown in Fig. 5. Water enters via an orifice in a vertical wall. The opening is normally protected by a coarse screen or 'trash rack' of vertical steel bars fixed at ~15 cm centres. Beyond this is a travelling band or drum screen of ~8 mm square mesh opening which removes entrained fish and debris. While it has been shown (R.H.A. Holmes, pers. comm. and Turnpenny and Utting, 1981) that live fish released behind the coarse screens into the screenwell area can escape from the system, the hazards of turbulence in the screenwells and of toxicity due to chlorine injected to prevent bio-fouling render this opportunity unlikely as a general rule. The design expectation should therefore be that fish are enabled to escape before passing through the coarse screens.

The vertical openings of onshore intake designs lend themselves to fish escape since the water currents are predominantly horizontal at the coarse screens. The main consideration for fish escape is therefore that the approach velocity at that point, under all operating conditions, is kept within the swimming speed ranges of the fish as indicated in Section 4.1. It is preferable that a uniform velocity profile be achieved across the face of the screens but, if not, that the conditions for fish escape are met at the maximum velocity value.

A difficulty of some canalized onshore intake designs is that the point of maximum approach velocity in the canal is at some distance ahead of the coarse screens and not at the screen face. An example is at Fawley Power Station, where velocity values at the canal entrance may reach 150 cm s^{-1} at full load on a low spring tide, whereas the approach velocity at the screens is around 80 cm s^{-1} (Turnpenny and Utting, 1981). As a consequence, by the time fish come into contact with the coarse screens and attempt to escape, poorer swimmers become trapped within the system. The obvious answer to this problem is to avoid designing narrow constrictions in the canal ahead of the coarse screens but this is not always practical due to increased likelihood of siltation. As a protective measure, some form of behavioural barrier or warning system might prove effective in reducing fish ingress (see Section 5).

4.2.2 Offshore intakes

Offshore intakes vary widely in design, but generally comprise an offshore structure connected by a sub-sea tunnel to the shoreline. Older designs, such as Sizewell 'A' are open-topped and have strong vertical draw-down currents, whereas more recent designs such as Dungeness 'B'; Wylfa (both operational) and Sizewell 'B' (not yet built) have capped intakes with a more horizontal flow pattern (Fig. 6).

It is difficult to make comparisons of performance for capped and uncapped structures currently operating in Britain. Some evidence is provided by Spencer and Fleming (CEGB internal communication), who conducted a comparative survey of fish catch at Dungeness 'A' and 'B' power stations. The 'A' station intake is not a capped design, but is partially enclosed by a concrete in-fill on top of the intake grill which complicates the flow pattern. The 'B' station, on the other hand, is a capped design. Over a twelve month period, 'A' station catches per unit CW flow were invariably higher than 'B' station catches, the ratio of numbers caught for

'A':'B' ranging from 1.2:1 to 65:1. The differences may, however, have been partly due to differences in approach velocity, though no velocity measurements have been made to substantiate this. Nevertheless, this example perhaps emphasises the importance of the design of capped intakes and the fact that blocking the top of an intake without due regard to the flow pattern is not sufficient to guarantee fish protection.

Development of intake designs with horizontal flow is a specialized subject which cannot be treated in depth here. As a simple criterion for a fish protecting intake, Schuler and Larson (1975) proposed that "to create the desired uniformity in entrance velocity and to increase the time for reaction (of fish) to the flow, the cap and lip of the riser must extend horizontally from the riser body 1.5 times the height of the opening" (Fig. 6c). There are, however, reasons unrelated to fish protection for adopting capped intake designs. Goldring (1984) showed that capped intakes have superior characteristics for selective withdrawal of cooler water in thermally stratified environments - another example of how intake design must reflect a variety of requirements. An optimal solution should not be difficult to achieve with available mathematical models of fluid flow, capable of simulating the three-dimensional flow around an intake structure.

The horizontal flow pattern around an offshore structure is equally important. In still water, inflow is uniform around the structure and streamlines are normal to the trash-rack bars. In a tidal cross-flow, the distribution becomes biased, with most of the water entering close to the upstream radial axis where the approach velocity is consequently higher (Fig. 7). It would be expected from this that catch rate at an offshore structure sited in a tidal stream would tend to be maximal around mid-flood and mid-ebb, and minimal around the slack water period. This has indeed been shown to be the case at Sizewell 'A' Power Station where the CW intake structure is located within a longshore tidal flow and where it has been possible to make hourly measurements of fish catch and tidal velocity (Fig. 8).

Normal-to-bar velocities are in general lower in this situation (Fig. 7) but the velocity along the tidal axis remains the same. It is therefore important that the peak value, and not the average velocity figure is selected to enable fish to escape. In hydraulic model tests carried out at CERL (B.T. Goldring, pers. comm.) using a capped, circular intake with a nominal approach velocity (flow/screen area) of 25 cm s^{-1} , the measured peak velocity in a simulated 50 cm s^{-1} tidal crossflow was 70 cm s^{-1} . Using mathematical models of fluid flow, it is possible to simulate velocity profiles in crossflow conditions for any given intake configuration, and this should greatly assist in specifying the design of structure necessary to achieve acceptable approach velocities.

As a principle, it is not possible to achieve maximum approach velocities of less than the tidal cross-flow velocity using a circular intake structure. Where the maximum tidal velocity at the depth of the intake opening is higher than the recommended approach velocity for fish protection, an alternative intake design is required. A hydraulic model of a side-entry intake, with openings orthogonal to the tidal flows, has been tested successfully at CERL (B.T. Goldring, pers. comm.), but such a design would undoubtedly be more costly to construct than a circular intake and

would only be worth considering where fish exclusion was of paramount importance.

Alternative possibilities, such as locating the intake in a lower velocity tidal stream or abstracting from close to the sea-bed boundary layer where velocity will be lower, also merit consideration, but the possibility of higher fish densities in these areas, and increased silt and weed ingress, must also be taken into account.

5. DETECTION OF INTAKES BY FISH

Several sources of information may contribute to detection of intakes and orientation to currents, including visual and tactile cues, sound and hydraulic stimuli resulting from flow fields around intakes.

This section considers the sensory cues which may be available to fish in the vicinity of an intake and how these cues may be reinforced by improved intake design or by addition of supplementary stimuli.

5.1 Hydraulic Flow Patterns and Physical Contact

Flow fields around water intakes possess a number of hydraulic characteristics which fish may be able to detect. Large-scale (relative to body size) turbulence is recognized as a whole-body displacement, detected by labyrinthine receptors, while small-scale turbulence on the body surface is detected by the lateral line organ (Arnold, 1974).

The main turbulence around intakes will be in proximity to the structure itself, for example around screen bars, and in the downstream turbulent wake of an offshore intake structure located in a tidal cross-flow (Goldring, 1984). Since in the latter case, most of the water (and fish) entering the intake will arrive from the up-stream direction, the downstream wake is unlikely to be of use to them as a means of detecting the intake. Small-scale turbulence around structural components is therefore likely to be the main turbulent feature which fish detect.

It has been shown that fish can respond to shearing surfaces in the water (Bainbridge, 1975). The normal response is for the fish to turn into a higher velocity flow when passing through a shearing surface. It is not expected that discrete shearing surfaces would be a deliberate design feature of the water intakes, though velocity gradients perpendicular to the streamlines do occur and will be evident for example across the intake screen surface at an offshore intake (Fig. 7). In theory, at least, this should elicit a rheotropic response causing the fish to swim head upstream, aligned parallel to the streamlines. This behaviour would ensure that they were facing an appropriate direction for escape when they reached the structure. In the absence of any other stimuli, a fish so aligned may attempt to escape as its tail touches the screen bars or some other part of the structure, or it encounters small-scale turbulence associated with these components. The proportion of fish making contact in this way will depend on bar width and will be higher for larger bar widths and smaller spacings.

Louvre Screens

The sensitivity of fish to shearing surfaces is utilized in a mechanical screen known as the 'louvre screen'. The louvre screen consists of a horizontal array of vertical slats and flow straighteners set at an angle to the water flow like a venetian blind on edge (Fig. 9). As the flow strikes the louvres, eddy-currents are set up between the louvre elements. This enables the fish to orientate to the screen and pass along the screen face to the by-pass. Louvre screens were first devised in North America (Bates and Visonhaler, 1956), and have since been tested widely in experimental systems (Arnold, 1974; Environmental Protection Agency, 1976). Under optimal conditions, guiding efficiency is commonly >90%, whether in daylight or darkness, so that there is no requirement for illumination. The main parameters that vary are: louvre angle to flow, screen angle to flow, louvre spacing, number of flow straighteners, approach velocity, by-pass velocity and by-pass width. Too many variations of these parameters have been tested to list all here, but some details of experiments carried out in relation to Scottish hydro-electric developments in the 1960's (W.R. Munro, unpublished reports) will provide an illustration. These experiments used hatchery-reared salmonids and an experimental louvre array fitted into an aquaduct flume with the following parameter values:

Screen angle to flow:	12°
Louvre angle to flow:	90°
Louvre spacing:	5, 10 or 15 cm
Maximum approach velocity:	120 cm s ⁻¹
By-pass velocity:	1.4 × approach velocity
By-pass width:	45 cm

Under these conditions, over 90% guiding efficiency was attained.

An important point to note is that the fish orientates itself perpendicular to the screen array and attempts to maintain a constant distance between itself and the barrier as it swims. The velocity at which it must swim to do this is therefore much lower than the approach velocity. In Fig. 9 this is shown by the vector diagram, where V_s is the approach velocity and V_f the fish's swimming velocity. V_f is given by $(V_s \tan \phi)$, where ϕ is the screen angle. For example, for a maximum approach velocity of 120 cm s⁻¹, and a screen angle of 12°, the fish need only swim at a velocity of 26 cm s⁻¹ in order to escape.

Despite demonstrations that louvre screens are effective for guiding fish without the need for supplementary lighting, very few louvre screens have been constructed for other than experimental purposes. A potential problem is the likelihood of weed and debris accumulation on the louvres which would impede the flow and impair fish guidance. The problem can be overcome by using horizontal or vertical travelling louvre screens (Ray *et al.*, 1976) but these are costly and not amenable to all applications. The concept of louvre screening is adaptable to a variety of intake configurations including offshore marine intakes (Mussalli, Taft and Larsen, 1980) and aquaducts (Sonnichsen *et al.*, 1973).

5.2 Light

The Importance of Light for Fish Exclusion.

Visual cues are pre-eminent in allowing fish to orientate to currents because of the wide variety of visual information usually available. The minimum threshold velocity for detection of water currents by fish using visual cues is about an order of magnitude lower than that for tactile cues (i.e. 'brushing' the sea bed or attached weed: Arnold, 1974).

The importance of light in enabling fish to escape from fishing gears is well known, and night fishing is frequently found to be more effective since visual escape cues are obscured (Roessler, 1965). For similar reasons fishing in turbid waters can be more successful than in clear waters (Murphy, 1959).

The role of visual cues in avoidance of water intakes by fish is indicated by the diurnal patterns of screen catch. Fig. 10 shows the averaged hourly index of catch measured on 41 dates at Sizewell Power Station, Suffolk and indicates that peak catches occurred at night. Van den Broek (1979) reports fish catch rates 1.5 times higher at night than in daylight at Kingsnorth Power Station, Kent. Similar observations are recorded by Grimes (1975) in the USA and Hadderingh (1982) in the Netherlands. Hadderingh states that fish lost orientation at light intensities < 300 lux (surface measurement) and that fish impingement increased below this.

At Dungeness 'A' Power Station in Kent, Turnpenny and Utting (1980) showed that the catch of sprats increased severalfold after dark with an increase in the mean size of fish. This was interpreted to be the result of larger fish being able to see and avoid the intake by day but not by night. Smaller fish, on the other hand, although they could see the intake by day could not swim fast enough to escape.

It is noteworthy that no nocturnal increase in fish catch has been found at Fawley Power Station, Hampshire (Langford, Utting and Holmes, 1977). This site has an onshore canalized intake with overhead safety lights, which presumably enable fish to orientate to the intake at night.

For similar reasons, turbidity appears to affect catches, although there is no quantitative documentary evidence of this. At a number of UK power stations investigated by CERL, catches have been found to increase following stormy weather, most probably as a result of fish becoming disorientated by the increased turbidity. Continuously high turbidity levels in the Severn Estuary around Hinkley Point Power Station (range $152-1432$ mg l^{-1} solids: R.J. Aston and A.G.P. Milner, pers. comm.) probably account for the lack of any discernible diurnal pattern in the fish catch (P.A. Henderson and R.H.A. Holmes, pers. comm.), since the intake is obscured by suspended particles throughout the 24 hour period. In such situations it is unlikely that lowering the approach velocity, would be of any benefit to fish unless additional warning signals were provided.

Artificial Light

Langford (1983) reviewed experience of using artificial light to control fish ingress. Reactions of fish are mixed (attraction or repulsion) depending on species and lighting conditions. Haddington (1982) for example successfully used arrays of surface and underwater lights at Bergum power station to reduce fish entry and by a combination of negative phototaxis (repulsion) and increased visual orientation. Some species were attracted, a finding which is not unexpected since artificial light is widely used in commercial fishing to draw fish towards nets (Ben-Yami, 1976). Other researchers have attempted to use the phototactic response to guide fish towards fish rescue systems (Haymes, Patrick and Onisto, 1984) or away from intakes. A CEBG scheme to exclude sprats from Dungeness 'A' Power Station relied on this principle, but was unsuccessful (N. Robinson, T. Wickett, pers. comm.), and the approach in general is unpredictable because of the ambivalent reactions of fish to light.

A method which appears more promising is use of artificial light to make the intake visible to fish. At power stations where there is a marked nocturnal increase in fish catch, this should act to reduce catches to daylight levels. The light level employed is critical. It should be adequate to make the intake visible under all turbidity conditions at a distance of a few metres from the intake bars, while at the same time not attracting additional fish into the danger zone. This can be achieved most effectively by lighting the intake structure from within so that the bar elements are silhouetted. Under these conditions, dark adapted fish of a number of species have been shown to elicit an optomotor response at light levels above 10^{-3} lux (Pavlov, 1970). However higher light levels may be necessary to compete with background illuminance, and the levels required would have to be determined experimentally according to local circumstances.

