# DIVERSION AND ENTRAPMENT OF FISH AT WATER INTAKES AND OUTFALLS

Dr D J Solomon

R & D Report 1

NRA

National Rivers Authority

# DIVERSION AND ENTRAPMENT OF FISH AT WATER INTAKES AND OUTFALLS



**Research Contractor**
**Dr D J Solomon**
**Foundry Farm**
**Kiln Lane**
**Redlynch**
**Salisbury**
**Wiltshire SP5 2MT**

**National Rivers Authority**
**Rivers House**
**Waterside Drive**
**Aztec West**
**Almondsbury**
**Bristol BS12 2UD**



**R&D Report 1**

**National Rivers Authority**
**Rivers House**
**Waterside Drive**
**Aztec West**
**Almondsbury**
**Bristol BS12 4UD**
**Tel: 0454-62440**
**Fax: 0454-624409**



**First Published 1992 ISBN 1 873160 29 1**



## Dissemination status

Internal: Released to Regions
External: Released to Public Domain

## Statement of Use

This document reviews the current best practice relating to design and specification of appropriate systems for protecting indigenous fish populations from entrapment. It is intended for use as a guide when issues including fish entrapment and diversion need to be addressed.

## Research Contractor

This document was produced under contract 307 by:

Dr D J Solomon
Foundry Farm
Kiln Lane
Redlynch
Salisbury
Wiltshire SP5 2MT
Tel: 0725-22523
Fax: 0725-27964

## NRA Project leader

The NRA's Project Leader for R&D Contract 307 was:
Mr Greg Armstrong - Thames Region

## Design and Printing

This document was designed and produced by:
Stott Meredith Design and Communication Limited, Hebron House Sion Road, Bedminster, Bristol BS3 3BD.
and printed by:
Stanley Hunt Printers, Midland Road, Rushden, Northants NN10 9UA

**Additional Copies of this document may be obtained at the price of £17.00 per copy inclusive of postage and packing from:**

**National Rivers Authority**
**Newcastle - upon -Tyne X**
**NE38 8QA**

Please enclose a cheque or a postal order made payable to the National Rivers Authority

# Preface

Among the NRA's many responsibilities is the duty to maintain, improve and develop fisheries for salmon, trout, eels and freshwater fish generally. In order to do so, the NRA has a number of powers relating directly to fisheries activities. Of equal importance are those powers and duties relating to the management of water resources and the attainment of high water quality, both of which are fundamental to the maintenance of healthy fish populations and the ecosystems upon which they depend. The provision of good water quality, however, is not in itself sufficient; there are other factors which affect populations, particularly the 'physical' aspects of their environment, one of which is addressed in this report.

Such is the impact of human activities on the environment, little of it remains in anything like a natural state. In the case of rivers, large stretches have been subject to engineering in one way or another. There are thousands of abstractions from rivers, and tens of thousands of discharges are made to them. Pumping water from one area to another inevitably results in some degree of damage to the aqautic fauna and flora, but this has always been difficult to quantify; and if it cannot quantified, the cost-benefit of any preventative action cannot be assessed. This report, therefore, was commissioned in order to obtain a thorough review of the scale of the problem of fish entrapment at the point of abstraction and discharge, and the means by which such a problem could be reduced. The result is a fascinating insight into the interface between biology and engineering; it will be of great assistance to both parties and greatly assist the NRA in furthering its fisheries and water management responsibilities in the optimum way.

R. J. Pentreath

**DR R J PENTREATH**
**Chief Scientist**

**July 1992**

# CONTENTS

# List of Figures



# List of Tables

# Executive Summary

Water intakes and outfalls associated with many human activities are artificial features of the aquatic environment which can cause entrapment and death of fish and/or obstruct their migrations. In discharging its duty to maintain, improve and develop fisheries under the Salmon and Freshwater Fisheries Act 1975, it is necessary for the National Rivers Authority to judge the potential impact on fish populations of abstraction and discharge points in order to decide if action should be taken to prevent or ameliorate any adverse effects.

Information on the extent and nature of the potential or existing problems nationally, and literature describing existing or potential solutions for preventing and/or ameliorating adverse effects nationally and internationally were diffuse. This report draws together experience of the problem, outlines and describes effective screening technology for different situations, together with temporal and spatial considerations. It thus provides an effective guide to enable Officers of the Authority to make better informed judgements as to the necessity for, and specification of, mechanisms for protecting indigenous fish populations.

Recommendations are made to further investigate both ecological mechanisms which affect fish entrapment, and potential additional fish exclusion mechanisms. Progress in these fields would further improve our ability to protect the resource. These, together with recommendations to both strengthen the existing legislation (S14 Salmon & Freshwater Fisheries Act 1975) with respect to screening provisions and to apply it more rigorously, should be considered by the Core Function Managers Group. Regional, or National, abstraction licence databases should include screening details and the requirement both for screens, and records of them, identified to Water Resources Managers.

This work will immediately improve national understanding of the potential problems of fish entrapment at intakes and outfalls and provide a basis for a more coherent approach in determining which specific mechanisms should be employed to ameliorate adverse effects on the fisheries resource. It also identifies areas of Research and Development, and improvements to existing legislation, which would further enhance the Authority's ability to discharge its duty to protect fisheries.

# SUMMARY

## INTRODUCTION

This document reports on a desk study, with back-up site visits, with the following overall objective:-

> "To assess the nature and potential scale of fish entrapment at water intakes and outfalls for coarse, salmonid and estuarine fish species. To evaluate the protective mechanisms currently employed and review other potential mechanisms."

## ASSESSING THE PROBLEM

There are currently over 14 000 licensed abstractions from non-tidal surface water in England and Wales, plus a number from estuarial waters. The total licensed volume is of the order of twice the total dry-weather flow (Q95) of surface water, but not all licences are fully taken up and many have a prescribed flow rule to protect low flows. Few details of the numbers of intakes that incorporate fish protection devices are available, but the proportion effectively protected is low. (Section 1.2, 2.3).

To some extent the risks to fish represented by entrainment depend upon the use to which the water is put, but most represent a degree of danger to fish. Abstraction to reservoirs, while not necessarily resulting in danger to fish, nevertheless represents a loss to the river. Little information was available on injuries caused to fish by impingement on intake screens, but mortality is likely to be high (Section 2.2).

Fish attracted into outfalls are likely to experience a delay in their migration, and in some cases mortalities have been reported due to fish penetrating through imperfect screens and then being unable to escape (Section 2.2).

Few studies were identified on the significance of losses of fish at intakes for fish stocks. A fish farm on the Hampshire Avon was estimated to kill about 5% of the salmon smolt run in some years, while reservoir abstractions from the lower Thames are estimated to take between 15 and 80% of the smolt run varying between years. Losses of 0+ coarse fish at these two intakes have been estimated to lie between the order of tens of thousands and millions per year (Section 2.2).

As results of detailed studies were lacking, NRA Regional Fishery Managers were asked to suggest whether fish losses etc at intakes and outfalls in the Region as a whole were (a) catastrophic, (b) major, (c) significant, (d) minor or (e) insignificant. For intakes, the response ranged from minor to significant for salmonids, and from insignificant to significant for other species. At outfalls, the responses ranged from insignificant to significant for salmonids, and insignificant to minor for other species (Section 2.4).

Positive migrations and redistributions of so-called non-migratory fish (e.g. cyprinids) at certain life-history stages appear to put them at major risk of entrapment at intakes. Movements of 0+ fish appear to peak in summer,at a fish length of 20-30 mm; movements of earlier, smaller stages may also occur. The large numbers of fry sampled at times in intakes highlights both the potential risks and the possibility of temporary reduction in abstraction to protect such fish. More information is needed on the biology and migrations of coarse fish juveniles (Section 2).

## POTENTIAL SOLUTIONS

A brief consideration of the legal background to protection of fish at intakes and outfalls suggest that adequate provision may exist but clarification and active application is required (Section 3.1).

Three basic approaches to reducing entrapment at intakes are considered:-

(a) physical screens;

(b) behavioural barriers and deflection systems;

(c) the scope for careful siting and operation of intakes to take water at places and times which reduce entrainment.

It is noted that these three approaches overlap and many intakes exploit all three principles (Section 3.2).

Fundamental criteria for intake design are considered and developed (Section 3.3). Appropriate mesh sizes for different fish are described (Section 3.4), and the relationship between fish swimming ability and acceptable intake approach velocities discussed (Section 3.5). A short list of intake screen designs considered promising in earlier reviews is considered (Section 3.6).

## PHYSICAL SCREENS

A short-list of screen types for consideration is drawn up on criteria of widespread use in the UK, those in UK use which have features of particular merit, and specific types in use or under development elsewhere which appear to show promise for UK use (Section 4.1).

Fixed mesh and bar screens are widely used and are considered appropriate for smaller intakes (Section 4.2). Moving and drum screens are concluded to be of generally little merit for protection of fish in the UK situation (Section 4.3). One type of drum screen, the "Econoscreen" appears to have potential for use to offer a good level of fish protection. The screen is driven by the flow of water, and a good, safe bypass route for fish is inherent in the design (Section 4.4).

One of the most effective screens for avoidance of fish entrapment is the Johnson passive intake. These incorporate cylindrical screens of wedgewire, and are being fitted to an increasing number of intakes in the UK. With appropriate design criteria of slot width and approach velocity a high degree of protection of even very small fish can be achieved. The extensive investigations of criteria for reduction of entrapment are reviewed and a number of installations described (Section 4.5).

Other potential applications of wedgewires are considered to offer considerable promise, including flat panels, weirs and the Eicher pressure screen (Section 4.6).

Sub-gravel intakes and wells which effectively draw surface-water, where their installation and operation is viable, would appear to offer a very high degree of fish protection. Examples of each are discussed (Section 4.7).

## BEHAVIOURAL EXCLUSION SYSTEMS

Within this group lie some of the most innovative and promising approaches to reduction of entrapment. They exploit reactions to sound, light, awareness of currents and sensitivity to electric field to guide fish without requiring the fish to come into contact with any fixed or moving machinery (Section 5.1).