An elaboration of this approach has been investigated by Patrick (1980, 1981, 1983) who used a combination of physical diversion barriers (ropes, chains, nets) and artificial lighting to exclude fish in a simulated intake system. He found that white strobe light, with a flash frequency >200 flashes/minutes, was more effective for fish exclusion than continuous illumination. Apparently the flashing light disturbed fish and caused them to stay away from its source, as well as illuminating the physical barrier. The rapid discharge characteristics of strobe light (flash duration ~ 60 μ s) make it more effective as a fish deterrent than flashing incandescent or metal halide lamps. It was not intended that the barrier should act as a direct physical restraint to fish, but that exclusion should be a visual response. With no light, the barrier was ineffective, and a light level of approximately 10 lux at the barrier was required to ensure that it would be visible under turbid conditions with the light source placed behind the barrier. The visual characteristics of the barrier were also shown to be important, the most effective design comprising vertical elements (chains) and horizontal elements (nylon ropes) at 15 cm spacings, with the diameter of the elements >3 cm. A pre-requisite for such a system to be effective is that the approach velocity should be within the fish's sustainable swimming speed range, in Patrick's experiments, values <32 cm s^{-1} being used.

Micheletti (1987) has recently reported on tests using strobe lights (200 flashes/min) at CW intakes in the USA. Success varied with species, but up to 56% reduction in fish ingress was recorded.

To summarize, artificial light can be used to supplement natural light, allowing fish to determine visually their approach towards an intake. Best results are obtained if the light source is placed behind a bar structure, the latter preferably with vertical and horizontal components at ~ 15 cm spacings. The problem of fish attraction towards the light source can be eliminated by using a white strobe light with a flash rate of >200 flashes/minute. Patrick (1983) also found no evidence of fish becoming habituated to strobe light.

There will be practical difficulties in maintaining an artificial lighting system at a marine intake structure. Perhaps the best solution would be to use powerful overhead lighting and to rely on particle scattering to produce even illumination. Such a system could possibly be mounted within non-submerged offshore intake structure. Alternatively, an overhead light source feeding a light guide dipped into the water might be feasible, provided that suitable provision was made for antifouling and cleaning.

5.3 Sound

Orientation to Sounds

Sound may also cause a fish to react to a water intake. Although sound generally does not appear to be an important source of information for orientation to currents (Arnold, 1974), fish do have a directional hearing capability (Blaxter, Gray and Denton, 1981) and thus should be able to detect their movement relative to a looming point source of sound.

Hearing in fish utilizes two separate sensory channels. Low frequency sounds (5-25 Hz) are detected by the lateral line and higher frequencies (up to 13000 Hz) by the auditory labyrinth. For most species, maximum sensitivity is in the range from a few hundred to one or two thousand Hz (Hawkins, 1973). It is not possible at present to assess the importance of sound as either a sensory cue or a deterrent at cooling water intakes. Undoubtedly machinery noise, particularly from pumps and moving parts in direct contact with the cooling water system will be transmitted via the inlet culvert to an offshore intake structure, but the frequencies and sound levels involved have not been measured. Furthermore, it is not possible to infer from catch statistics any effects due to these sounds since changes in sound levels are most likely to stem from variations in the pumping rate which, irrespective of noise level will markedly affect catch. Loeffelman (1987) reported that fish were repelled from the intake of a bulb-type hydro-electric turbine by the noise it produced. In a bulb turbine the generating unit is located underwater in the turbine draft tube, which acts like a megaphone. The main frequencies were in the range 80-800 Hz, i.e. at the optimum sensitivity of most fish, and the sound levels were as high as 197 dB (3697×10^{-7} watts cm^{-2}) close to the intake. This was clearly a phonotactic and not a rheotactic response.

Using Sound to Repel Fish

Several workers have investigated the use of artificial underwater sound to keep fish away from intakes. Records of killer whales and rock music played through underwater loudspeakers failed to elicit a startle response in fish. However, sounds with an associated shock wave were effective, for example, a wooden mallet struck on a submerged plank of wood or metal, or pneumatic 'poppers' of the type used in underwater seismic exploration. Poppers were used in short term tests at Redondo Beach Power Station (southern California), operated at a frequency of 6-12 cycles min^{-1} . Fish were repelled immediately and remained at a distance from the intake throughout a 3 h test period (Schuler and Larson, 1975). More protracted tests at two power stations over a two year period gave a 73-78% reduction of alewife, though there was less success with other species (Micheletti, 1987).

Loeffelman (1987) has proposed playing back recorded sounds from bulb turbines through underwater loudspeakers to deter fish from intakes. A powerful sound system would be required to reproduce sound levels found at actual turbine inlets.

As with lights, there will be practical difficulties, due to fouling, corrosion and wave action, with maintenance of any such system at a marine intake, particularly one located offshore. Some sort of pneumatic or electromagnetic device mounted within the intake structure with only a conduit in contact with the water might be more feasible than a system employing underwater transducers. This could be particularly effective against sprat and herring which belong to the same family as alewife (Clupeidae) and which have been shown to be capable of a directional startle response (Blaxter, Gray and Denton, 1981).

6. FISH ATTRACTANT PROPERTIES OF INTAKE STRUCTURES

Any sizeable structure projecting from the sea bed will serve to attract certain types of fish. The reasons for this are complex and the accumulation of fish around such structures may be related to a need to shelter from predators or tidal currents, or to take advantage of food resources around or attached to the structures. Some offshore intakes possess features akin to purpose-built artificial reefs. Just as cooling water intakes should be designed as the antithesis of a fishing gear, so the intake structure should be designed as the antithesis of an artificial reef.

A number of concepts can be found in artificial reef design. One is simply to simulate a natural rock reef by dumping rock, broken concrete or similar (Fig. 11b) which provides a substrate for settlement and crevices for invertebrates and fish. Reefs of this type tend to develop naturalistic communities and increase of fish productivity (Wilson, Togstad, Lewis and McKee, 1987). Another type of reef uses large open cage structures of wood, plastic, steel or concrete with a minimum of material occupying a maximum volume (Fig. 11a). Reefs of this kind are perhaps more important for shelter than for food (Ogawa, 1978). Redundant oil platforms are being used for this purpose.

It will be clear from this that offshore intake structures often embody characteristics of both of these kinds of reef. Schuler and Larson (1975) comment that the boulder rip-rap around the Redondo Beach Power Station intake and the structure itself, act as an artificial reef. This too will apply to many of the offshore intakes in the UK, where the practice has been to use boulder rip-rap around the base of the structure, and a latticed-girder super-structure to support navigation lights, cranes and maintenance equipment. An example is shown in Fig. 11c, where the similarities with purpose built fish reefs can be seen.

The fish attractant effects of an offshore intake structure can probably never entirely be overcome. In general, the engineer should attempt to minimize superstructure as far as possible, to simplify the number of structural elements, to keep surface area for colonisation to a minimum and eliminate as far as possible holes and crevices. Wake-eddies have been shown to be important for fish shelter, and therefore, streamlining elements of the structure may help to minimize available shelter. The vertical relief from the sea bed has also been shown to be significant; high structures accumulate more fish.

7. CONCLUSIONS

(1) At most sites, fish entry into water intakes is not a serious hazard to plant operation nor a threat to the fish stocks themselves. Therefore, the cost and effort devoted to fish protection in intake design and siting should be commensurate with the magnitude of the problem. By providing an understanding of the causes of fish ingress and the principles of fish exclusion, it is hoped that (a) design pitfalls may be avoided without necessarily incurring higher costs and, (b) where improved fish protection is essential the means of providing this will be more apparent. Any such measures should not be allowed to conflict with requirements to exclude weed and prevent siltation.

(2) The main requirements for fish exclusion from water intakes are summarized by three key words: detection, velocity, and direction.

Fish must be able to detect its approach to an intake if it is going to be able to react to escape.

The velocity of the water entering the intake must be low enough at the point of reaction for the fish to be able to escape.

The direction of water flow must be horizontal as fish are not good at escaping from a vertical draw-down.

All three of these requirements must be met simultaneously if fish are to escape.

(3) Detection of Intakes Intakes normally are detected visually. If the light level is low or the turbidity high, fish catch increases. Artificial light has been used successfully to improve detection of intakes by fish, but it can attract some species if strong illumination is used. Experimental evidence suggests that strobe lights can be used to illuminate intakes, whilst at the same time repelling fish. These are most effective if placed on the downstream side of an intake screen so as to silhouette

the bar elements. Low frequency pulsed sound, such as emitted by an acoustic 'popper', or a rumble such as produced by bulb turbine machinery, also shows some promise. Further work on the engineering practicability of operating either of these systems in a hostile marine environment is required. Louvre screens, which depend on hydraulic stimuli, can be used to deflect fish, and are effective in light or dark conditions.

(4) Approach Velocities The swimming capabilities of fish vary with species, size and water temperature. Because the fish at risk differ from site to site and also seasonally, it would be counter-productive to specify a standard intake approach velocity. Instead, the design velocity should be tailored to the species identified locally as being the greatest threat (to plant operations) or most at risk. Although swimming performance data presented in this Report are not exhaustive, they should be adequate for most needs. In calculating approach velocities, velocity components normal to the screen or trash-rack should be used.

(5) Flow Patterns around Intakes A capped intake converts a vertical drawdown into a horizontal water flow. Physical and mathematical models have been used successfully to model three-dimensional flow patterns around intakes. These will be useful in future to ensure that (a) flow is maintained in a horizontal direction and (b) that maximum velocities are kept below target requirements all around the intake structure in tidal crossflows. Where the velocity of the tidal crossflow precludes use of a 360° intake opening, side-entry intakes may have to be used.

(6) Fish Attraction Consideration must be given to the fish-attractant properties of the intake structure. All offshore structures will intrinsically tend to attract fish, but this can be minimised by simplifying the super-structure and keeping the area of rip-rap to the minimum required to prevent erosion.

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Tables 1-3, Drg. No. RL8.2.318-341 attached.

Table 1: Species of Fish Commonly Captured on Intake Screens
at British Coastal Power Stations

Family	Species	Common Name
Clupeidae	<u>Sprattus sprattus</u> <u>Clupea harengus</u>	Sprat Herring
Gadidae	<u>Gadus morhua</u> <u>Merlangius merlangus</u> <u>Trisopterus luscus</u> <u>Trisopterus minutus</u>	Cod Whiting Pout Poor Cod
Pleuronectidae	<u>Pleuronectes platessa</u> <u>Platichthys flesus</u> <u>Limanda limanda</u>	Plaice Flounder Dab
Soleidae	<u>Solea vulgaris</u>	Sole
Serranidae	<u>Dicentrarchus labrax</u>	Bass
Mugiladae	<u>Liza auratus</u> <u>Crenimugil labrosus</u>	Grey Mulletts
Atherinidae	<u>Atherina boyeri</u>	Sand Smelt

Table 2: Swimming Speed Coefficients for Selected Fish Species

U_{crit} is calculated from Equation (7).
References indicate data sources used to compute the coefficients.

Species	Coefficients			Source Reference
	a	b	n	
Sprat } Herring }	9.3	0.58	285	Turnpenny, 1983; Blaxter and Hunter, 1982
Cod } Whiting } Pout } Poor Cod }	3.8	0.56	170	Turnpenny, 1984
Plaice } Flounder } Dab } Sole }	3.8	0.56 *		Wardle, 1976, Beamish, 1966
Bass	6.2	0.82	56	Turnpenny, 1980 + unpublished
Grey Mulletts	6.2	0.82	67	Turnpenny, 1980 + unpublished
Sand Smelt	5.0	0.55	166	Turnpenny and Bamber, 1983
Salmon	8.0	0.32	35	Brett, 1967

n = number of experimental observations.

* = gadoid values assumed

Table 3: Maximum Approach Velocities Which Will Enable Fish to
Escape at Different Water Temperature

	Age Group 0 and Older				Min. Length	Age Group 1 and Older			
Temp °C	2.5	7.5	12.5	17.5	Age 1	2.5	7.5	12.5	17.5
<u>Species</u>	<u>cm s⁻¹</u>				<u>cm</u>	<u>cm s⁻¹</u>			
Sprat	30	40	50	60	8	50	64	78	92
Herring	30	40	50	60	12	50	65	80	94
Cod	15	30	40	55	15	30	52	74	95
Whiting	10	25	40	50	15	35	55	79	102
Pout	8	15	20	29	20	34	60	83	105
Poor Cod	10	25	35	50	10	26	40	59	73
Plaice	8	15	20	30	8	28	48	67	92
Flounder	10	20	30	40	12	28	46	66	86
Dab	2	10	20	26	10	12	23	34	46
Sole	5	15	20	30	11	22	40	57	72
Bass	20	35	50	66	9	37	59	83	109
Grey Mulletts	20	35	50	60	10	30	50	69	89
Sand Smelt	10	20	30	40	7	24	40	53	70
	Age Group 1 and older					Age Group 2 and older			
Salmon Smolts	45	60	70	80	15	55	68	79	91

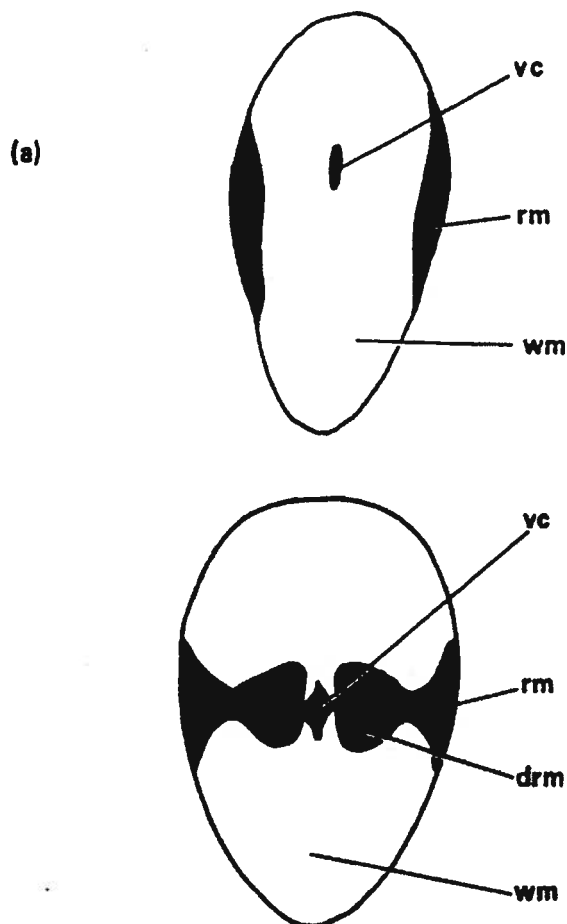


FIG. 1 FISH CROSS SECTIONS SHOWING THE DISTRIBUTION OF RED AND WHITE MUSCLE FIBRES:

**(a) A CLUPEID – THE ANCHOVY, *ENGRAULIS MORDAX*
(AFTER GREER WALKER, HORWOOD & EMERSON, 1980);**

**(b) A SCOMBRID – THE SKIPJACK TUNA,
KATSUWONUS PELAMIS (AFTER REYNER & KEENAN, 1967)**

**vc = VERTEBRAL COLUMN, wm = WHITE MUSCLE
rm = RED MUSCLE, drm = DEEP RED MUSCLE**

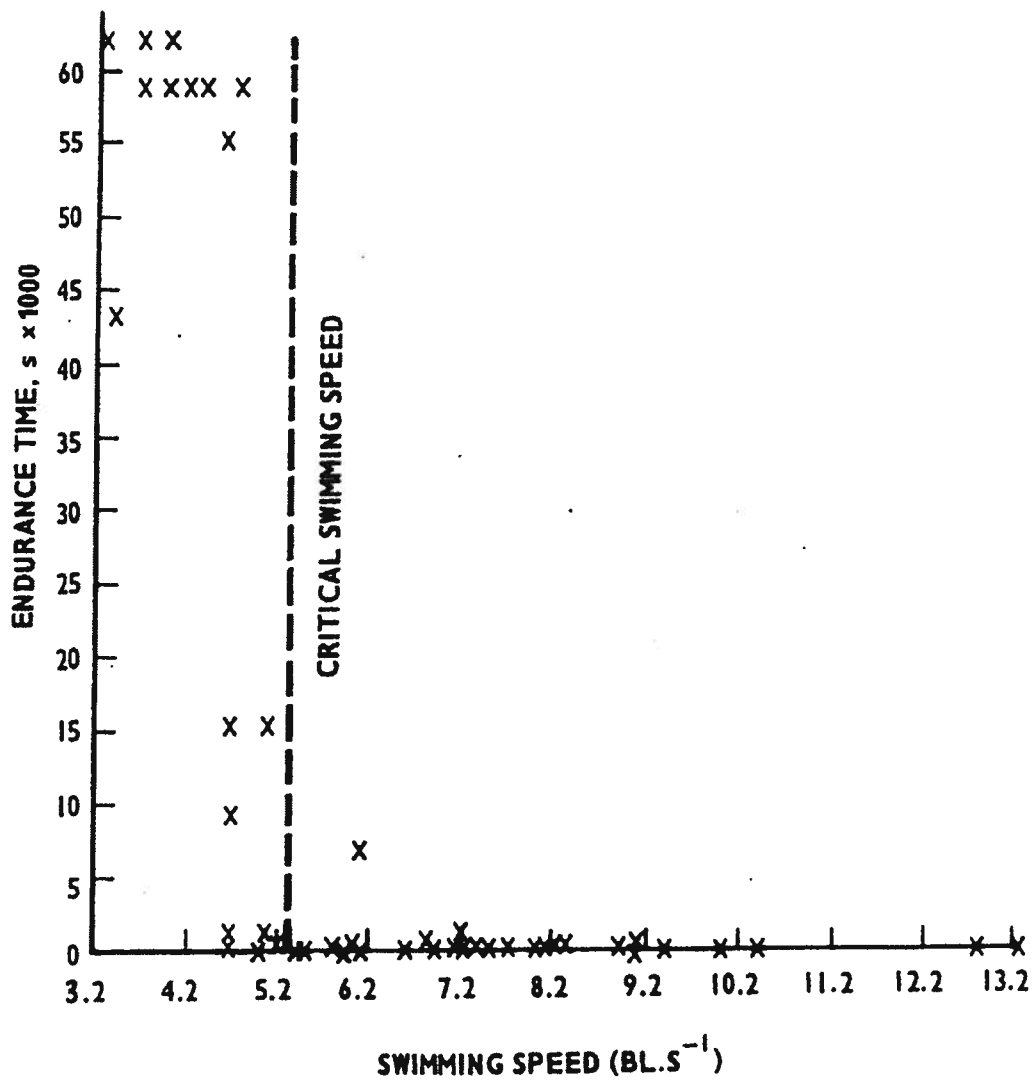


FIG. 2 COMPARISON OF FIXED VELOCITY AND INCREMENTAL SWIMMING SPEED TESTS FOR DETERMINING MAXIMUM SUSTAINABLE SPEED

VERTICAL BROKEN LINE INDICATES MEDIAN CRITICAL SWIMMING SPEED DETERMINED BY THE INCREMENTAL METHOD; POINTS INDICATE ENDURANCE TIMES OF INDIVIDUAL FISH AT DIFFERENT FIXED VELOCITIES. DATA FOR O-GROUP SAND-SMELT AT 11.4°C.

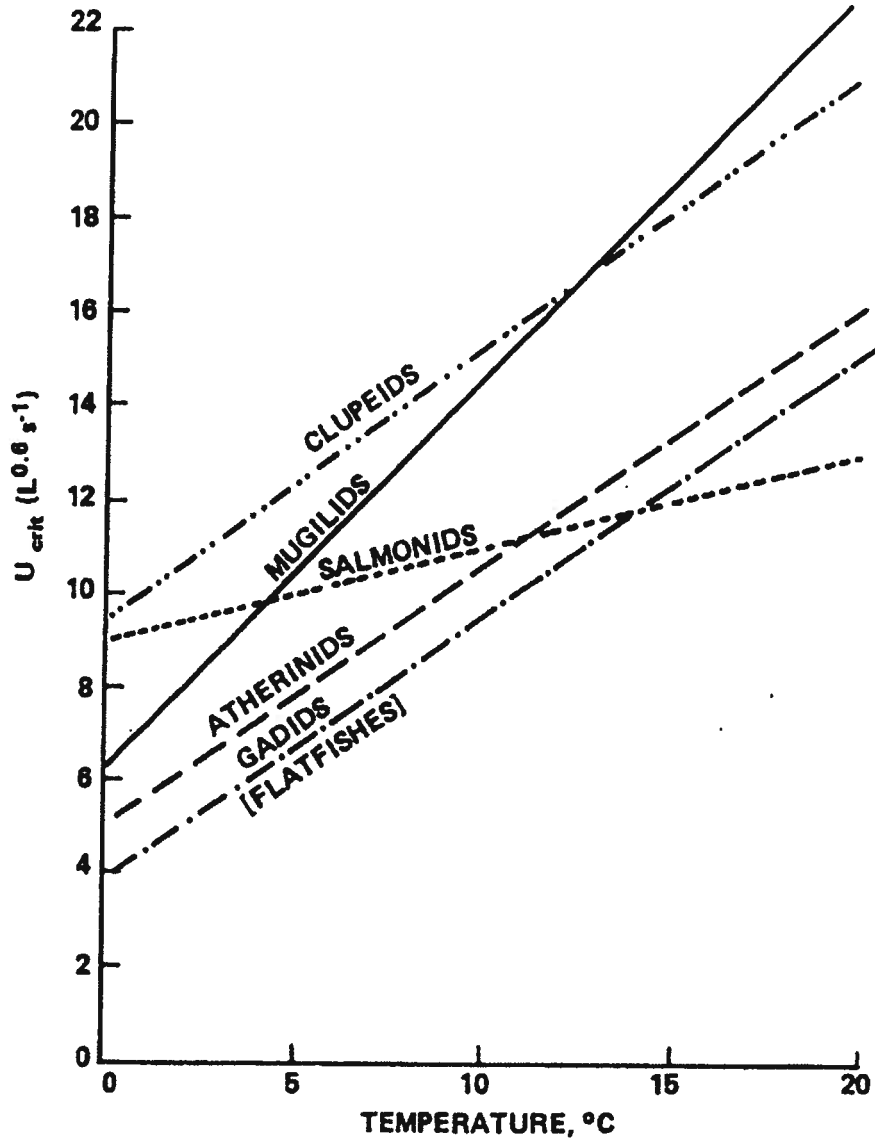


FIG. 3 SWIMMING SPEEDS IN RELATION TO BODY LENGTH AND WATER TEMPERATURE FOR VARIOUS GROUPS OF FISH (SEE TABLE 2 FOR SOURCES OF DATA)