Bubble screens (curtains of air bubbles) have been tried with mixed success for many years. The good results mixed in with the indifferent ones, and the recent observations that illumination by strobe lights can increase the effectiveness and reliability suggest considerable promise. Past investigations are therefore reviewed in some detail, and recommendations made for further investigation (Section 5.2).

Constant illumination on its own is of little value for diverting fish, but may enhance the effectiveness of other screens which depend upon the visual sense of the fish; in particular, strobe lights appear to show promise in this respect (Section 5.3).

Despite a history of indifferent results, acoustic system are concluded to offer great promise. Recent experiments in North America have shown how effective this approach can be if attention is paid to appropriate detail; for example, different signals are needed for optimal guidance of smolts and adults of the same species. Evaluation of the currently-available North American technology for UK situation is strongly recommended (Section 5.4).

Louver screens are an effective approach to reduction of salmon smolt entrainment in appropriate conditions. The site criteria are carefully reviewed. Floating louver arrays, screening only the top part of a deep water column, may have applications e.g. above dams (Section 5.5).

The velocity cap, a technique for reduction in entrainment at open intakes in the sea and large lakes, is briefly reviewed. It is likely to have value for UK applications in specific circumstances (Section 5.6).

Electric screens have had an uncertain history of effectiveness in reducing entrainment at intakes. Most UK installations have now been withdrawn. A review of results is recommended, as many investigations have not been published. There would appear to be considerable scope for electric screens to exclude fish from outfalls (Section 5.7).

## CONSIDERATIONS IN INTAKE SITING AND OPERATION

Observations on the discontinuous distribution, in both space and time, of fish considered vulnerable to entrapment (e.g. juvenile cyprinids, salmon smolts) suggest the possibility of progressive management of abstraction (Section 6.1).

Work mainly undertaken in the USSR has indicated that juvenile coarse fish are distributed in very specific patterns, and this has allowed decisions over siting of intakes which have cut entrainment considerably. It is suggested that there may be scope for this approach in the UK, ideally in conjunction with application of other screening technology. More information on the local distribution of coarse fish is needed (Section 6.2).

There is likely to be great scope for temporal modulation of abstraction to avoid peaks of number or migration. The observations that the majority of annual entrapment of juvenile cyprinids takes place in just a matter of days or weeks encourages such an approach. Similarly, salmon smolt migration is known to be concentrated in a period of relatively few days. Again there is a need for more information on juvenile fish behaviour (Section 6.3).

## RECOMMENDATIONS AND R&D REQUIREMENTS

The following areas are highlighted as justifying further attention (Section 7.2):-

(a) the abstraction licence database should incorporate details of screening requirements and screens employed, and this information should be readily retrievable (Section 7.2.2).

(b) a concise legal summary of the existing legislative provisions for screening requirements should be prepared and the provisions more actively employed. The legistlation should be reviewed and developed to cover all types of abstraction and species of fish.(Section 7.2.3).

(c) subject to (b) above, surface water abstraction licences should, whenever feasible and appropriate, incorporate a requirement for fish screening (Section 7.2.4).

A requirement for further R&D on the following subjects is identified:-

(a) ecology and behaviour of juvenile coarse fish, with particular reference to migration and dispersion (Section 7.2.5).

(b) elucidation of the extent and dynamics of fish entrapment in the UK (Section 7.2.6).

(c) laboratory and field studies are suggested for evaluation and specification of bubble/strobe light behavioural screens (Section 7.2.7).

(d) field evaluation of the available North American technology for diversion of fish by acoustic methods (Section 7.2.8).

(e) evaluation and specification of electric screens for exclusion of fish from outfalls (Section 7.2.9).

It is suggested that (b), (c), (d) and (e) could be undertaken at a single or small number of sites. It is recommended that an appropriate site is sought that is not an operational abstraction intake (Section 7.2).

# 1. INTRODUCTION

## 1.1 Study Objectives.

The study was designed around the following objectives:-

#### 1.1.1 Overall project objective.

To assess the nature and potential scale of fish entrapment at water intakes and outfalls for coarse, salmonid and estuarine fish species. To evaluate the protective mechanisms currently employed and review other potential solutions.

#### 1.1.2 Specific objectives.

1. To carry out a comprehensive literature review of the research which has been undertaken to assess and describe the nature of fish damage/ mortality at abstraction and discharge points.

2. To quantify the number and type of abstraction and discharge points in England and Wales suspected to be causing damage to fish populations.

3. To carry out a review of the literature relating to protective mechanisms used at abstraction and discharge points. Other potential solutions.

4. To describe examples of protective mechanisms currently employed in England and Wales and to critically assess their effectiveness.

5. To assess whether future research in this field would be beneficial to the NRA and if so:-

    i) identify methodologies that could be used to estimate the scale of losses, mortalities and/or damage caused to fish populations at abstraction or discharge points.

    ii) identify suitable sites where the scale and nature of detrimental effects could be assessed.

## 1.2 Background

Water is abstracted from inland waters and estuaries for a wide range of uses including public water supply (PWS), power station cooling, other industry, irrigation and fish farming. While much of the water is returned to rivers either directly e.g. by hydro electric generating stations and fish farms or indirectly e.g. PWS via sewage treatment works (STW), there is clearly a risk of damage to fish entrained with the abstracted water.

With minor exceptions all abstractions of surface water in excess of 20 $m^3/d$ require to be licensed by the NRA. There are over 14 000 such licenses for abstractions from inland waters in England and Wales. The total licensed volume is of the order of 40 000 Ml/d, representing about 23% of total mean run-off. At times of low river flows, the proportion of overall river-flow licensed for abstraction is significantly greater. There is clearly potential for considerable damage to fish stocks to be effected by these abstractions. However, remarkably little quantitative information appears to be available on the actual levels of damage done and the extent to which fish stocks and fisheries suffer as a result.

Abstractions from estuaries are fewer but tend to be very much larger in volume. Most estuary abstractions are used for cooling power generating equipment or petro-chemical works.

Most large abstractions have some sort of intake screening, but exclusion of waterborne debris is the usual reason; protection of fish is generally a secondary consideration. Perhaps for this reason there has been little evaluation of the effectiveness of screening devices in excluding and protecting fish. In some instances there is the suspicion that the screens themselves cause damage to fish, or are sited in a manner that does not allow fish to escape the influence of the intake.

In addition to water abstractions, water is often pumped from low-level drains and carriers for land drainage purposes. This may also pose a threat to fish well-being.

This study, with the objectives stated in section 1.1, is therefore timely or indeed may be considered significantly overdue. While it has not been possible to undertake a detailed analysis of all types of installation this report nevertheless identifies the more promising approaches to fish protection, and makes recommendations for further investigations.

## 1.3 Definitions

#### 1.3.1 Impingement

The process whereby fish become impinged upon a physical screen, generally but not always because they are too large to pass through the mesh. Impinged fish may subsequently escape or pass through the screen.

#### 1.3.2 Entrainment

The process whereby fish are drawn into an intake with the water flow. Strictly speaking entrainment and impingement as used in this report are mutually exclusive, though as explained above an impinged fish may subsequently become entrained. Where a physical or behavioural screen is installed the fish are not considered to be entrained until they have passed this point with the abstracted flow.

### 1.3.3 Entrapment

A general term to cover both impingement and entrainment.

### 1.3.4 Mesh size, slot size

Unless clearly stated otherwise, mesh dimensions and slot sizes are internal i.e. aperture dimension.

### 1.3.5 Intake velocity

The mean water velocity at the screen aperture i.e. the total abstracted volume divided by the open area of the screen excluding the mesh/bar material.

### 1.3.6 Approach velocity

The mean water velocity at some undefined distance from the screen, most meaningfully at the point where fish become aware of the danger and attempt to escape. Generally lower than the intake velocity.

All abstraction and flow rates are quoted in megalitres per day (Ml/d).
1 million gallons per day (Mgd) = 4.55 Ml/d.
1 cubic metre per second ($M^3$/s, cumec) = 86.4 Ml/d.

# 2. ASSESSING THE PROBLEM

## 2.1 The biological background

### 2.1.1 Non-tidal waters

As water intakes and outfalls can only influence fish in the immediate vicinity, the risks of damage are limited to:-

- those fish residing in the immediate area;
- those fish carried passively with current e.g. very young fry; and
- those fish migrating past the intake either downstream or upstream.

In the case of outfalls, the only group of fish likely to be influenced are those migrating upstream.

Even fish that are considered to be strictly local in their movements may at times move over a fair distance on a seasonal basis. There is also growing evidence that many so called non-migratory species, e.g. cyprinids do in fact undertake significant redistributions within river systems at various times in their life-cycles.

Lightfoot and Jones (1976) observed dispersion of young roach from marginal habitats in July at a length of about 30 mm. Movement was downstream in direction, but there was some evidence of an upstream compensatory migration during autumn floods. Linfield (1985) presented evidence, based upon differential length/frequency distributions in different river reaches, of large scale movements of fish over tens of kilometres in some Anglian river. The suggested mechanisms were downstream displacement of fry, and upstream movement of spawning adults. Jordan and Wortley (1985) described seasonal redistributions of roach and other cyprinids over distances of at least 4 km in the Norfolk Broads system. Hancock et al (1976) observed barbel migrating at least 12 km upstream of their normal habitat to spawn on the Driffield Beck.

The extent of movements of very young fry of coarse fish is unknown. They are very small (typically 7.5 mm in length at hatching) and difficult to sample and identify. Observations suggest that there may be a considerable spread downstream from very localised spawning areas, into river margins. The fish then remain relatively sedentary until the redistribution at a size of 30 mm or so already described. The extent of the initial dispersion and the second phase of movement appear to be very variable between years, probably largely dependent upon flow, weed cutting practices etc (Dr G Lightfoot, pers. comm.).

Clearly migratory species such as salmon, sea trout, eels and shad, which pass up and down river at least once during their life cycle are potentially at risk.

A most important consideration in determining the potential impact of intakes on fish, and for designing optimal devices and operations, is the discontinuous distribution of migrating fish in both time and space. The scope for avoiding abstraction at certain times and places to reduce the potential impact on fish is considerable, and is discussed in section 6.