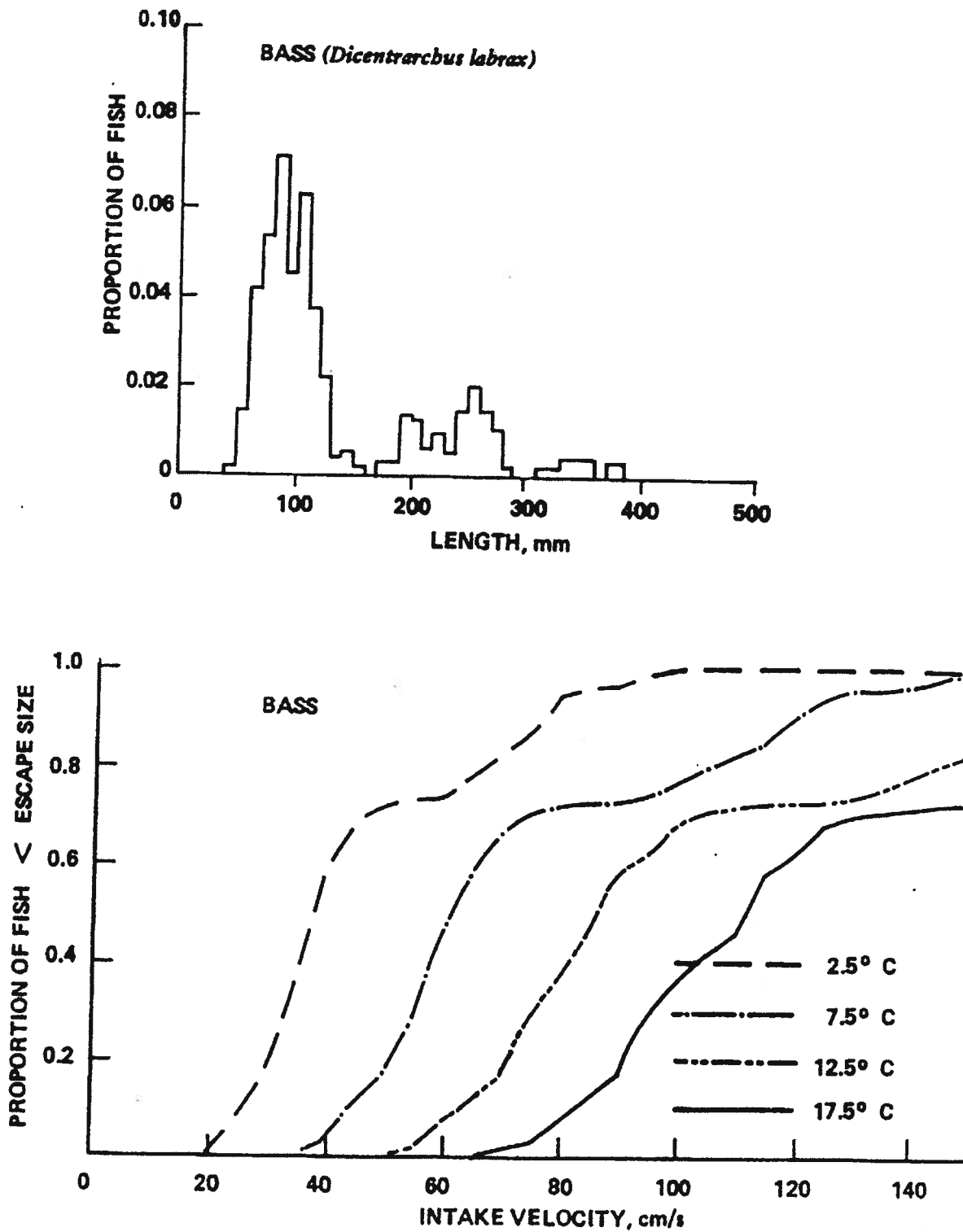


FIG. 4(a) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated

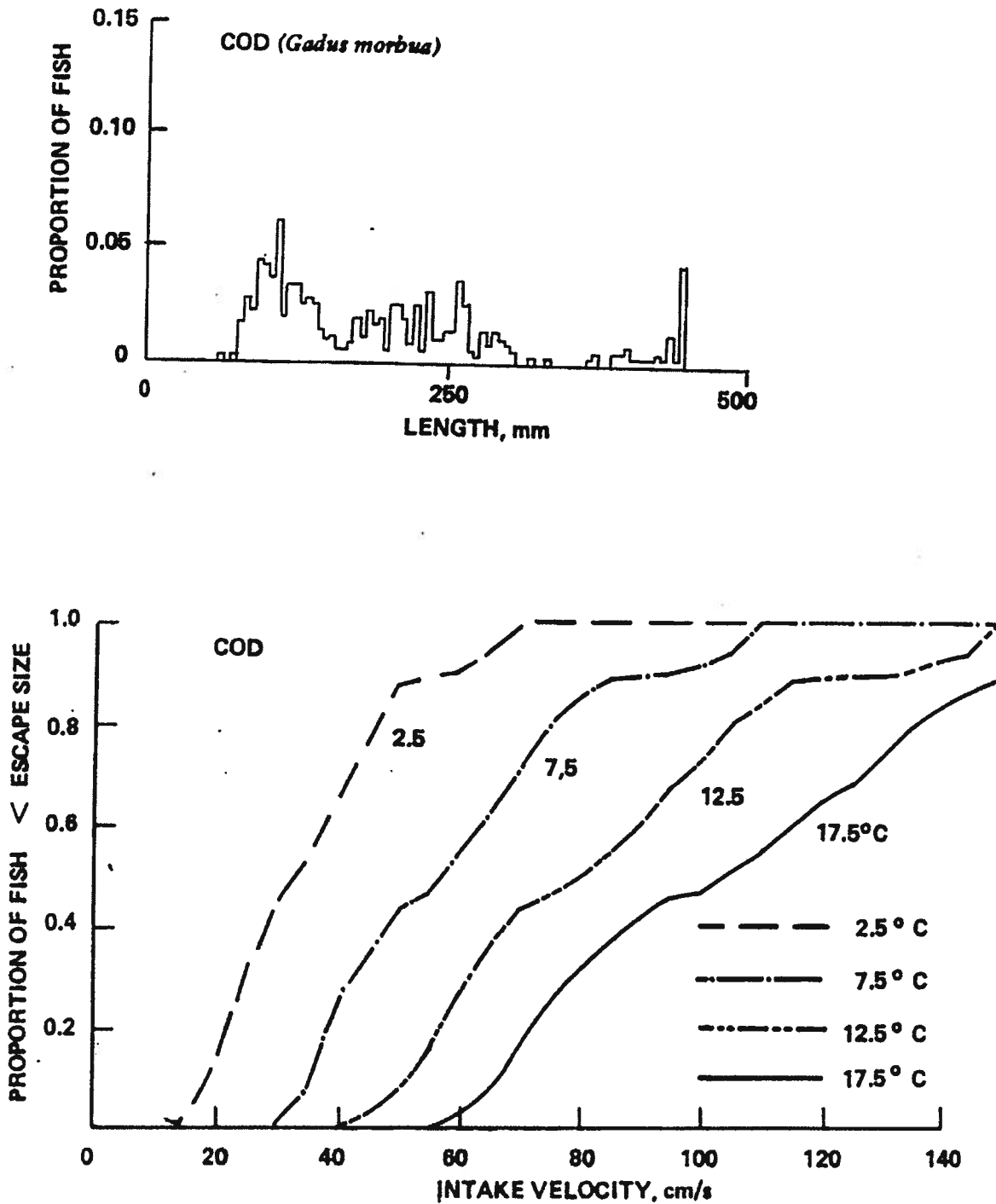


FIG.4(b) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated

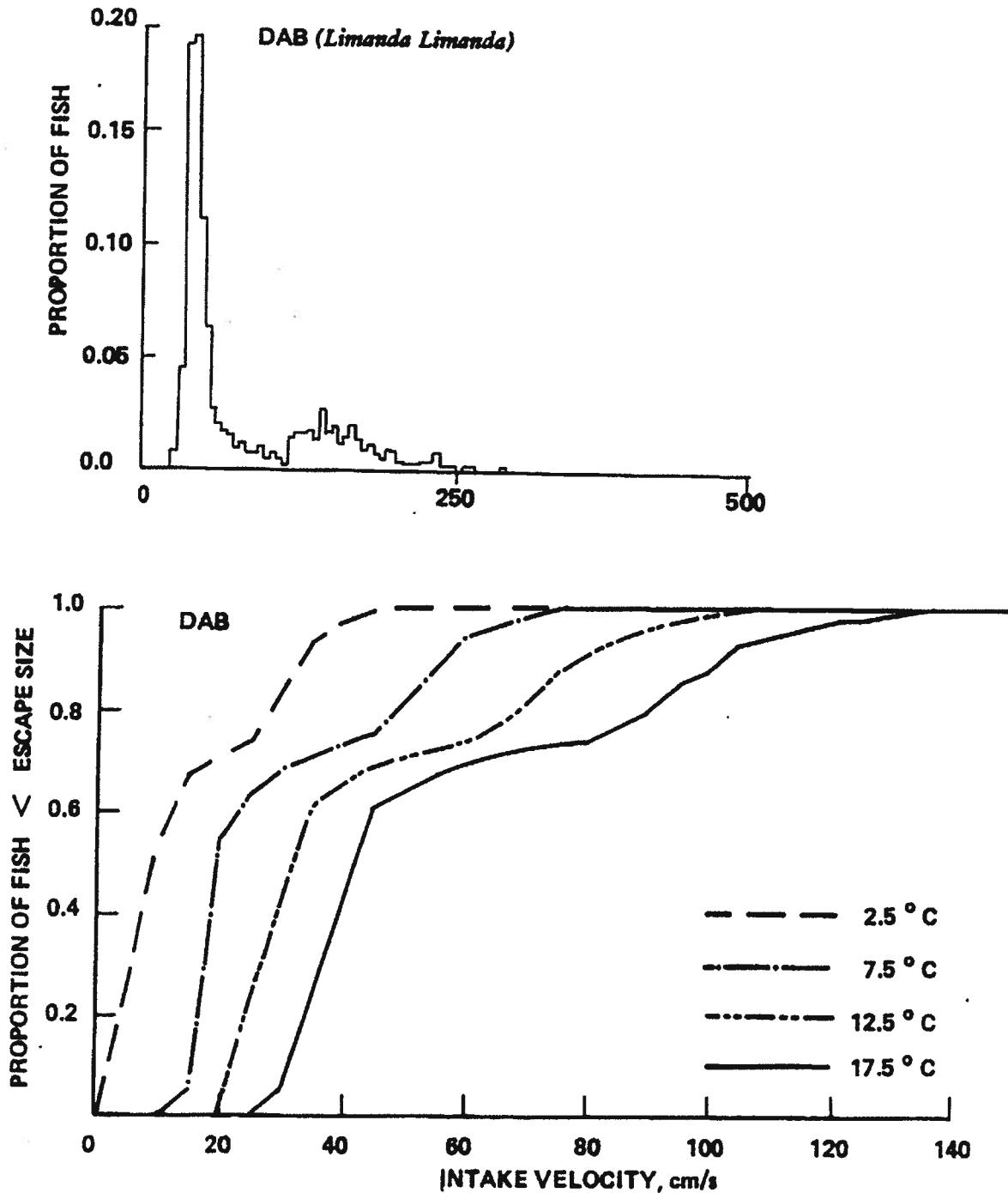


FIG. 4(c) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated

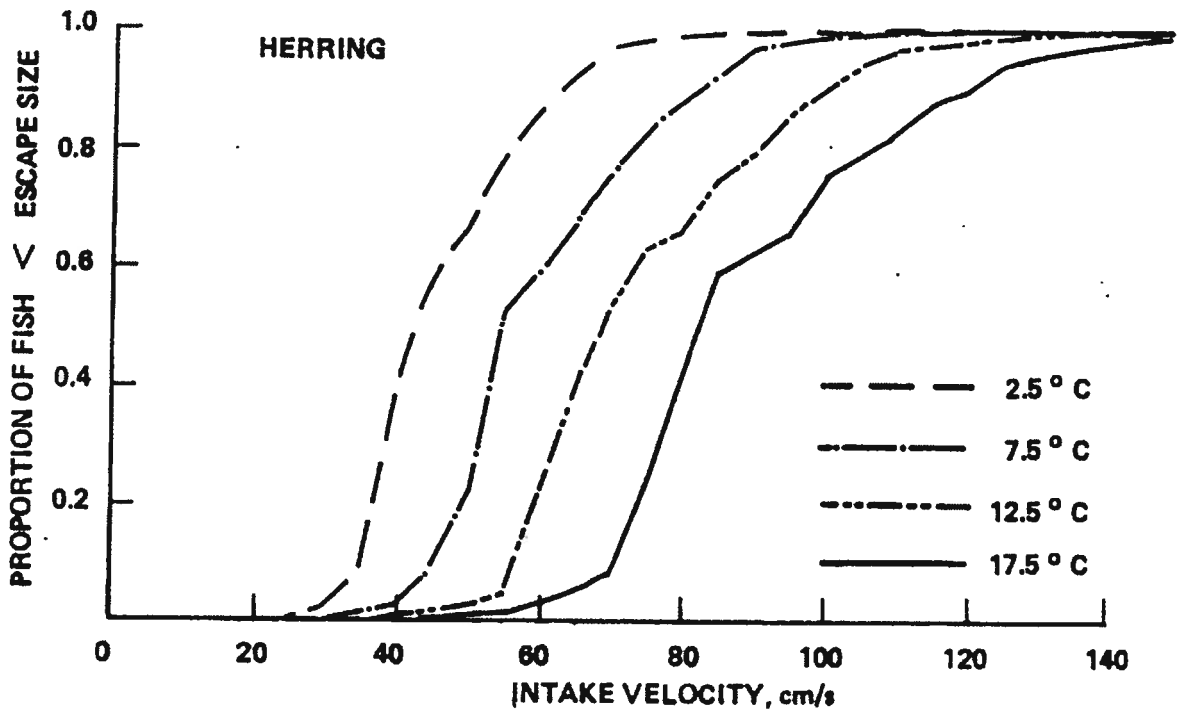
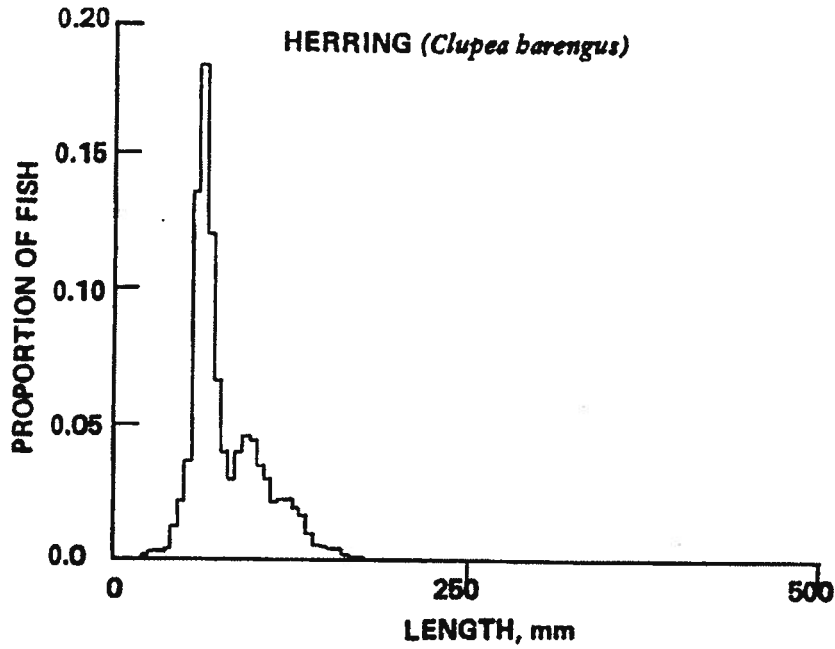


FIG. 4(d) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated

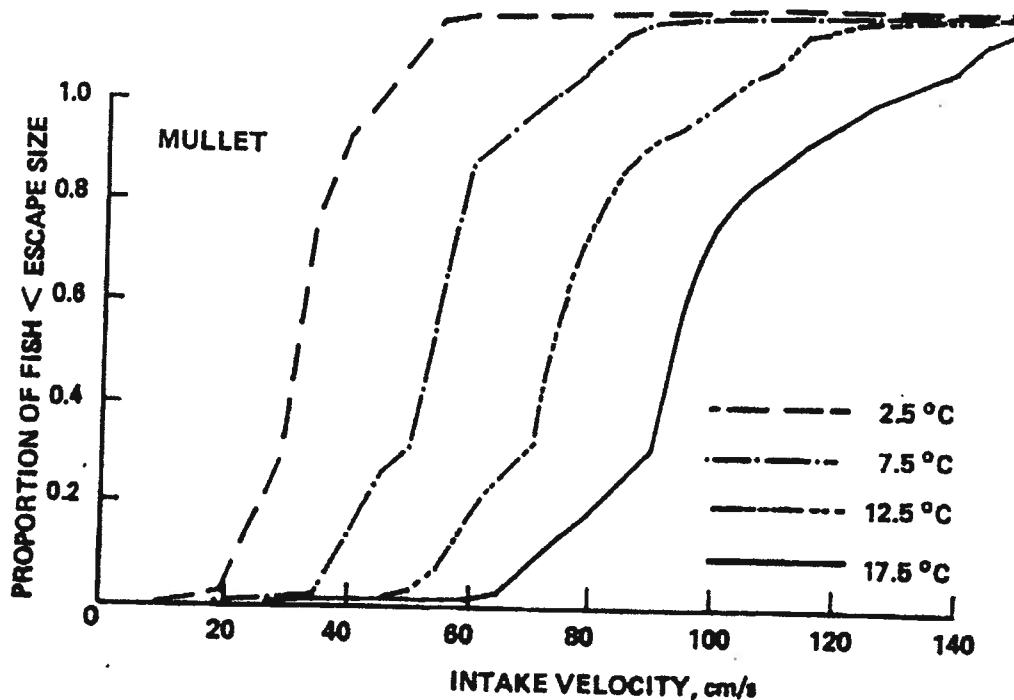
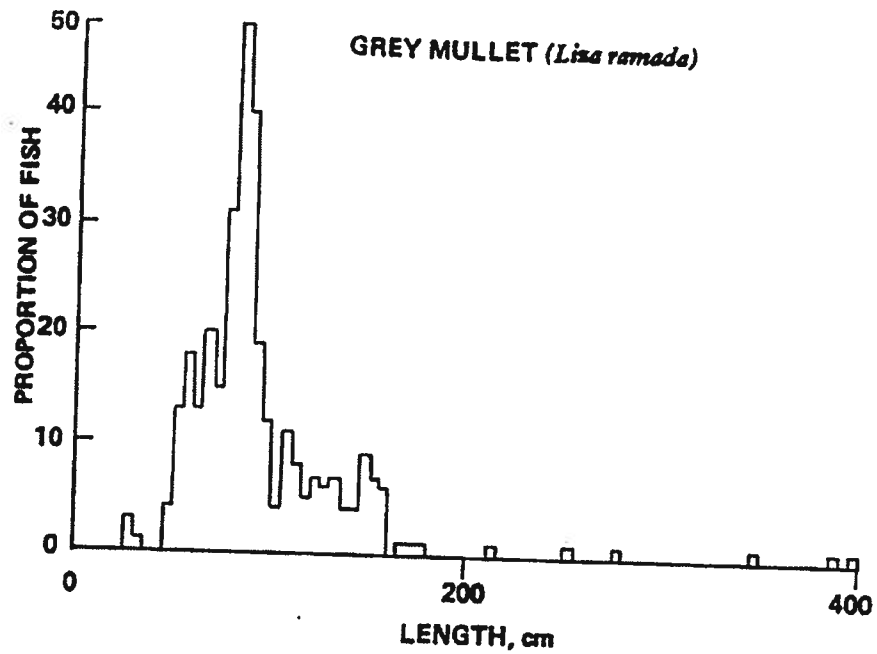


FIG. 4(a) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated.