### 2.1.2 Estuarial waters

Behaviour patterns of fish in estuarial waters are quite different from those in inland waters. Fish are often present only on a seasonal basis, and they may be present in very large numbers. The tidal regime generally means that the populations are highly mobile, and very vulnerable to entrainment in intakes. On occasions, power stations are forced to temporarily cease operation when vast quantities of sprats block intake screens (Turnpenny et al 1985; Figure 2.1).

**Figure 2.1**

**Small fish impinged on the intake screens at Sizewell Power Station. (The fish are mostly sprats, with small numbers of flatfish and gadoids. (Photograph reproduced with permission of Dr. A Turnpenny, National Power))**

Migratory fish passing between fresh water and the sea and vice versa are also potentially vulnerable. The operators of Uskmouth Power Station mount a salmon smolt rescue operation each spring, removing fish from the intake wells just in front of the drum screens. A hatchery is also operated to replace fish which are considered to be effectively lost by entrainment and impingement. Many euryhaline species also make regular migrations into estuaries e.g. smelt, flounders. Some marine species also tend to inhabit estuaries in their juvenile stages e.g. bass.

## 2.2. Potential damage to fish and fisheries

### 2.2.1 General

There are three aspects to considering the impact of intakes on fish and fish stocks:-

(a) what happens to fish drawn into, or that swim into, unscreened intakes and outfalls or through the screens of screened intakes or outfalls?

(b) what happens to fish that come into contact with physical screens but are not drawn into the intake?

(c) what are the implications of the effects of (a) and (b) in terms of fish population dynamics, and fisheries management?

Each of these are now considered in turn.

### 2.2.2 Fish drawn into intakes

The fate of fish drawn into intakes from which they cannot, or do not, escape back upstream is dependent of course on the use to which the water is put.

In the case of abstractions for direct water supply, fish are likely to die in the pumps or at a filter stage, with effectively total mortality. Many fish entrained in water pumped into storage reservoirs are likely to survive, as high volume/low head pumps are relatively benign for fish passage. Thames Region suggest that large numbers of juvenile coarse fish enter the London Reservoirs in this way. However, they represent a total loss with respect to the river from which they were drawn. Irrigation is also likely to represent 100% mortality with respect to entrained fish.

The fate of small fish entrained in power station cooling water is unknown. The considerable and rapid temperature rise (often 10°C or more), the physical trauma of passage through pumps and condenser tubes, and the effect of chlorine added to reduce biofouling are all potentially lethal to fish. However, investigations by the Fawley Marine and Freshwater Biology Unit of National Power have been inconclusive, with major problems of sampling small fish in the outfall in a manner that did not itself cause damage to fish. In their assessments of the impact of coastal power stations they assume a total mortality of entrained fish. However, this is in order to encompass a "worst case" rather than because total mortality is the best estimate of the situation (Dr A Turnpenny, pers. comm.).

Fish entrained with water used to generate hydro-electricity may well survive passage through the turbines, depending upon turbine design and operating characteristics, fish size and fish species. This is too wide a subject to review fully here; a thorough review of fish passage through low-head turbines was conducted by Solomon (1988). Briefly, for many species e.g. small salmon, the main cause of mortality appeared to be mechanical damage caused by contact with fixed or moving machinery. For more delicate fish e.g. juvenile shad, other mechanisms also appeared to cause damage; possibilities include shear (turbulence) and pressure changes. In the case of mechanical damage, fish size is a critical factor; consideration of a theoretical large tidal-energy turbine indicated a mortality of about 2-3% for salmon smolts, but 13-100% for adult salmon depending upon operating conditions. This factor has been recognized by the North of Scotland Hydro Electric Board (now Scottish Hydro), who considered that passage of smolts through low-head turbines caused a lower mortality than attempts to exclude them from passage; however, salmon kelts are excluded from all stations (Aitken, Dickerson and Menzies, 1966).

The likely fate of fish drawn into fish farms is uncertain and little studied. An investigation by Wessex Water Authority at a fish farm on the Hampshire Avon indicated that many fish drawn in died in turbulent conditions in water distribution boxes with screened outlets; small fish passing through the screens are likely to have been consumed by trout. Salmon smolts entrained are also believed to have experienced 100% mortality unless action was taken to rescue them (Dr G Lightfoot, pers. comm.). In general terms, the fate of fish drawn into fish farms is likely to depend upon the species and size of fish, and the water distribution and screening arrangements within the farm and the species and stock density of the farmed fish. It is probably fair to conclude that mortality in such cases is significant.

### 2.2.3 Fish lured into outfalls

This problem will generally only affect fish actively migrating upstream, but in addition to the obvious migratory species (salmon, trout, shad), many species of coarse fish also make significant upstream journeys (Section 2.1).

The problem that this represents depends upon the situation. Where fish are unable to proceed far upstream e.g. because of grids or very high current speeds, they may soon return downstream to seek an alternative and more fruitful route upstream. However, salmon in particular may remain within an outfall channel for considerable periods, often many months. While they may eventually return downstream the delay may be undesirable for three reasons:-

- the eventual spawning distribution may be truncated.
- fish may be vulnerable to illegal exploitation within the confines of the outfall channel.
- the delay may restrict angling opportunities upstream.

Examples of these three effects are discussed in section 2.4.

More serious problems can arise when fish can gain access to areas where they may be damaged e.g. turbines; mortalities of upstream-migrating adult salmon have been reported from this cause in Scotland. Finally, an imperfect screen on an outfall can be a very real problem. Fish may locate passable gaps to gain upstream access, but be unable to locate or pass through them in a downstream direction. In December 1990, Wessex Region removed about 50 salmon from upstream of "fish proof" grids in the outfall channel of a fish farm on the Hampshire Avon. A file note at SouthWest Region gives details of a problem with salmon penetrating a grid on the outfall of a hydro-electric station at Pynes Waterworks on the Exe in 1958. A number of dead fish were removed from the upstream side of the grid. Many of the 51 fish rescued alive were damaged from attempts to penetrate the screen. Some large fish had become wedged in the grid and had died there.

#### 2.2.4 Fish impinged on intake screens

Wherever a physical mesh screen is installed, it is likely that, unless approach velocities are very low and the intake carefully sited with an adequate by-pass route (Section 3.3), some fish will become impinged. In some cases the fish may then escape with minimal injury, especially if contact is brief. Often the fish may be unable to escape (perhaps having become exhausted by attempts to avoid impingement) and die in situ. Where screens are cleaned, either by raking or by washing in the case of mechanical screens, fish will be removed with weed and other debris.

There is surprisingly little published information in the literature concerning the injuries and mortality rates caused by impingement on intake screens. Pagano and Smith (1977) investigated damage to fish impinged on a fine woven mesh screen. They found that mortality rates varied with species; otherwise the main variable was length of time of impingement, and for some species, approach velocity. Fish size was also important, with smaller fish showing a higher mortality. Fish surviving for 48 hours after tests were examined for signs of external injury. About 1.5% showed such signs; of these 50% was eye damage, 29% caudal fin, 6.4% gut, 5.3% other fins, 5.0% mouth and 4.7% head. No checks appear to have been made for internal injuries.

Large numbers of fish are at times impinged on the cooling-water intake screens at coastal and estuarial power stations. Turnpenny et al (1985) reported up to 40 000 sand smelt impinged at Fawley Power Station each week during February and March. Elsewhere impingement of sprats occurs at times at such a level that stations have had to temporarily shut down because the screens cannot be cleared. With the exception of stations likely to be affecting migrating salmonids, almost no attempt is make to return alive fish impinged on screens; they are collected in trash bins with weed and other debris. The reasons for not attempting to rescue fish elsewhere are (Dr A Turnpenny, pers. comm.):-

- most screens installations are old and do not incorporate return systems.
- fish occurring in largest numbers are clupeids; extremely delicate, and likely to be fatally damaged by impingement, even if returned.
- demonstration that the loss is of little consequence for populations or fisheries (Section 2.2.5).

The injuries apparent on fish impinged on power station screens are similar to those reported for turbine passage (Solomon 1988; see Section 2.2.2) including loss of scales, head damage and eye damage (see Figures 2.2 – 2.5).

As already mentioned, some power stations likely to entrap salmon smolts operate rescue mechanisms. At Oldbury (Severn Estuary) the band screens incorporate troughs at the bottom of each panel to hold water and fish, and the fish are separated from the weed by falling through a rake system to an escape channel. The mortality rate of fish experiencing this process is unknown, but it is suggested that it is likely to be significant.

The situation for British freshwater species appears to be quite unstudied. However, in view of the fact that the fish most likely to be impinged in numbers (salmonid smolts, and juvenile cyprinids a few cm in length - see Section 2.1) are considered to be very delicate and likely to die as a result of even minor damage, it is reasonable to consider that all fish impinged do in fact die.

#### 2.2.5 Impact on fisheries

The subject of the extent to which mortality or effective loss of fish at intakes matters to fish populations and fisheries has been little studied for British freshwater species, though there is some information for marine fish, North American species, and migratory salmonids.

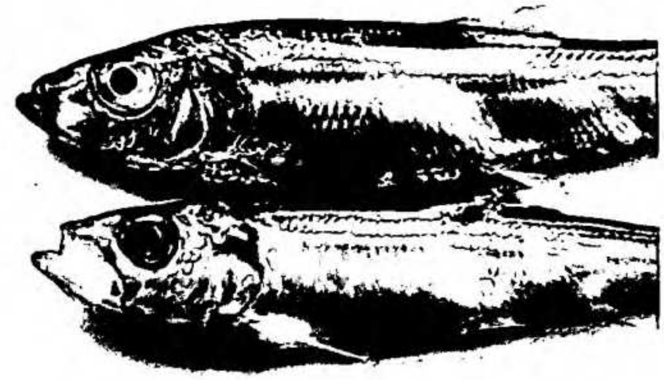


Figure 2.2

Figure 2.3

**Eye damage on fish impinged on the intake screens at Fawley Power Station. Significant scale loss is also apparent on one of the sprats in the upper photograph. (Photographs reproduced with permission of Dr. A Turnpenny, National Power.)**

The losses of marine species at coastal power stations is addressed by Turnpenny et al (1985). Although numbers of fish are often large, calculations show that losses are insignificant compared to the total population from which the fish are drawn. For species of commercial interest e.g. commercial fishing has an effect between 1000 and 100 000 times greater than power stations in terms of loss of fish. Even for species suspected of forming local sub-populations, which might be expected to suffer to a proportionately greater extent, no impact has been demonstrated. Henderson et al (1984) studied populations of sand smelt *(Atherina presbyter)*in the vicinity of Fawley Power Station since generation started in 1971. This species has consistently been the numerically dominant fish in the annual screen catch, and spends its whole life locally; polymorphic differences have been noted between adjacent coastal populations as little as 20 km apart. It was concluded that operation of the power station had no significant effect on the long-term stability of the local population.

Greater concern exists over the potential impact on some euryhaline species such as smelt (*Osmerus eperlanus*)and bass (*Dicentrarchus labrax*) though no studies on the impact of entrapment could be identified.

Pgano and Smith (1977) describe several studies which generated models of the impact of power station impingement and entrainment on populations of striped bass *(Morone saxatilis*) on the East Coast of North America and California.

In the case of salmon, it is generally accepted that, from the smolt stage onwards, there is little density-dependent adjustment of mortality; thus destruction of smolts will result in a proportional decrease in the numbers of adults returning to the river. Similarly, adult fish destroyed or delayed at outfalls will have a direct effect on the numbers of fish remaining. Although the relationship between numbers of fish present and numbers caught by anglers may not be a straight line, in general terms a reduction in numbers of fish will lead to a reduction in catch. Spawning stock would also be reduced. Although losses of smolts at intakes are fairly frequently reported, few are fully quantified. In an investigation of the situation at a large trout farm on the Hampshire Avon, a total of 1059 smolts was counted as entrained during the run in 1987, calculated to be of the order of 5% of the run at this point (Dr G Lightfoot, pers. comm.). The number and proportion are likely to vary annually depending upon river flow; April 1987 experienced a higher than average flow on the Avon, thus proportion abstracted would have been relatively low.

A model of smolt entrainment at Walton Waterworks has been developed by Thames Region. Comparison of maximum rates of abstraction with river flows indicated that up to 40% of the river flow may be abstracted during typical April/May discharges (Solomon 1986). There was the scope for a similar proportion of smolts to be entrained, though it was noted that any tendency for smolts to avoid being drawn through the trash screens might reduce the proportion, while a tendency for smolts to migrate along the shoreline might increase it. Subsequent observations based on catches of marked smolts in a louver screen trap in the intake channel have validated and modified the model (Clarke 1988; Gough 1991). At high intake volumes smolts appear to preferentially enter the intake with the accelerating current; further, abstraction tends to be maximised at night (lower pumping costs), which coincides with the peak of smolt migration. The model suggests that smolts losses are approximately 1% with 7% of river flow abstracted; 10% with 14% abstraction; 50% with 42% abstraction, and approaching 100% with 77% abstraction. Extrapolation to include the other major intakes on the lower Thames suggests that up to 80% of

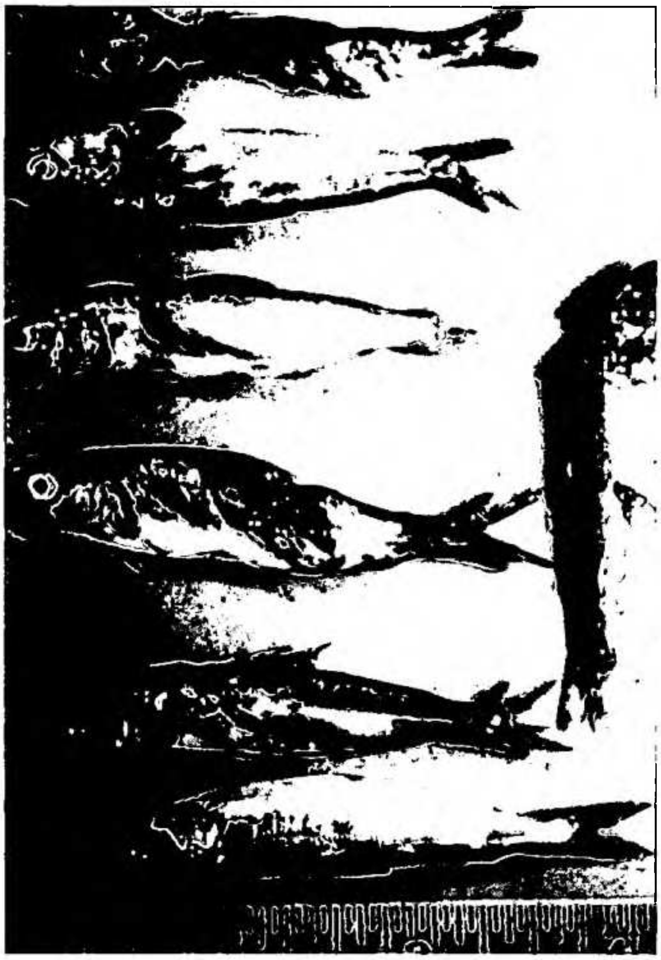


Figure 2.4


Figure 2.5

**Juvenile salmon damaged by passage through a low-head turbine on the Columbia River. (Photographs reproduced with permission of Dr Wesley Ebel, National Marine Fisheries Service, Seattle, USA.)**

smolts might be lost in a yearof low April/May flows such as 1976, while in wet years such as 1981 the figure could be of the order of 15%, assuming maximum abstraction rates. In practice, maximum abstractions are likely in dry years, but not in wet years, depending upon level of reservoir storage.

The situation with other freshwater species is much less well-defined. It appears that the main vulnerable stage for cyprinids is as 0+ fish in summer, at a length of 25-35 mm and also perhaps as newly hatched fry (Section 2.1). It is not known to what extent density dependent mortality operates after this stage, and thus what scope the population has to compensate for the loss by reduced natural, density dependent mortality. As this phase of migration appears to represent a widespread dispersion it is likely that the main phase of density dependent mortality has in fact passed. There is clearly a need for investigation of the population control mechanisms and movements of coarse fish to further elucidate this matter.

There are virtually no quantitative studies of the losses of freshwater fish at intakes in the UK. A semi-quantitative study at a fish farm on the Hampshire Avon (Dr G Lightfoot, pers. comm.) indicated that losses in a year are very variable and could easily total of the order of tens of thousands of young cyprinids per annum. Observations from a louver screen trap installed in the intake of Walton Waterworks on the Thames are of interest here. The trap, described in section 5.5.4 was installed to sample entrained salmon smolts, but has also captured many coarse fish. These are mainly 0+, with some 1+ but very few older year classes. Older fish trapped were mostly damaged or diseased; it is likely that the trash screens, with a clear gap of 32 mm, prevented the entry of most larger fish to the channel. Few fish of less than 18 mm were caught in a three-year trial period, and efficiency of capture of all juvenile coarse fish was very low; trials suggested between 3% and 10%. The total number of 0+ fish captured between April 25 and September 9 1989 was 87 408, suggesting a total entrainment of between 874 000 and 2.9 million 0+ fish. The number of 1+ fish captured in the same period was 1933; assuming a 10% trap efficiency for these larger fish indicates a total entrainment of the order of 20 000 1+ fish. Unknown numbers of fish of less than 18 mm were also entrained; their low numbers in catches is believed to be at least partly, if not overwhelmingly, due to the mesh of the cod-end failing to retain them. Numbers of very small fry were observed on occasions when weed was caught in the cod-end but they were not enumerated (Mr G Armstrong, pers. comm.).

What proportion of the local populations these entrapped samples described above represent is unknown, but is of an order of magnitude that could represent a significant proportion.

## 2.3 Abstractions in England and Wales

At the start of this investigation a short questionnaire was sent to Water Resource Managers in each NRA region requesting information on the numbers of surface-water abstractions, including a breakdown by size. The questions posed in the questionnaire are reproduced in Appendix A.

**Table 2.1. Surface water abstractions in England and Wales. Volume figures are for Ml/d.**

| | Number of licences. | | | | | Licensed | Total |
|---|---|---|---|---|---|---|---|
| | Total | >10 | 5-10 | 1-5 | <1 | volume | run-off |
| | | | Ml/d | | | Ml/d | Ml/d |
| Northumbrian | 166 | 17 | | 149 | | 3065 | 11405 |
| Yorkshire | 1878 | | | | | 5076 | 15120 |
| Severn Trent | 3119 | 70 | 20 | 151 | 2886 | 10823 | 19700 |
| Anglian | 3035 | 59 | 46 | 2930 | | 2050 | 1100 |
| Thames | 664 | 22 | 5 | 28 | 609 | 3585 | 6299 |
| Southern | 1018 | 22 | 3 | 28 | 965 | 1920 | 9210 |
| Wessex | 832 | 23 | 13 | 45 | 751 | 840 | 13504 |
| South West | 622 | 69 | 26 | 63 | 464 | 5605 | |
| Wales | 2224 | 100 | 25 | 146 | 1953 | 23954 | 52531 |
| North West | 1410 | 129 | 61 | 223 | 997 | 7690 | 26740 |

The situation is complicated somewhat by the variable inclusion of Licences of Entitlement, being issued under the Water Act 1989, which bring into the licensing framework most previously exempt abstractions. However, the total number of licensed abstractions from non-tidal surface water is 14 346 totalling 64 878 Ml/d. Not all regions were able to provide the breakdown by size requested (Table 2.1) but approximately 3.6% of licences are for abstractions exceeding 10 Ml/d, while over 88% are for abstractions of less than 1 Ml/d. These totals exclude abstractions of quantities less than 20 m3/d (0.02 Ml/d), which are exempt from a licensing requirement. It should be noted that not all licences are fully utilised. In Thames Region in 1989, for example, only 73.6% of the total licensed volume was actually taken. Of the total for Wales of 23 954 Ml/d, 13 680 Ml/d is for hydro-electric generation; only 22% of this volume was actually abstracted during 1989-90.

The balance of uses to which the abstracted water is put varies regionally, but a breakdown for England and Wales for 1987 for non-tidal surface-water abstractions, excluding hydroelectric generation, was 58.4% water supply; 22.4% CEGB; 13.5% industry; 5.3% fish farming and watercress; and 0.34% other agriculture, including spray irrigation. The fact that much of the abstracted water is returned to the watercourse fairly promptly is of little relevance in this context unless the use to which it is put allows the safe passage of some entrained fish, for example some hydro-electric operations (Section 2.2.2).