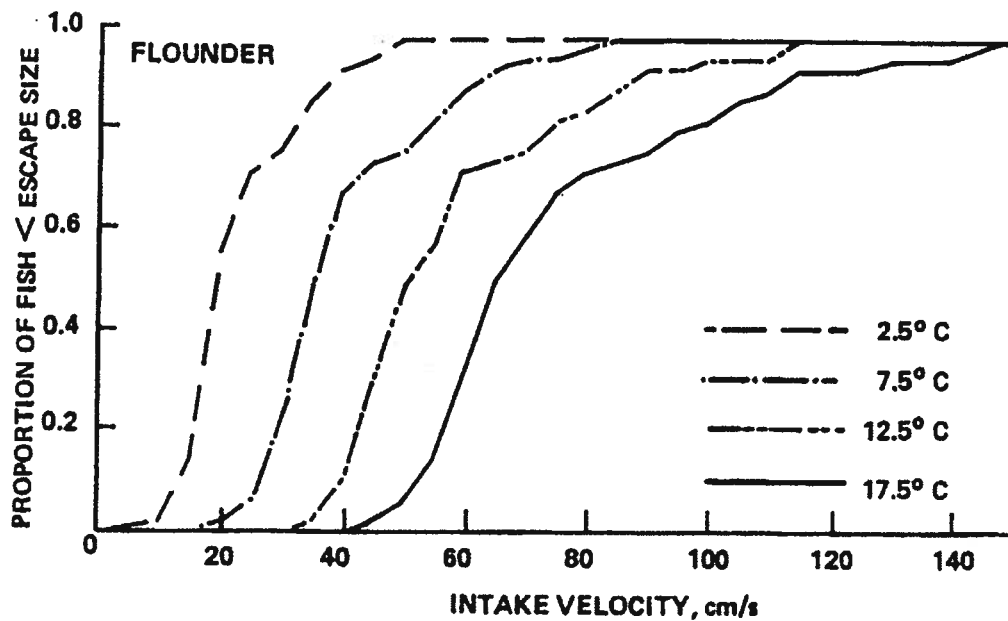
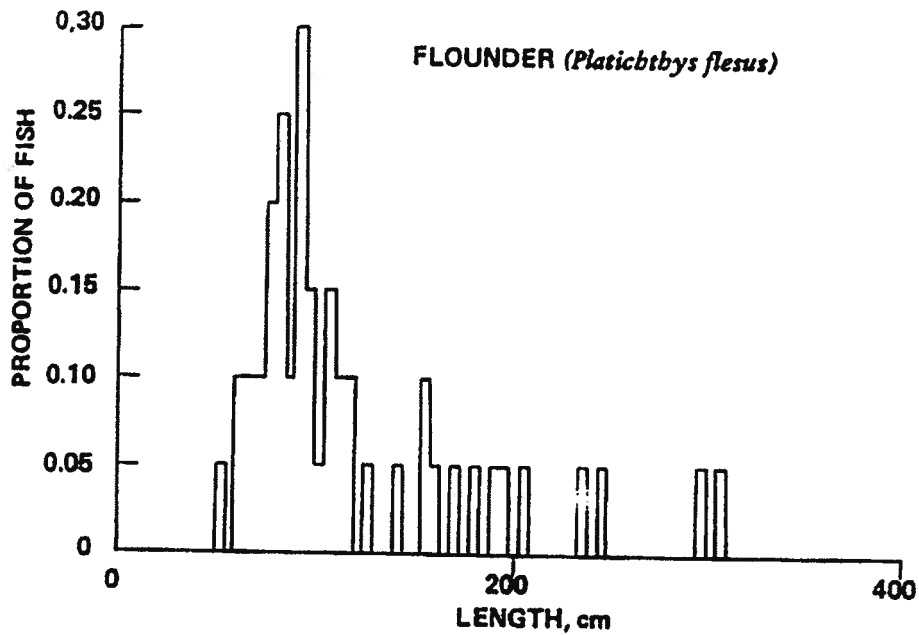


FIG. 4(f) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated.

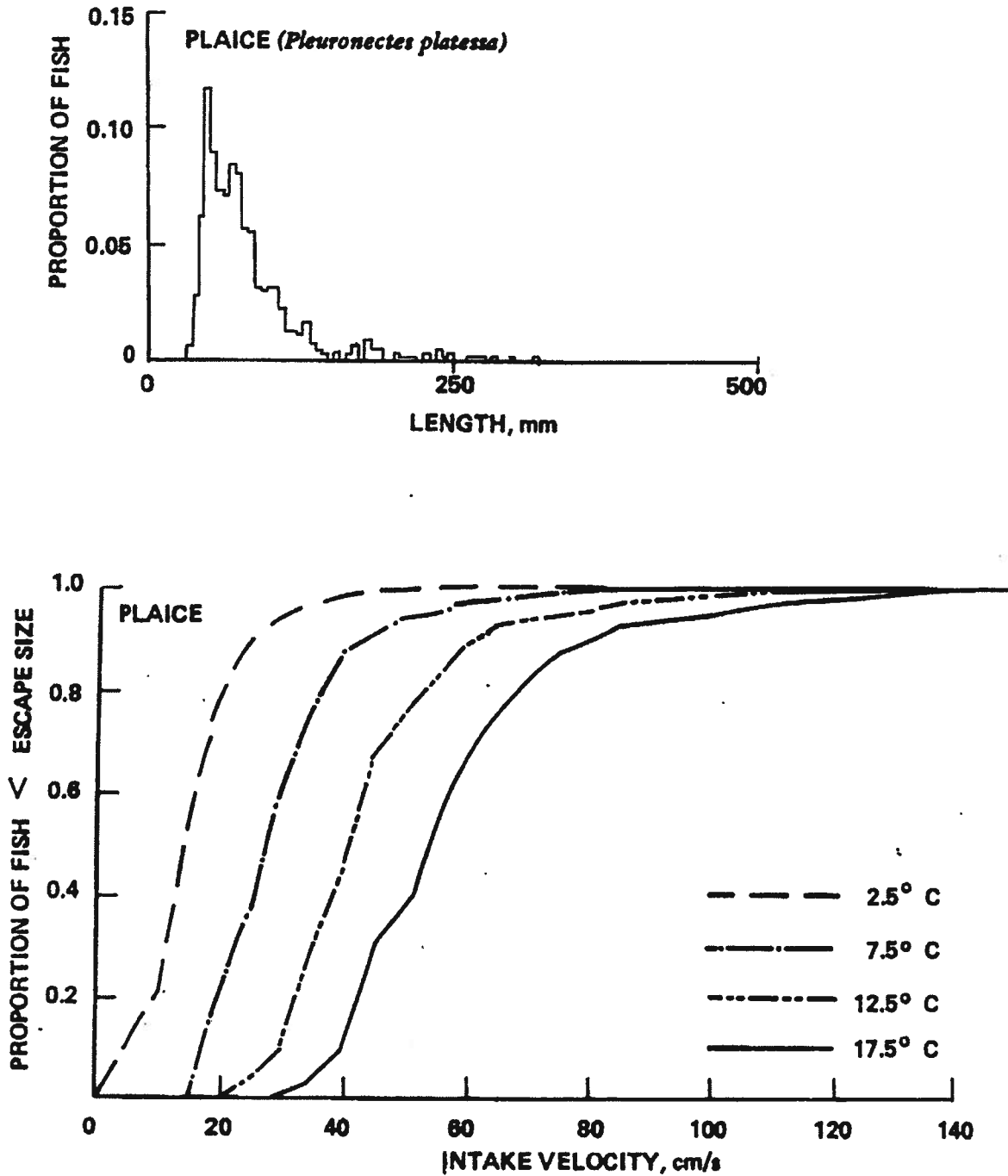


FIG. 4(g) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated

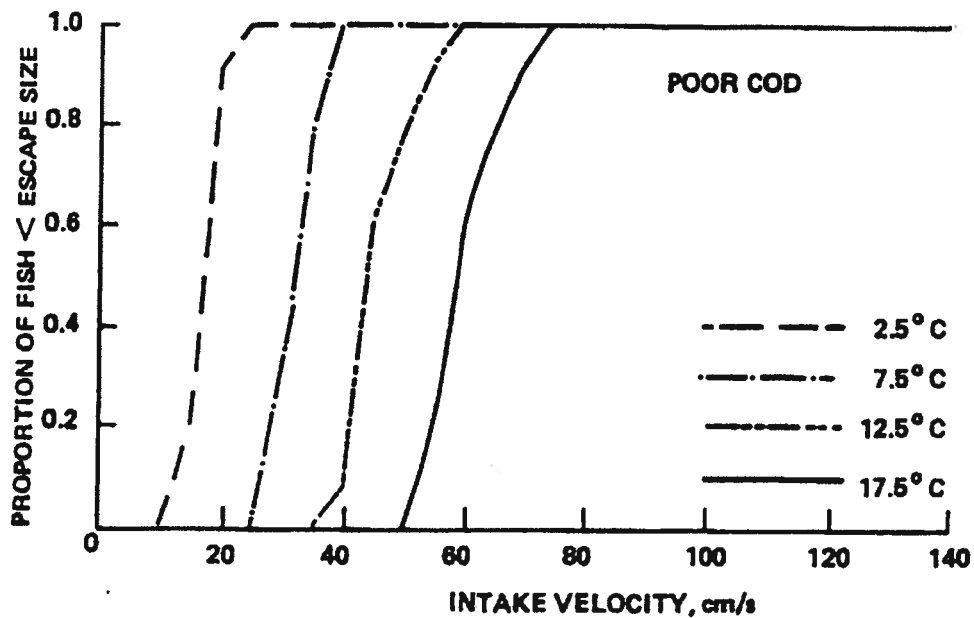
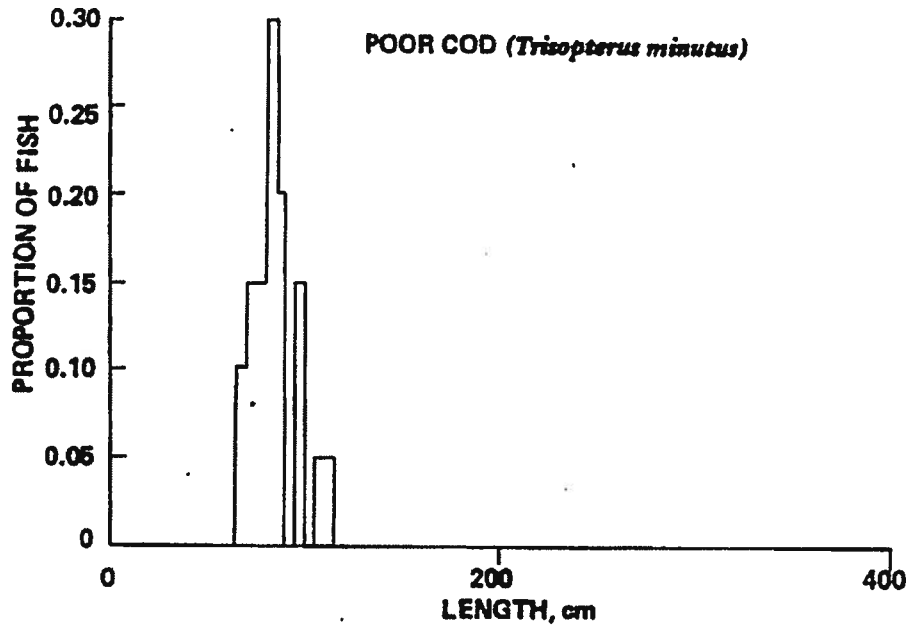


FIG. 4(h) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated.

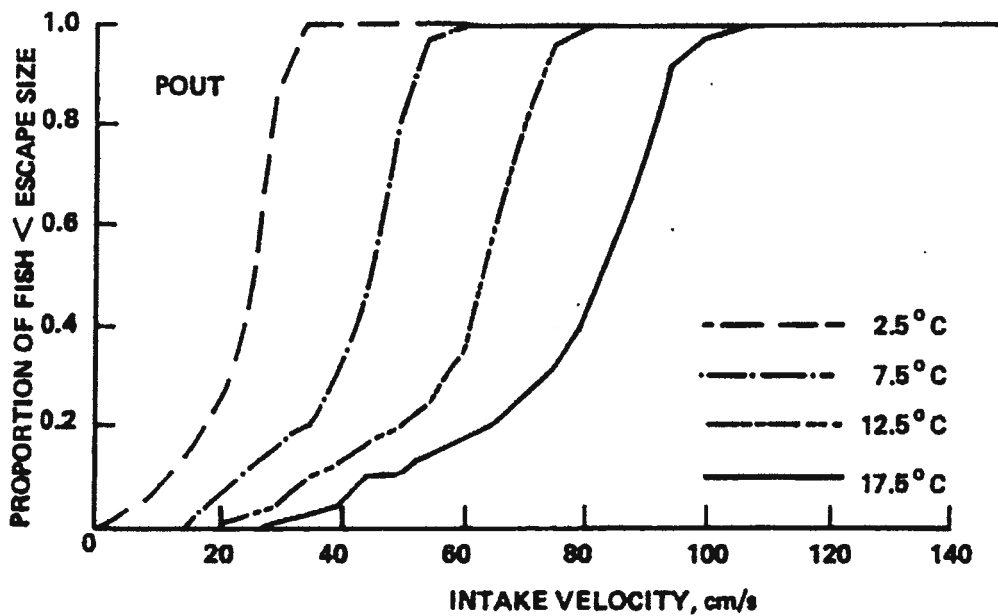
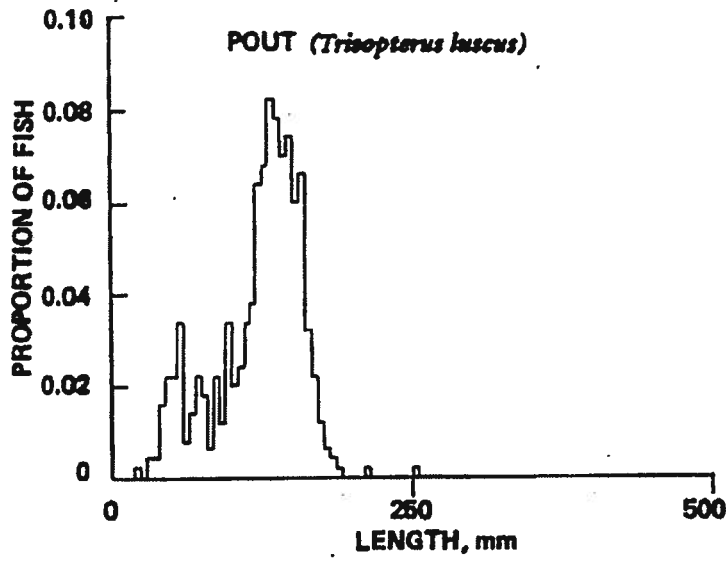


FIG. 4(i) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated.