An attempt was made to assess the total licensed abstraction in terms of the proportion of river flow that it represents. The total licensed take of 64 878 Ml/d represents about 36% of the total run-off for England and Wales of 165 500 Ml/d. It is of interest to consider the situation at times of low flows. Relatively few abstractions are restricted above a residual flow of the order of the Q95. In the questionnaire, regional Water Resource Managers were asked to "propose a reasonable estimate" of the proportion of mean flow that represents the Q95 for the region. While some declined to do so, several provided estimates that indicated a broad average of the order of 20%. Thus in a situation where maximum abstractions left a residual flow approximating to Q95 (33 100 Ml/d) the total abstraction would represent about 66% of river flow. In practice, as most abstractions are returned to the river either promptly or via STW, maximum abstraction is likely to be takeable at significantly lower total river flows due to effective re-use of water ie a higher proportion of flow could be abstracted. On the other hand, as already discussed, there is currently not a 100% take-up of licensed volumes. It is therefore not possible to obtain a more realistic impression of the proportion of river flows that might be abstracted, though it is clear that it is high.

The questionnaire also contained the following questions:-

- are you able to make any estimate of how many of the above abstraction points are likely to incorporate screens to prevent abstraction of fish? and

- does your abstraction database contain information on intake screening requirements or provisions?

Surprisingly, virtually all Regions answered "no" to both questions. Two suggested asking the Fisheries Officers (which was of course done - Section 2.4). Only Yorkshire Region gave a positive answer to the first question (but not the second), which was "About 30". A recent condition now used in Yorkshire Region requires the installation of vertical bar screens on intakes.

## 2.4 Regional assessment

As detailed in section 1.1, one of the specific objectives of this study was to quantify the number and type of abstraction and discharge points in England and Wales suspected to be causing damage to fish populations. At an early stage in the investigation it became apparent that achievement of this objective was quite unrealistic. As discussed in section 2.3, NRA Regions do not even hold details of which intakes incorporate screens. Discussions with regional fisheries staff showed that there was likely to be little specific information available - certain problem sites were known (particularly for salmonids) but enumerating all sites causing mortality was out of the question.

An alternative approach was clearly needed to obtain an overall picture of the problem. Regional Fisheries Managers were therefore asked to complete a questionnaire (reproduced in Appendix A) which attempted a semi-quantitative analysis.

Regional officers were asked to indicate in their view, whether the fish losses at intakes in their region were (a) catastrophic, (b) major, (c) significant, (d) minor or (e) insignificant. Separate returns were requested for migratory salmonids and other fish. The responses are summarised in Table 2.2.

**Table 2.2. Responses by Regional Fisheries Officers to Questionnaire. Assessment of impact of fish losses at intakes.**

| Region | Migratory salmonids | Other species |
|---|---|---|
| South West | Significant | Minor |
| Wessex | Minor | Significant |
| Southern | Significant | Insignificant |
| Thames | Significant | Minor |
| Anglian | n/a | Minor |
| Welsh | Minor | Insignificant |
| Severn Trent | Minor | Insignificant |
| North West | Minor | Minor |
| Northumbrian | Minor | Minor |
| Yorkshire | Unknown | Significant |

For migratory salmonids [excluding Anglian Region (not applicable) and Yorkshire Region (unknown)] the returns were all "significant" or "minor". For other species returns showed a greater range, from insignificant to significant.

Two Regions (Anglia and Yorkshire) also raised the issue of land-drainage pumps, which have been known to cause mortalities on occasions. Little quantitative information is available, but losses may be significant in areas where most of the run-off is pumped to a higher level.

**Table 2.3. Responses by Regional Fisheries Officers to Questionnaire. Assessment of impact of delays to fish caused by outfalls.**

| Region | Migratory salmonids | Other species |
|---|---|---|
| South West | Significant | Minor |
| Wessex | Significant | (possibly significant) |
| Southern | Minor | – |
| Thames | Insignificant | – |
| Anglian | n/a | Insignificant |
| Welsh | Minor | Insignificant |
| Severn Trent | Insignificant | Insignificant |
| North West | Minor | – |
| Northumbrian | Significant | – |
| Yorkshire | Minor | – |

Regional officers were also asked to indicate their views on the problems of fish entering outfalls, using the same categories of impact. The results are summarised in Table 2.3. For migratory salmonids (excluding Anglian Region) returns ranged from no significance to significant. Those indicating a "significant" return were able to quote specific instances; unlike with problems of small fish drawn into intakes, a problem with adult salmon or sea trout entering outfalls is likely to be readily apparent. The list of problem sites was not exhaustive, but locations representing a real problem probably number only a few tens throughout the whole of England and Wales. However, where a problem occurs it can be major and a continuing concern to fishery managers. Very incomplete responses for other species showed a preponderance of no significance; only South West Region ("minor") and Wessex ("possibly significant") put the problem at a higher level. In both these cases specific cases were identified. On the River Exe, coarse fish are attracted into the outfall of a flood relief channel near Exeter. On the Hampshire Avon, a salmon rescue electric fishing operation in a trout farm outfall channel indicated that large numbers of adult coarse fish had also entered the channel. However, this would appear to be a strictly local problem.

# 3. POTENTIAL SOLUTIONS

## 3.1 Legal background.

Two Acts of Parliament appear to provide mechanisms whereby an abstractor can be required to install and operate fish screens. Section 14 of the Salmon and Freshwater Fisheries Act 1975 states that:-

(a) Where water is diverted from waters frequented by salmon or migratory trout by means of any conduit or artificial channel and the water so diverted is used for the purposes of a water or canal undertaking or for the purposes of any mill, the owner of the undertaking or the occupier of the mill shall, unless an exemption from the obligation is granted by the water authority for the area, place and maintain, at his own cost, a grating or gratings across the conduit or channel for the purpose of preventing the descent of the salmon or migratory trout.

(b) In the case of any such conduit or artificial channel the owner of the undertaking or the occupier of the mill shall also, unless an exemption is granted as aforesaid, place and maintain at this own cost a grating or gratings across any outfall of the conduit or channel for the purpose of preventing salmon or migratory trout entering the outfall.

(c) A grating shall be constructed and placed in such a manner and position as may be approved by the Minister.

(d) If any person without lawful excuse fails to place or to maintain a grating in accordance with the section, he shall be guilty of an offence.

(e) No such grating shall be so placed as to interfere with the passage of boats on any navigable canal.

(f) The obligations imposed by this section shall not be in force during such period (if any) in each year as may be prescribed by byelaw.

(g) The obligations imposed by this section on the occupier of a mill shall apply only where the conduit or channel was constructed on or after 18th July 1923.

It will be noted that this clause only covers salmon and migratory trout. A mill is defined as including any erection for the purpose of developing water power. There is an exemption in the case of mills (but not water or canal undertakings) where the conduit or channel was constructed before the passing of the 1923 Act. The Bledisloe Report (1961) recommended that "the powers of a river board in this respect should be extended to all diversions of water from rivers and to all forms of barriers to fish, including such devices as electric screens, idle wheels, etc, and should apply to non-migratory as well as as migratory fish." The 1975 Act broadened the definition of a grating to take account of this recommendation, but regarding the types of abstraction and species covered it merely repeated the wording of the 1923 Act. This legislative provision appears to have been little used, however. MAFF records show only seven approved gratings in the whole country, all under the 1923 Act with none having been approved since 1957. It is strongly recommended that this legislative provisions be applied more vigorously, and that changes in the legislation as suggested by Bledisloe are sought.

The second legislative mechanism for requiring fish screens is via abstraction licences issued under the Water Resources Act 1963. Conditions may be applied to such licences, including a requirement for fish protection devices. The Yorkshire Region place such a condition on all new licences, and South West Region have also done so on some new licences. It would appear that such a condition cannot be imposed on an existing licence to which it does not already apply, nor can it be imposed on a Licence of Entitlement issued under the Water Act 1989, except under the provisions in the Water Act 1963 for revocation or variation of a licence (Section 4.3).

## 3.2 General principles

There are three basic approaches to reduction in entrapment of fish in abstracted water, though they overlap to some degree. The three are:-

- physical screens with a mesh size that prevents passage of the fish under consideration. Includes drum screens, wedge wire screens, and sub-gravel intakes.
- behavioural screens, that exploit behavioural responses of fish to divert them to an alternative route. Includes louver screens, bubble screens, electrical screens, sound stimuli.
- exploitation of the discontinuous distribution of fish in time and space e.g. by careful siting and operation of the intake - termed the ecological approach by Pavlov (1989). Includes deep-water siting of intakes, and diurnal or seasonal modulation of abstraction.

In practice, the three merge to a considerable extent. Most fish excluded by physical screens ideally do not touch the screen at all, but avoid being impinged against it by a behavioural response. Smaller fish may avoid being entrained by an escape reaction to the visual and hydraulic stimuli near the screen. Thus for these fish, the screen is operating as a behavioural barrier. There is scope for all screens, physical and behavioural, to be increased in effectiveness by careful siting so that fewer fish require to be excluded or diverted. Similarly, avoiding operation during periods of peak migration can be a useful approach to reducing entrainment and impingement. It is constructive however, to consider these approaches singly so that the contribution of each can be assessed.

## 3.3 Fundamental criteria

Although the design criteria will vary considerably according to the size and type of fish that are being targeted for protection, the size and type of intake, and the type of screen being considered, certain fundamental principles apply. It is helpful at this stage to attempt to list them:-

- the intake should be sited to minimise the numbers of fish approaching it thus being put at risk of entrapment;

- ideally the abstraction should be suspended during times when numbers of fish approaching are at their peaks, unless exclusion efficiency is very high;

- physical screens should have mesh dimensions and characteristics to prevent passage of the fish targeted for protection, and to minimise damage to fish coming into contact with it;

- a behavioural screen, in reducing the entrapment of the "target" species, should not by its operation lead to increased entrapment of other species;

- behavioural screens, and ideally physical screens, should represent a repellent stimulus at some distance from danger, and in a manner that allows fish to take appropriate avoiding action;

- a suitable safe route should be easily and rapidly found, ideally found by default, by fish diverted from entrainment;

- the approach velocity near the screen should be low enough to allow fish to escape entrainment under all conditions when fish are likely to be at risk, including, where appropriate, low water temperatures;

- the repellent stimulus of a behavioural screen should not be such that it discourages or delays safe by-pass passage as well as preventing entrapment.