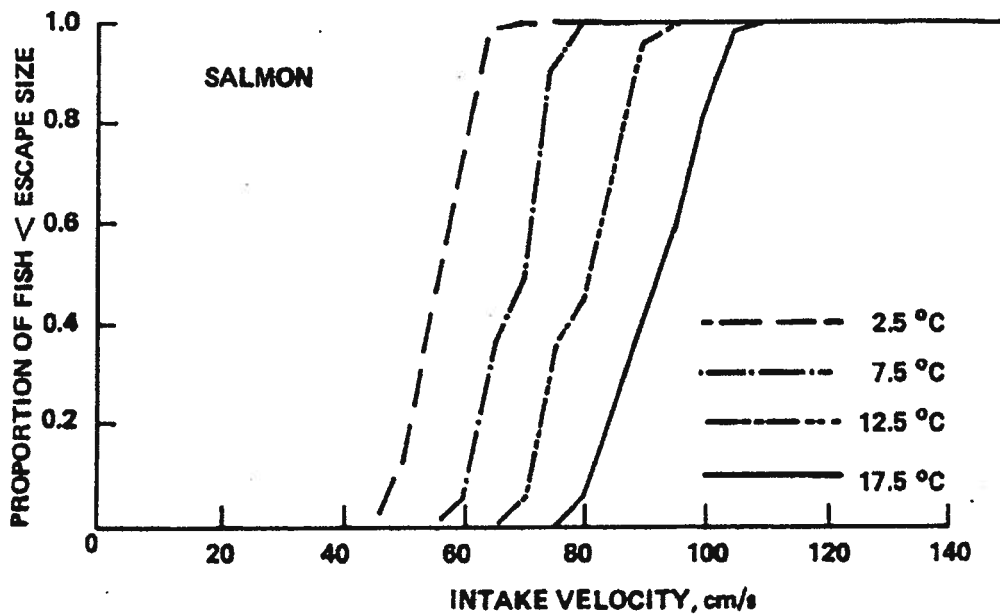
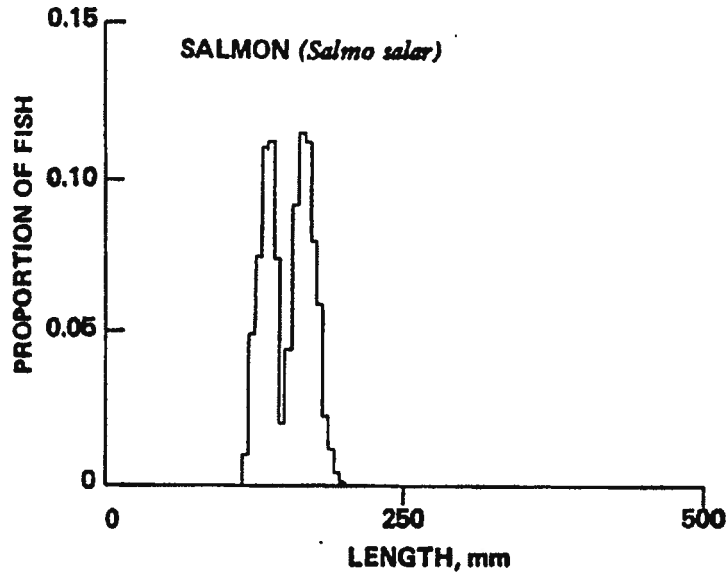
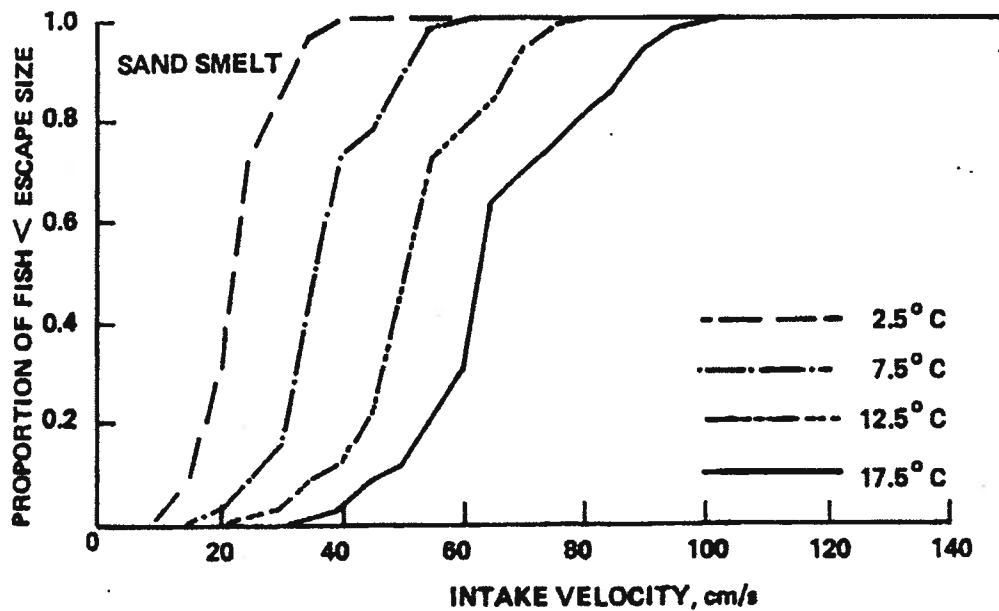
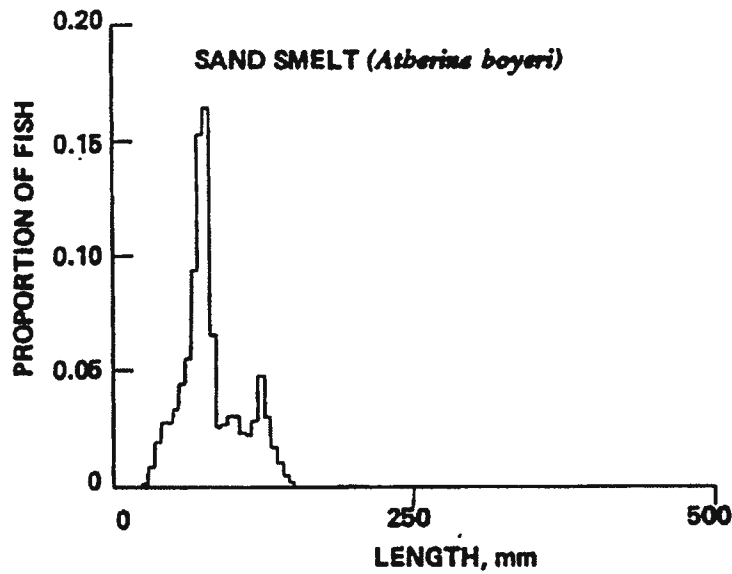


FIG. 4(j) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated.



(FIG. 4(k)) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated.