## 3.4 Biological considerations in design criteria

### 3.4.1 Fish size and mesh size

In contrast to a number of species of interest in entrapment studies in North America and elsewhere, no British freshwater fish have eggs that are pelagic or drift with the current. Thus entrapment of eggs in intakes is not an issue here.

The size of fish at the time that they are vulnerable to entrapment is clearly important both in terms of required mesh sizes for exclusion and swimming ability to avoid entrapment. The downstream dispersion of cyprinid juveniles appears to be a discontinuous process. There is an initial dispersion from the spawning area to marginal zones; the extent of these movements is not known. The fish then appear to be relatively sedentary for some weeks, before undergoing a significant redistribution at a length of 20-30 mm (see below). Pavlov (1989) noted that 90-95% of entrapment occurred in one or two summer months at some sites in Russia, and at one site in Southern Ukraine 65-91% of annual entrapment of bream *(Abramis brama)* silver bream *(Blicca bjoerkna)* and bleak *(Alburnus alburnus)* took place in 2-8 days. In a study of fish entrained in the intake for a trout farm on the Hampshire Avon, the length of individuals of the four main species were measured (Figure 3.1). Juvenile cyprinids are about 7.5 mm in length at hatching, and it can be seen that such very young fry were not represented in the entrapment samples though very small fry are likely to have been inefficiently sampled. Roach started to appear in numbers at about 20 mm peaking at 30 mm. Dace and bream were present in very low numbers at 20 mm, again peaking at about 30 mm. Chub started to build-up from 15 mm, peaking at about 22 mm (Dr G Lightfoot, pers. comm.).

Salmonid fry are about 30 mm in length at emergence from the gravel, and then exhibit a dispersion to the nursery areas. However, this is generally of very limited geographical extent, usually only of the order of hundreds of metres (Solomon 1983). A second functional redistribution takes place during the winter months, and may involve migrations of some kilometres though generally still restricted to headwater areas. The fish are likely to be 6-10 cm in length at this time. Salmon smolts are generally 12-20 cm in length, and sea trout 15-25 cm.

Derivation of the mesh size required (M) to preclude passage of fish of certain shapes and sizes has been undertaken by Bell (1973) and Turnpenny (1981). Turnpenny used a formula based upon fish length and a "fineness ratio" for the species derived from measurements of width and depth of fish of a range of sizes. This ratio ranged from about 2.9 for a deep bodied species such as Black bream *(Spondyliosoma cantharus)* to 16.0 for eels *(Anguilla anguilla).*

Fish down to 25 mm were included in the populations used to derive the ratios, but not very small or larval fish. Turnpenny extrapolated down to 20 mm for sprat *(Sprattus sprattus)* to derive a requirement for a mesh of 2.5 mm square to exclude such fish; mesh of 4 mm square would exclude sprats of 35 mm. The species listed were predominantly marine, but included salmon with a fineness ratio 4.65 based upon a sample of fish from 40-160 mm in length.

The relationship between fish length and mesh aperture (M) for salmon is shown in figure 3.2. This is based upon the greater dimension of width and depth - in the case of salmon this is depth. Turnpenny (1988b) suggests that, in order to increase screen porosity, a rectangular mesh 2 M wide x 1 M tall would

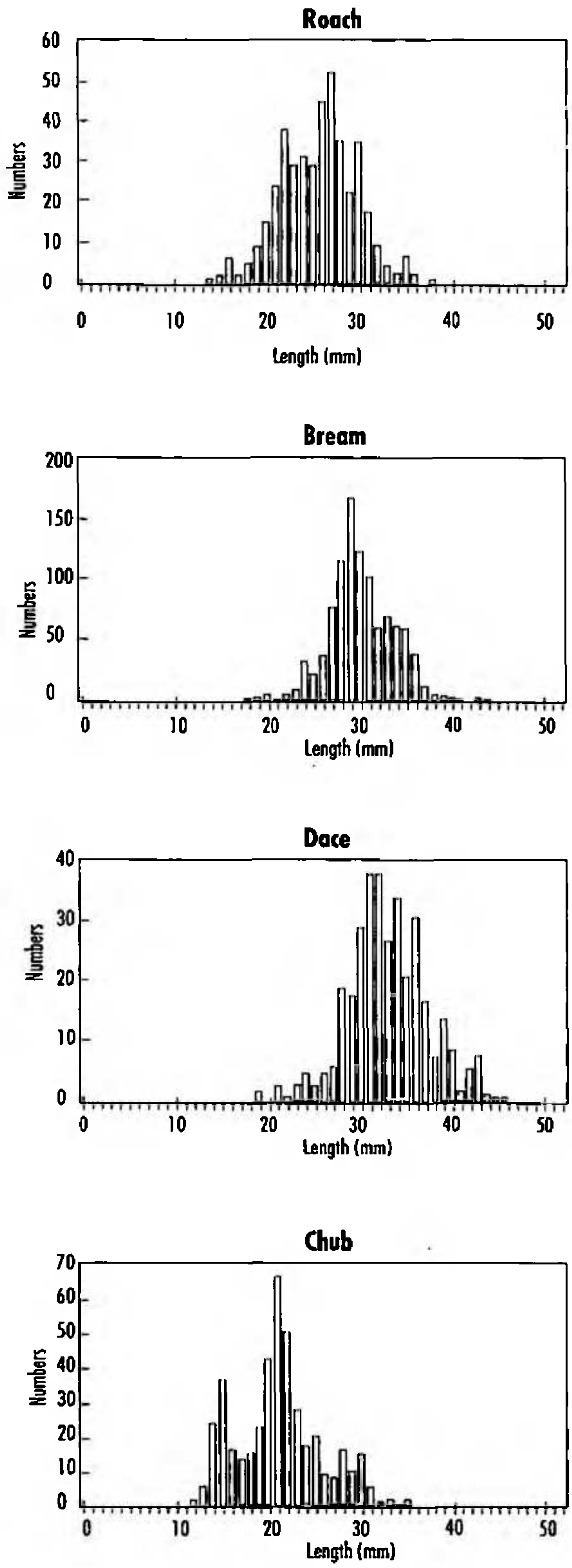



**Figure 3.1**

**Length - frequency distributions of juvenile cyprinids entrained in the intake of a trout farm on the Hampshire Avon, June - November 1986. (Dr G Lightfoot Pers. Comm.).**

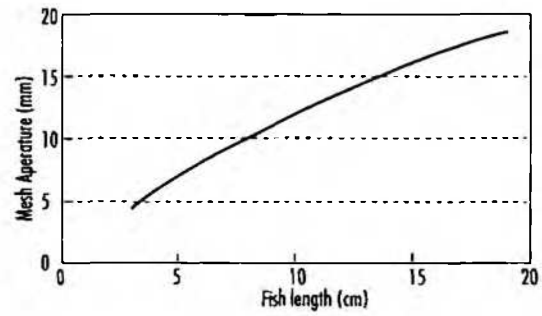



**Figure 3.2.**

**Mesh size required to exclude juvenile salmon, using the formula proposed by Turnpenny (1981).**

be adequate - this takes advantage of the fact that the fish is unlikely to be willing to turn on its side to penetrate a screen. These figures support the mesh dimensions adopted by the North of Scotland Hydro Electric Board (NSHEB) (Aitken et al 1966); for salmon smolts they have used mesh apertures 12.5 mm high, 25.4 mm wide, giving a value for M of 12.5 mm. Using Turnpenny's equation this would preclude passage of all salmon over about 11.5 cm.

It is of course the smallest fish that are to be excluded that dictate the mesh size requirement, and the relationship for larger fish is of little relevance. However, exclusion of adult salmonids from tailraces can of course be effected by screens of considerable mesh size. Using Turnpenny's figures, salmon of 60 cm could be excluded by square mesh or horizontal bars with a spacing of 32 mm. This is clearly unnecessarily small, and suggests that significant extrapolation beyond the size range used to derive the constants and relationship is of doubtful validity. NSHEB have used a standard of 42 mm between vertical bars for exclusion of adult salmon, and 32 mm for sea trout.

#### 3.4.2 Swimming speed and screen approach velocity

Clearly if a fish approaching an intake is to avoid entrapment it must be capable of swimming faster than the approach velocity in order to escape (Section 3.3). Fish swimming speed is a complex subject and a detailed analysis is beyond the scope of this report. Useful reviews exist elsewhere (e.g. Blaxter 1969, Wardle 1977, Turnpenny 1988a). The discussion here will be limited to principles and conclusions.

Most fish are capable of two levels of swimming activity. So called cruising or sustained swimming is achieved by use of the dark red aerobic muscle. Bursts of faster speed are achieved using the much larger white anaerobic muscle; there is a strict limit on the duration of maintained burst-speed imposed by the build-up of an oxygen debt that needs to be cleared when all the stored glycogen has been converted to lactic acid; this may take some hours. While it might be concluded that the maximum burst speed might be appropriate for consideration as a critical approach velocity, Turnpenny (1988a, 1988b) presents convincing arguments for considering the much lower cruising speed in this context. Behavioural observations indicate that fish near intake screens swim gently to avoid impingement, and may remain for considerable periods in this mode before eventually becoming exhausted and dropping back. Turnpenny discusses why fish apparently fail to use a fast burst to escape danger. He suggests that, as the fish perceive no apparent danger they are reluctant to use burst speed to escape. He suggests that there is a distinct survival disadvantage to casual use of the anaerobic musculature, including the "recovery" period of up to 24 hours when burst speeds will be unavailable. He compares this situation to that of fish observed in the mouth of trawls; the fish cruise between the otter boards until exhausted. If scared by a diver, the fish use a burst of speed to easily overhaul the net. Turnpenny describes similar behaviour by shoals of clupeids disturbed in front of the intake screens at Fawley Power Station.

It therefore appears that sustained swimming speed is that which should be compared to screen approach velocity to consider the risks of fish entrapment. Burst speeds should also be borne in mind, however, as a mechanism for escape where a behavioural "scarer" might be employed to reduce entrapment.