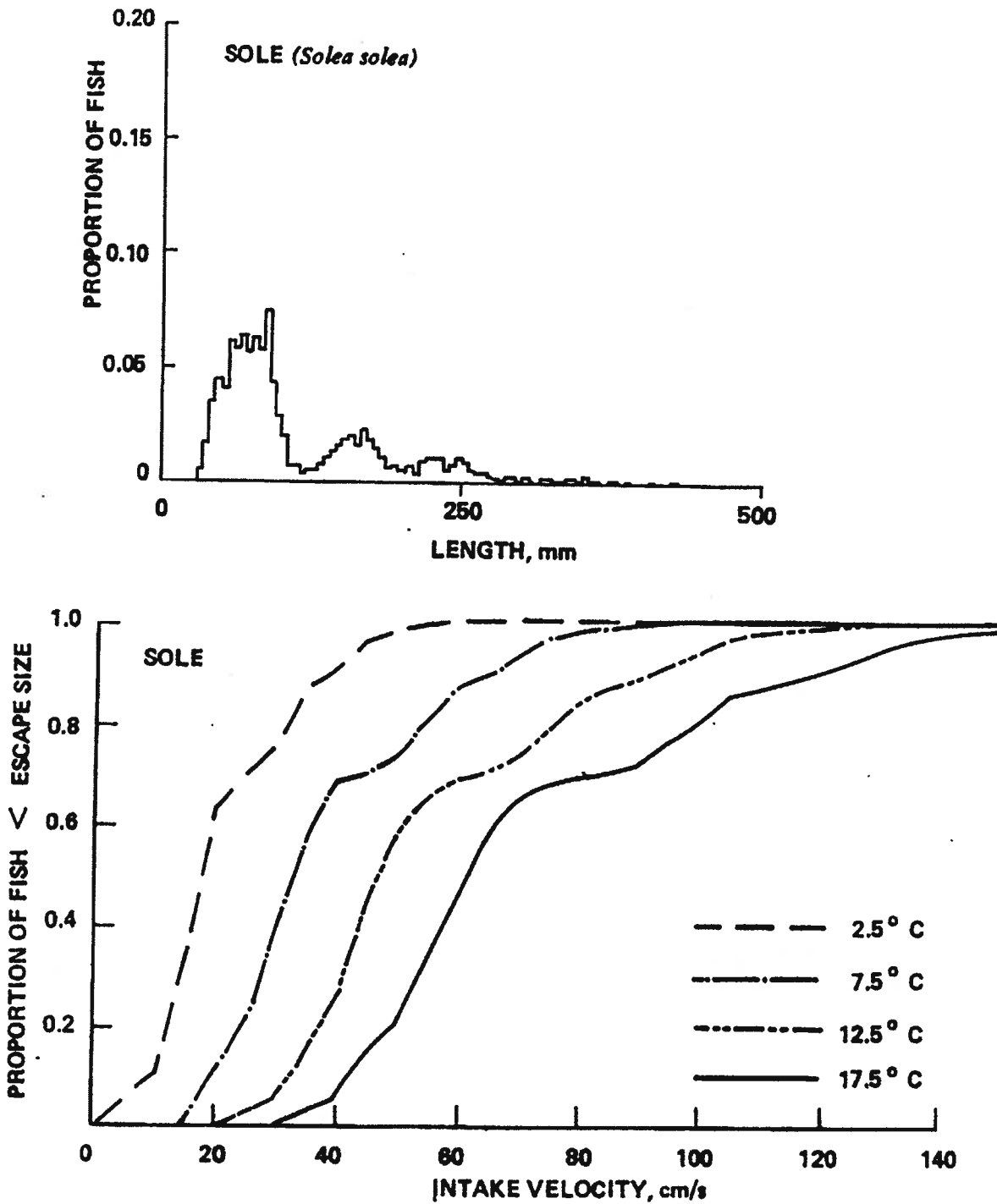


FIG. 4(l) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated

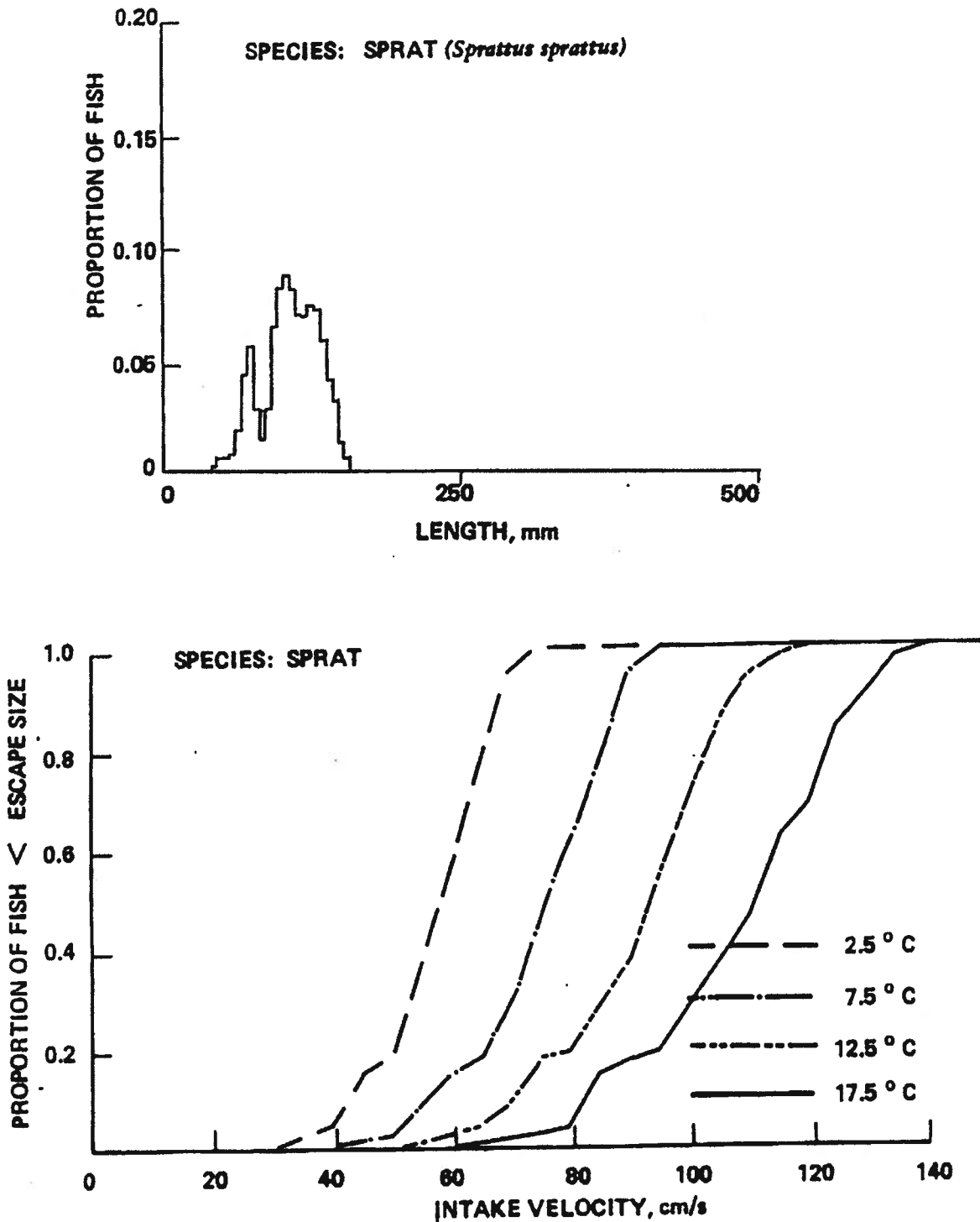


FIG. 4(m) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated

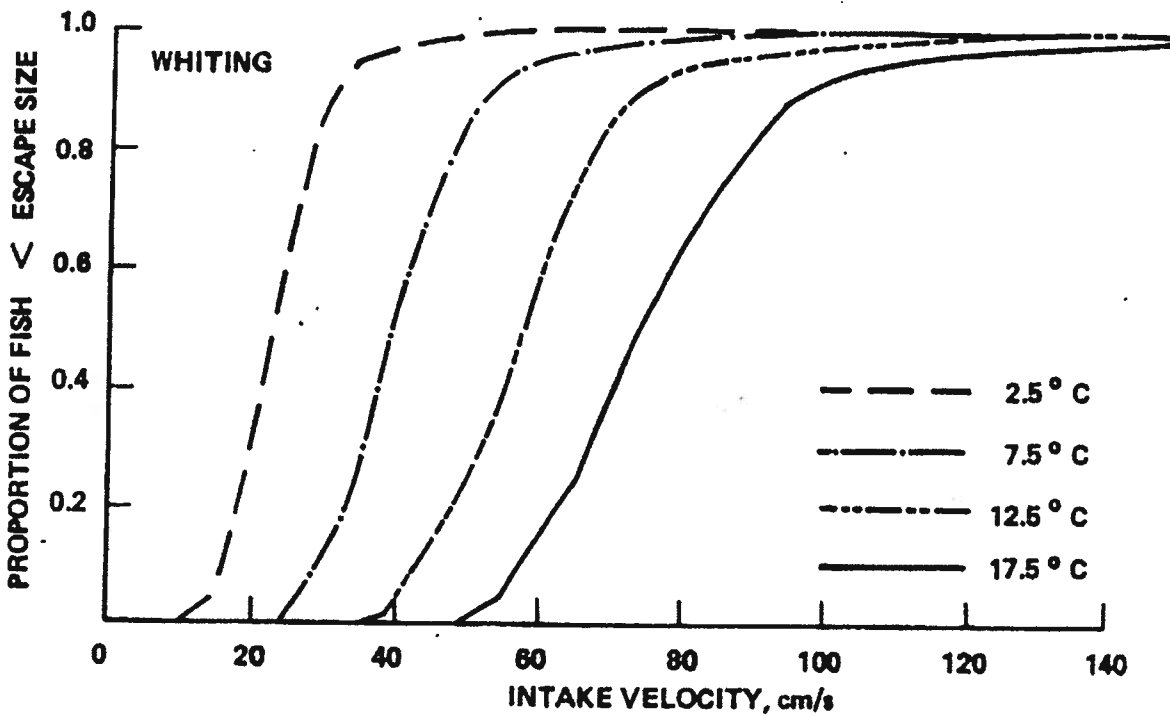
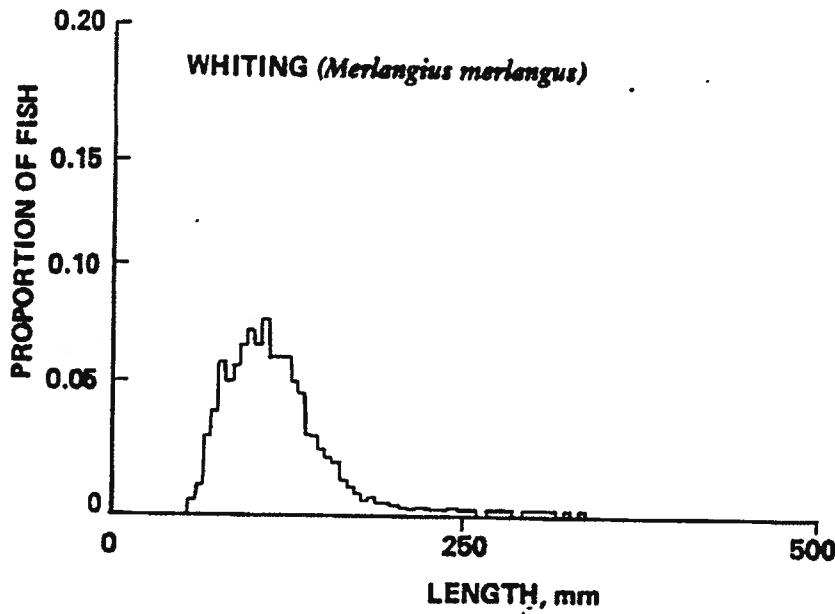


FIG. 4(n) CURVES DEPICTING THE PROPORTION OF FISH TOO SMALL TO ESCAPE FROM WATER INTAKES, IN RELATION TO WATER VELOCITY AT DIFFERENT WATER TEMPERATURES. The upper histogram shows the fish length distribution on which the curves have been calculated

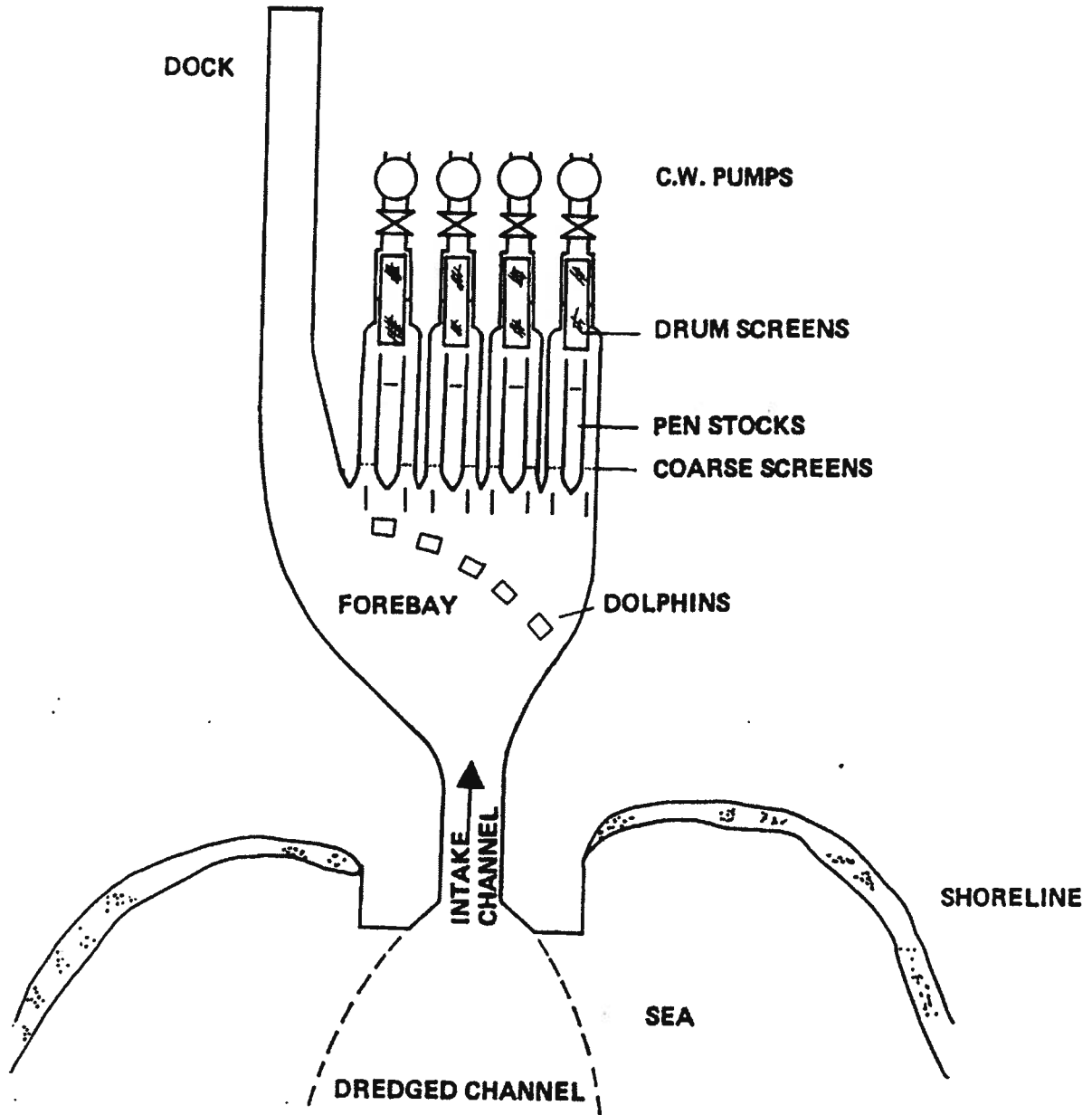


FIG. 5 LAYOUT OF THE ONSHORE INTAKE SYSTEM AT FAWLEY POWER STATION, HAMPSHIRE

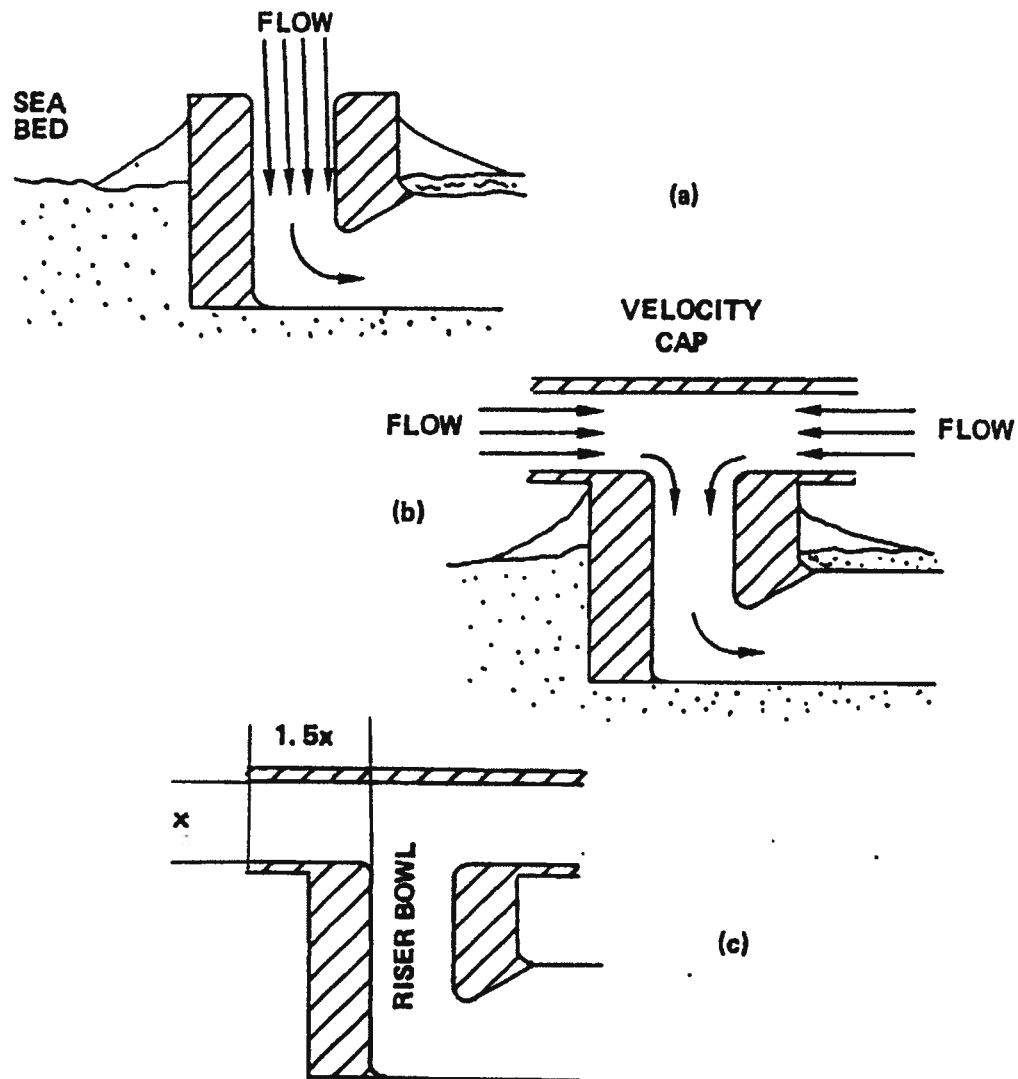


FIG. 6 THE VELOCITY CAP. (a) Section of uncapped intake showing vertical draw-down pattern, (b) section of velocity capped intake showing horizontal flow pattern, (c) as (b) but showing critical relationship between vertical opening (x) and length of horizontal entrance ($1.5x$) for fish reactions. Intake grills omitted. (After Schuler and Larson, 1975)

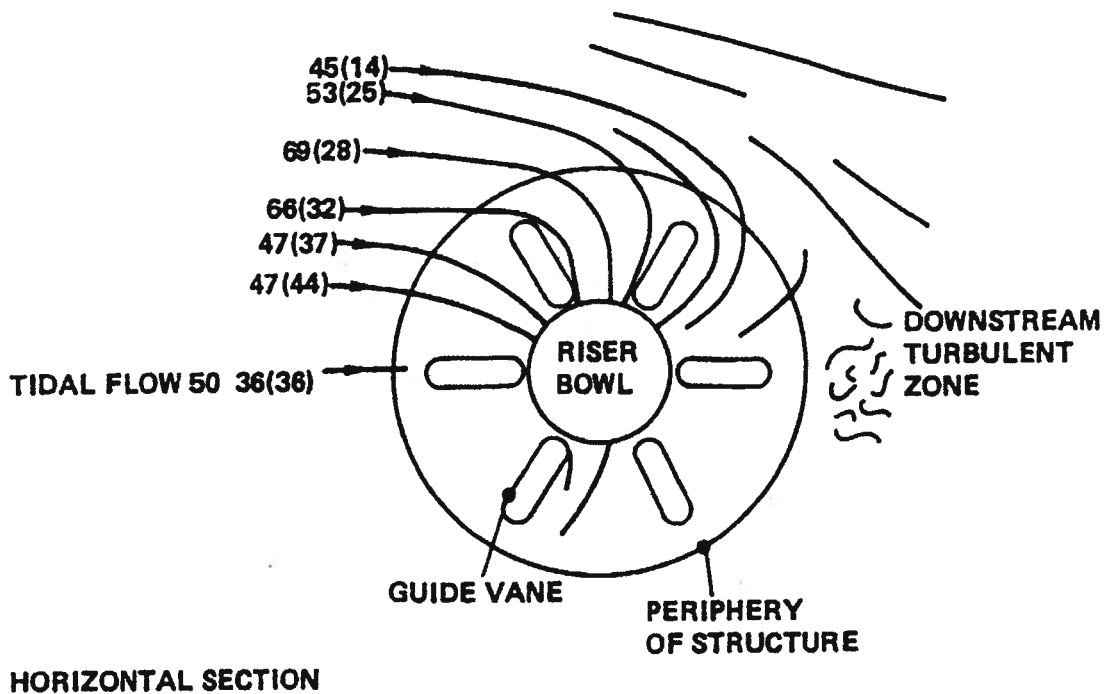


FIG. 7 HORIZONTAL DISTRIBUTION OF STREAMLINES AND WATER VELOCITY AROUND A CIRCULAR CAPPED INTAKE STRUCTURE IN A TIDAL CROSSFLOW.

Intake flow = $13.7 \text{ m}^3 \text{ s}^{-1}$, tidal velocity = 50 cm s^{-1} , velocity values shown are as measured at mid-intake level along the direction of streamlines at the periphery of the intake structure. Values in parentheses are vectors normal to the periphery. All values are in units of cm s^{-1} . [Based on trials with a 1/50 scale model at Central Electricity Research Laboratories, B.T. Goldring, pers. comm.]

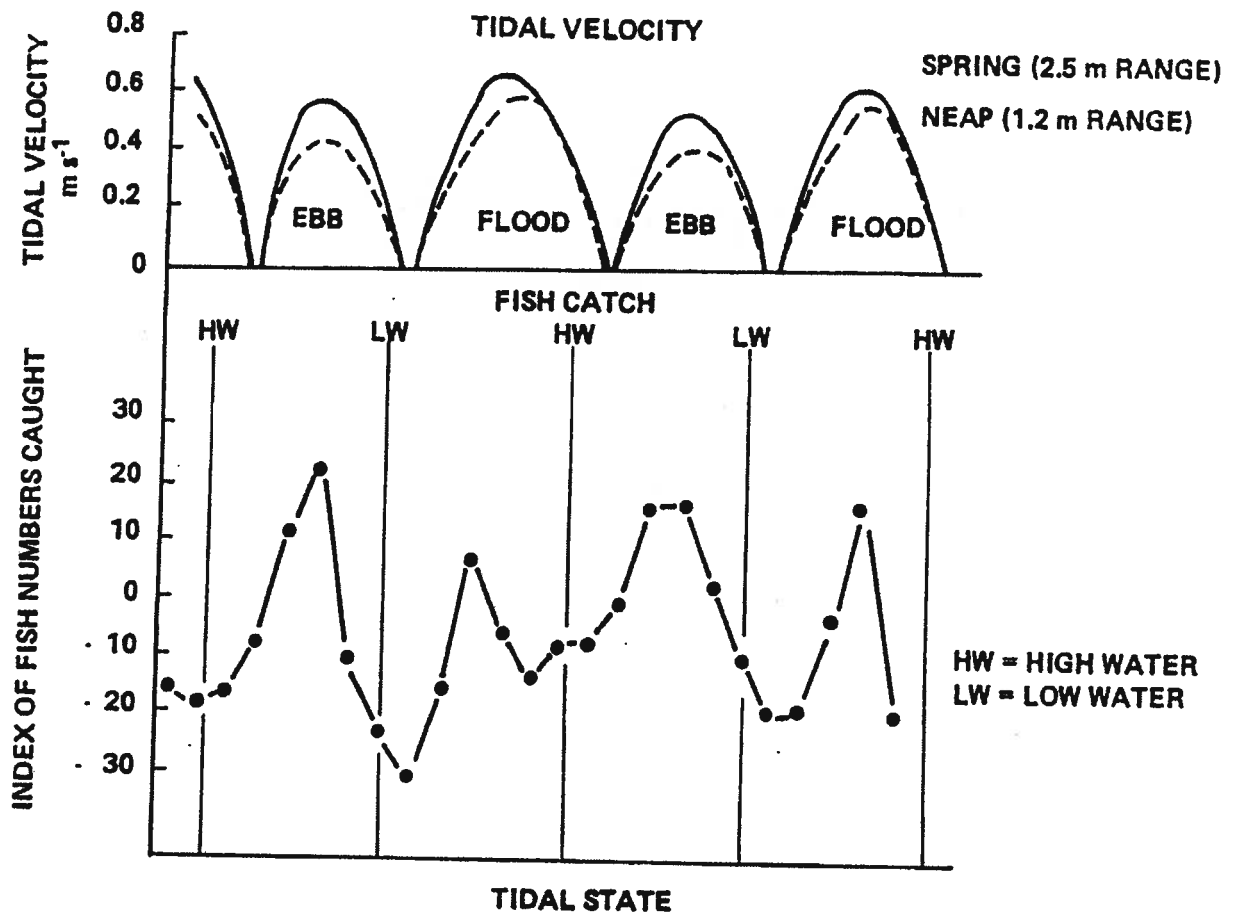


FIG. 8 RELATIONSHIP BETWEEN FISH CATCH, TIDAL STATE AND TIDAL VELOCITY AT SIZEWELL 'A' POWER STATION
 (Based on hourly samples collected on 41 days, April 1981-May 1982. Figures standardised as $\text{Index} = (x - \bar{x})/s$, where x is mean hourly fish catch for each 24 h period, \bar{x} is the hourly fish catch for any one hour and s is the 24 h standard deviation. Tidal velocities measured by moored current meter 100 m south of intake

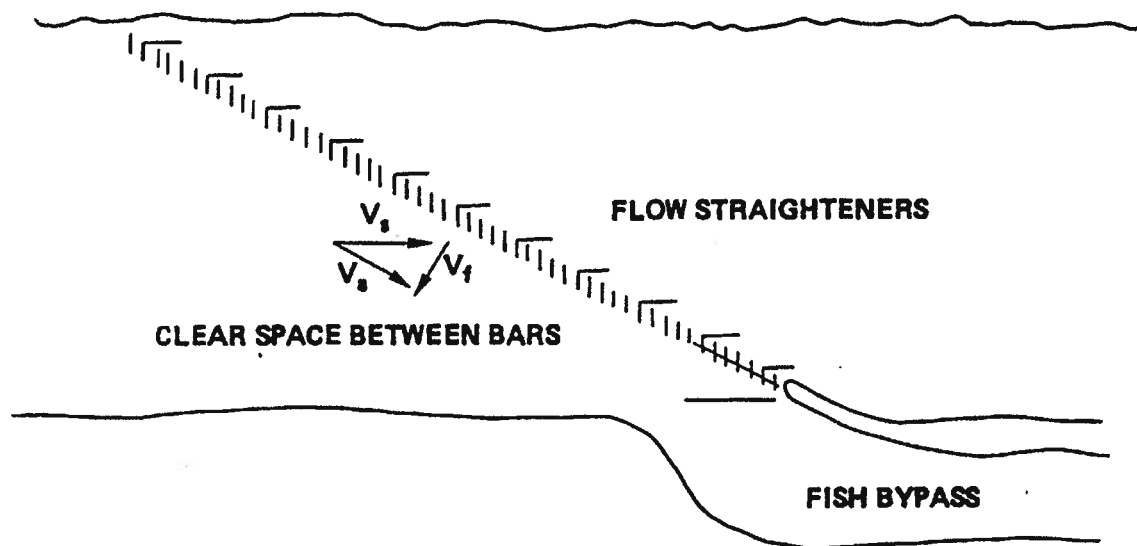


FIG. 9 SCHEMATIC DIAGRAM OF A LOUVRE SCREEN (PLAN VIEW) WITH VECTOR DIAGRAM OF THE RELATIONSHIP BETWEEN APPROACH VELOCITY (V_a) AND THE FISH'S SWIMMING VELOCITY (V_f) REQUIRED FOR ESCAPE.

(V_a is the velocity at which the fish moves laterally along the screen (from Environmental Protection Agency, 1976))

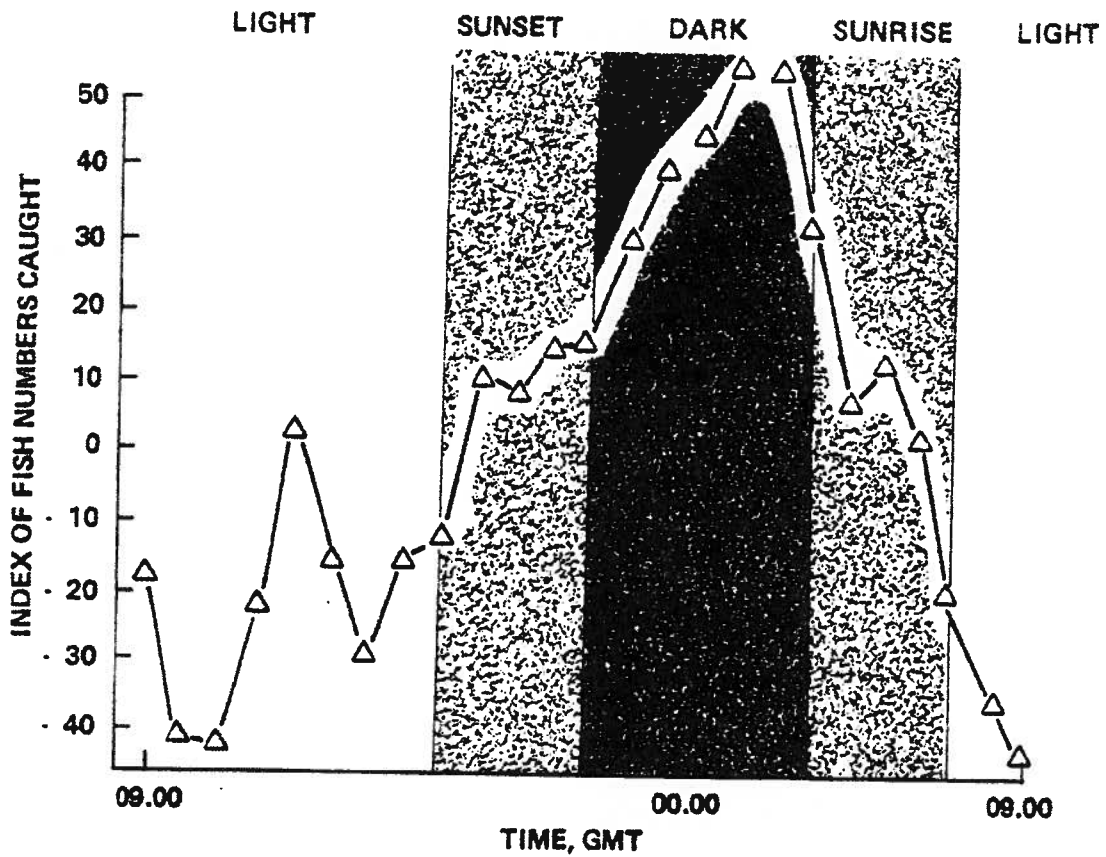
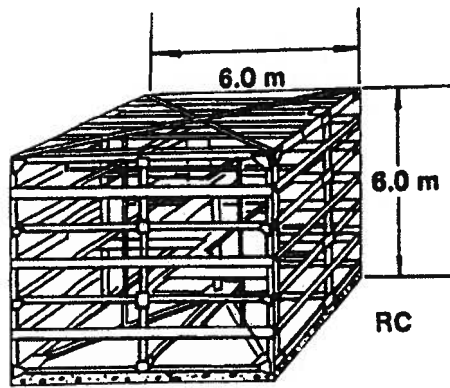
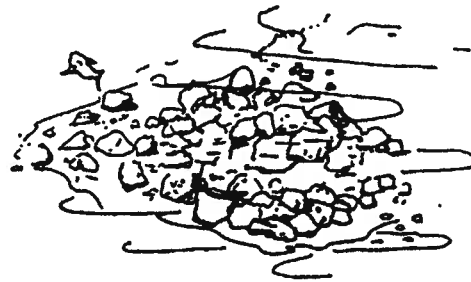


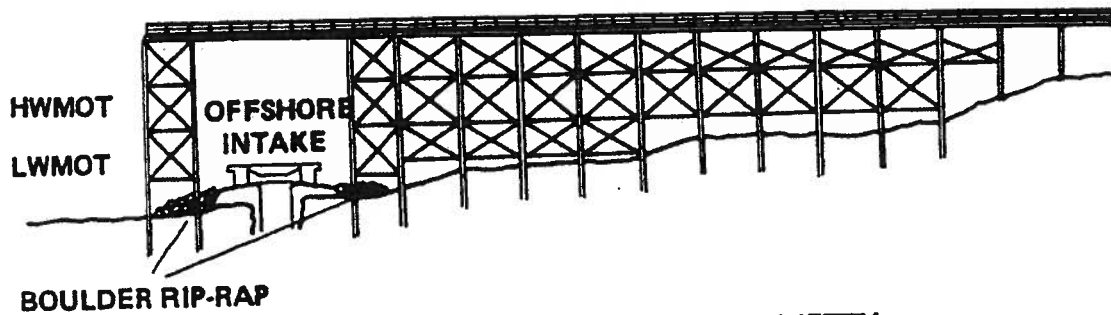
FIG. 10 DIURNAL PATTERN OF FISH CATCH AT SIZEWELL 'A' POWER STATION, AVERAGED OVER 41 SAMPLING DAYS. (see caption to Fig. 8 Lightly stippled areas show range of times of dusk and dawn from mid-winter to mid-summer. Dark stippling shows hours of darkness common to all dates)



(a) JAPANESE CUBIC STEEL FISH AGGREGATING REEF (KOSAI CLUB, TOKYO, JAPAN)



(b) BOULDER REEF (FROM WILSON et al., 1987)



(c) TYPICAL OFFSHORE INTAKE WITH JETTY SUPERSTRUCTURE AND BOULDER RIP-RAP

FIG. 11 INTAKE STRUCTURES AS ARTIFICIAL REEFS. (a) & (b) show two concepts in artificial reefs for fish aggregation, (c) shows how both of these concepts are unwittingly incorporated into offshore intake structures

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