For salmon smolts, Turnpenny (1988b) used results obtained elsewhere for sockeye salmon to calculate maximum sustained swimming speeds for a range of temperatures. For a 15 cm fish these ranged from 45 cm/s at 2.5°C to 80 cm/s at 17.5°C However, experimental evidence for smolts of Atlantic salmon suggest that these figures are too high. Thorpe and Morgan (1978) found that while 12 cm parr could maintain station in current speeds up to 7 body lengths per second (BL/s), smolts at 7-8°C were unable to hold station in current speeds above 2 BL/s (fish length 13-14.5 cm). McCleave and Stred (1975) found that smolts with a mean length of 21.9 cm could sustain a swimming speed on average of 2.37 BL/s; water temperatures were 7-12°C For salmon smolts, which average about 15 cm in length, it is therefore suggested that the often applied criterion of 30 cm/s is a broadly appropriate approach velocity for avoidance of entrapment.

As discussed in section 3.4.1, cyprinids appear to be most vulnerable to entrapment during the dispersion phase of 0+ fish at a length of about 20-30 mm. Lightfoot and Jones (1976) investigated maximum sustained swimming speeds for small roach of 7.5 mm to 29.5 mm in length. Maximum sustained swimming speeds averaged about 9.6 BL/s at 18°C For 20 mm fish this equates to 192 mm/s. No figures are available for the young of other freshwater species. To allow for inter-specific variation in swimming ability, lower temperatures and for fish smaller than 20 mm in length, a maximum intake velocity of the order of 15 cm/s is suggested for protection of juvenile cyprinids.

## 3.5 Previous reviews

Two extensive reviews of intake screening technology have been undertaken in recent years. A brief discussion of their conclusions is useful here as a basis for consideration of promising techniques.

Ruggles and Hutt (1984) reviewed available and potential methods for excluding fish from hydro-electric intakes. They thus concentrated on methods suitable for large volumes of water, often with minimal bypass facilities. Their "promising" short list comprised:-

- submersible travelling screens;
- Eicher pressure screen;
- horizontal fixed screens;
- inclined fixed screens;
- louvers;
- surface discharges (bypasses).

Taft (1986) undertook a similar exercise, again with hydro-electric plants in mind. His short list was:-

- angled stationary screens;
- angled stationary screen/light hybrids;
- inclined pressure screens (= Eicher screen);
- louver/light hybrids;
- submerged travelling screens;
- spilling/light hybrids;
- other bypass system/behavioural barrier hybrids.

A wider range of screening techniques is considered in this report for three reasons:-

- some techniques suited to small intakes are less so for large intakes and and thus were ruled out by the above reviews;

- new information has become available on some behavioural diversion techniques that changes the conclusions on their viability;

- the reviews discussed above concentrated predominantly on salmonids.

# 4. PHYSICAL SCREENS

## 4.1 Introduction

Under the heading of physical screens come all those devices that physically prevent passage of fish by meshes, bars, perforated sheets or gravel. As discussed in section 3.2, ideally physical screens act predominantly as behavioural screens as fish avoid contact with the screen by appropriate responses; nevertheless, the classification is a useful one.

Listing of physical screen types is somewhat problematical as they tend to merge and overlap, making any classification somewhat artificial. Clearly however some breakdown is needed, and that used here depends to some extent upon the mesh material used, and the strategy for keeping the screens clean. The listing does not attempt to be exhaustive, and is limited to:-

- general types in widespread use in the UK;
- specific types in use in the UK which appear to be well-suited for avoidance of entrapment of fish;
- specific types in use or under development in other countries which appear well suited for avoidance of entrapment.

In considering the "suitability" of specific screen types, account is taken of the fact that most abstractions in England and Wales are of limited volume, that the sites are sometimes remote and not generally continuously manned, and that reliability, low cost and low maintenance are important criteria.

Using the above criteria, the types of physical screen now considered in more detail are:-

- simple fixed mesh or bar screens. Simplest form, widespread in use but with major limitations;
- moving or travelling screens, with automatic cleaning. Includes drum screens, band screens etc. Often installed at large intakes. Relatively poor for fish well being, and unlikely to be installed for fish exclusion alone;
- "Econoscreen". An innovative water driven drum screen with distinct promise;
- Johnson passive intake screens. Cylindrical screens with wedge-wire mesh, several now installed in the UK. In the right situation appear to be a near-ideal solution;
- Other wedgewire screens. Several options in the UK and elsewhere with promise for specific applications;
- Sub-gravel intakes and wells. Where feasible, an ideal solution with water treatment advantages too.

These types are now considered in detail.

## 4.2 Fixed mesh or bar screens

While fixed screens, of appropriate mesh and installed in a manner that allows easy avoidance by fish, can prove to be excellent at preventing entrapment of fish, in practice they rarely appear to do so. This arises for several reasons:-

- generally installed with removal of trash rather than fish protection in mind, the mesh spacing is often inappropriate for fish exclusion;
- often requiring frequent cleaning, screens may be poorly maintained (leading to large gaps appearing within or around the screen) or even removed altogether;
- even if appropriate approach velocities are designed, partial blockage of a screen can greatly increase the effective approach and intake velocities;
- screen siting and provision of adequate alternative routes may be less than ideal.

A redeeming aspect is that a well designed and sited screen, may act as an effective behavioural barrier to divert fish which could in fact pass easily between the bars. In particular, a screen with rectangular bars may act as a louver screen (Section 5.5).

The above features are illustrated in Figures 4.1 - 4.6.

A neat and effective fixed screen is used at a small intake (2.3 Ml/d) at Brockenburrow on a tributary of the River Bray in North Devon, for a PWS abstraction operated by South West Water Services (SWWS). A horizontal panel is perforated with slots approximately 75 x 6 mm, and is mounted immediately above a small weir (Figure 4.5). The abstracted water falls by gravity through the panel. The screen is largely self-cleaning, but is manually cleaned as necessary. Although leaf-removal was the main aim, it is likely to be effective at preventing entrapment of fish in excess of 5 cm length. It is likely that its fish protection could be improved still further if the panel were to be of wedge-wire with say a 2 mm slot width (Section 4.6).

In conclusion fixed screens can be effective for reducing fish entrapment if appropriately designed and sited, but the problem of debris blockage probably limits their use to small volume intakes or continuously manned sites. If salmonid smolt exclusion is the primary concern screens need be installed only during spring, when waterborne debris problems may be less than, say, during the autumn.

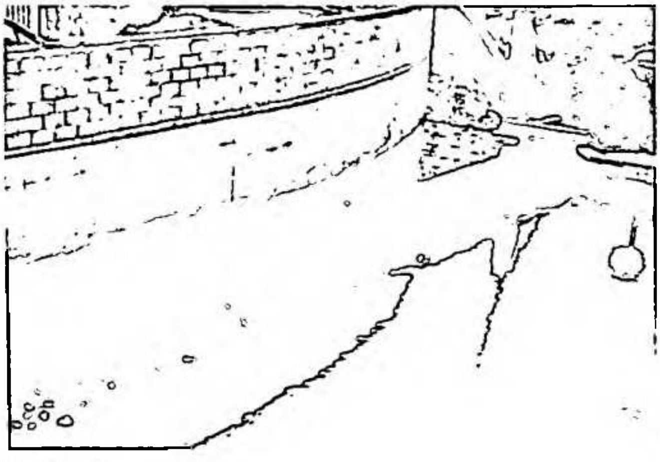


Figure 4.1

Intake screen on the lower Thames at Datchet. This screen is about 200 m from the entrance of the channel and thus offers no realistic alternative route for fish passage. The grating gaps of 38 mm and approach velocity at full licensed abstraction of about 67 cm/s are likely to lead to large-scale entrainment of both juvenile cyprinids and, if present, salmon smolts.

Figure 4.2

Intake screen on the lower Thames at Hythe End. This screen is very close to the entrance of the intake channel. Even with the 45 mm gap between bars it is likely to act as a behavioural barrier, though if the screen was truly flush with, or better still projected from the bank line the alternative safe route would be more readily found.

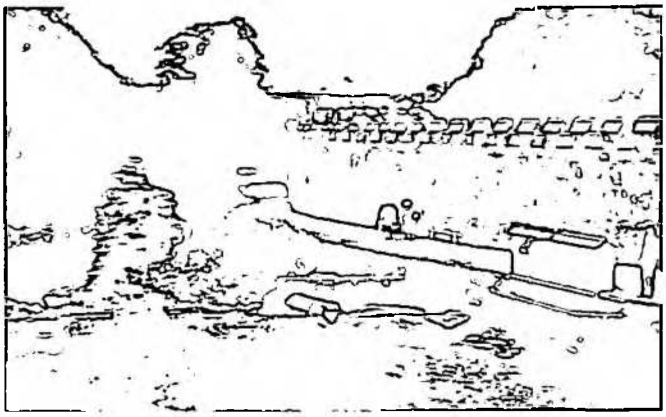


Figure 4.3

Intake screen on the River Tavy at Abbey Weir, Tavistock. This screen is optimally sited, with the grid line projecting beyond the bank line, and a readily available alternative route down the fish pass.

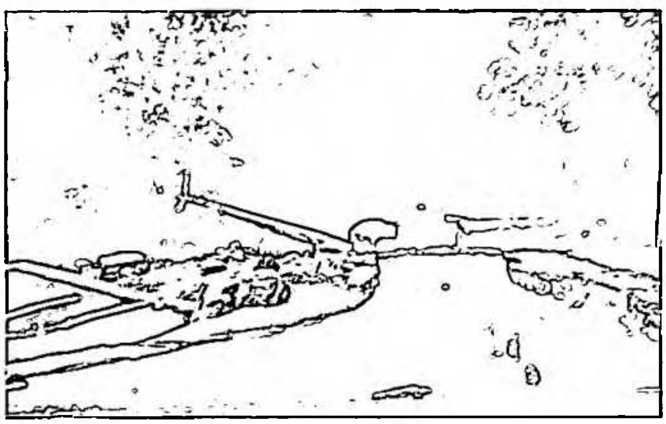


Figure 4.4

Intake screen on the River Tavy at Hillbridge. This screen is on a hydroelectric abstraction. At times of low flow virtually all the flow is taken, providing no alternative route. A small bypass channel through the weir adjacent to the screen would improve the situation.

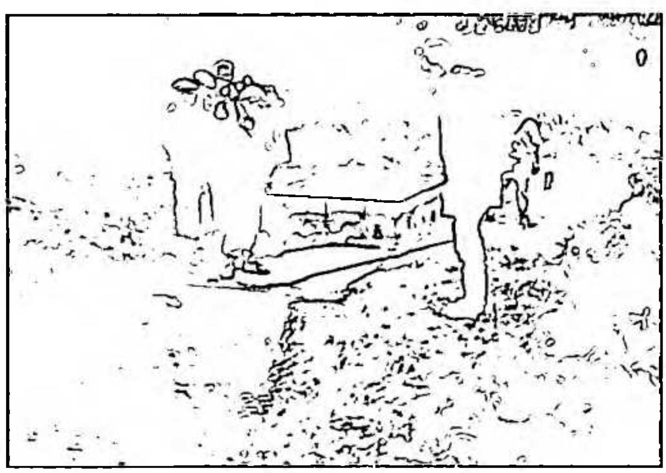


Figure 4.5

Horizontal intake screen at Brockenburrow, North Devon on a SWWS public water supply abstraction. The outline of the submerged screen can be seen.

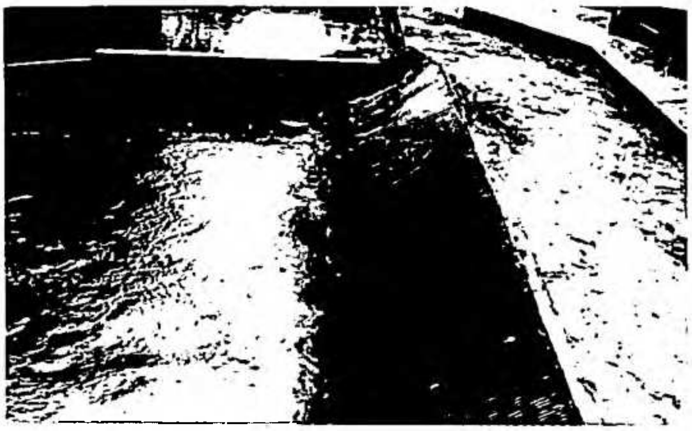


**Figure 4.6**

**Partial blockage of screen by weed (above) or debris (below) can render an otherwise satisfactory screen much less effective for avoidance of fish entrapment, by greatly increasing the approach and intake velocities.**

## 4.3 Moving or travelling screens

Moving screens, such as drum and band screens, have often been installed in the past on large abstractions, particularly at power stations. In nearly all cases the reason for installation has been debris removal to protect pumps, prevent blocking of pipes or as a preliminary to water treatment. Any protection afforded to fish has been incidental. In fact, most installations represent very little in the way of fish protection.

Fish impinged on the screens are generally removed when that part of the drum or panel is lifted from the water, and backwashed. All impinged material, including the fish, are then returned to the watercourse, or more often dumped into a perforated skip. Only in a few cases is any attempt made to separate the fish from other impinged material e.g. at Oldbury on Severn Power Station (Section 2.2.4). Travade (1985) describes a fish recovery system on a drum screen at Le Blayais Power Station in France. However, for delicate species such as juvenile cyprinids and salmon smolts, damage experienced during impingement may well be fatal, however carefully the fish are subsequently treated.

A major problem with most large moving screens is that they are some distance from the river, and there is usually no escape route from the screen-well except against the inflowing current. Fish are known to reside for considerable periods of time in screen pits. At Uskmouth Power Station salmon smolts are rescued from the pit, but the system involved itself may cause damage to the fish. There would appear to be scope for development of a bypass escape route from screen-wells.

In general terms, large drum and band screens as currently installed appear to offer little in the way of fish protection and their specification for this purpose cannot be recommended.

## 4.4 "Econoscreen"

The "Econoscreen" is a rotating drum screen manufactured and supplied by Econoscreen Environmental UK. It offers two overwhelming advantages over powered drum screens:-

- the drum is driven by the water itself, thus requiring no power supply or fuel costs;
- the screen is sited in a channel with a through flow, allowing easy alternative routes for fish passage.

Details of two installations have been provided by the manufacturers. One was installed at an intake operated by British Steel on the River Derwent at Workington. The abstracted volume is about 22 Ml/d, and the screen has been operating with minimal problems for four years. The second more recent installation is on a fish rearing unit at Carlisle, which has operated since October 1990 without stoppage.

There have been many attempts to develop self-powered rotary screens in the past, but virtually all have failed for one reason or another. The "Econoscreen" appears to have overcome the problems experienced by its predecessors and represent a viable screen option.

The screen and its operation are illustrated in Figure 4.7. Although normally operated half submerged, the existing installations have continued to operate effectively while submerged in floodwater. The screen requires that at least 25% of the flow is not abstracted; this greatly eases the problem of providing a safe bypass route for fish. The exact mechanism of avoidance of fish entrapment is uncertain, but as long as the bypass flow is sufficiently large fish are likely to avoid impingement by behavioural reactions. The manufacturers point out that any fish impinged on the screen will be released within a few seconds as the drum revolves; impinged material drifts away as that section of the drum reaches the water surface. What damage might ensue to delicate fish such as salmon smolts by short-term impingement is uncertain, but there is clearly flexibility to adjust intake velocities and screen mesh material for optimal performance with regard to entrapment. No water velocity figures are available from the manufacturers.

A limitation is the requirement for some structure within the channel to support the screen, or provision of a controlled flow leat; however, many existing abstractions operate on leats in any case. Otherwise installation costs are low; ex works prices for self installation are currently £3550 for a unit handling 9 Ml/d, and £11 550 for a 45 Ml/d unit.

In conclusion, the "Econoscreen"appears to be a very realistic option for sites where installation is appropriate ie leats. There would appear to be great potential for achieving minimal entrapment of a range of sizes and species of fish by employment of appropriate velocities and mesh materials.

**(a)**

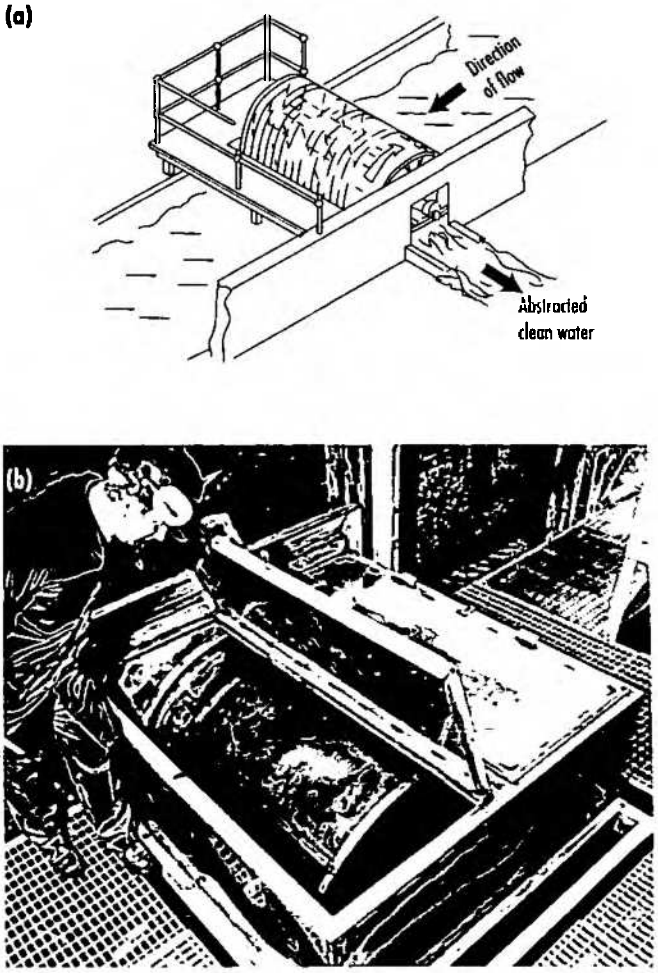



**Figure 4.7**

**The Econoscreen. (a) - diagram of installation.**
**(b) - screen at British Steel intake at Workington. (Illustrations reproduced with permission of Econoscreen Environmental UK).**

## 4.5 Johnson Passive intake screens

Johnson passive intake screens are an innovative approach to screening that represents a considerable improvement over conventional fixed screens in terms of fish impingement. They have been installed at numerous sites in the US, and at over a dozen in England and Wales; the UK site installation list is given in Table 4.1.

The most usual design is cylindrical and the screening material used is a wedge wire with a gap of the order of 2 mm (Figure 4.8). The screen is installed in open water, not in a side channel from which fish might find difficulty escaping. Critical features as far as fish protection is concerned are:-

- small gaps which preclude passage by most fish;
- low approach velocity (typically 15 cm/s) allowing fish to avoid impingement and entrainment;
- uniform approach velocity - no "hot spots";
- a very smooth external texture, that minimises abrasion damage to fish contacting the surface.

The screens require to be installed in a depth of water that allows for free water space all around - minimum depth of about twice the cylinder diameter is stipulated by the manufacture for horizontally-mounted screens. Where water

**Table 4.1.List of UK installations of Johnson passive screens.**

| |
|---|
| SOUTH WEST WATER |
| 1.Bolham, R. Exe. |
| 2.Gunnislake, R. Tamar. |
| 3.Watercombe, R. Erme. |
| 4.Broadall, R. Yealm. |
| 5.Restormel, R. Fowey. |
| 6.Pynes, (Reservoir). |
| 7.New Bridge, Taw. |
| WELSH WATER |
| 1.Llyn Bodlyn Reservoir. |
| 2.Braich-Y-Rhu. |
| 3.Afon Fathew. |
| BOURNEMOUTH AND DISTRICT WATER CO. |
| 1.Matchams, R. Avon |
| 2.Longham, R. Stour. |
| WESSEX WATER. |
| 1.Blashford Lakes, Ringwood. |
| INDUSTRIAL |
| 1.Tate and Lyle, Silvertown, R. Thames. |

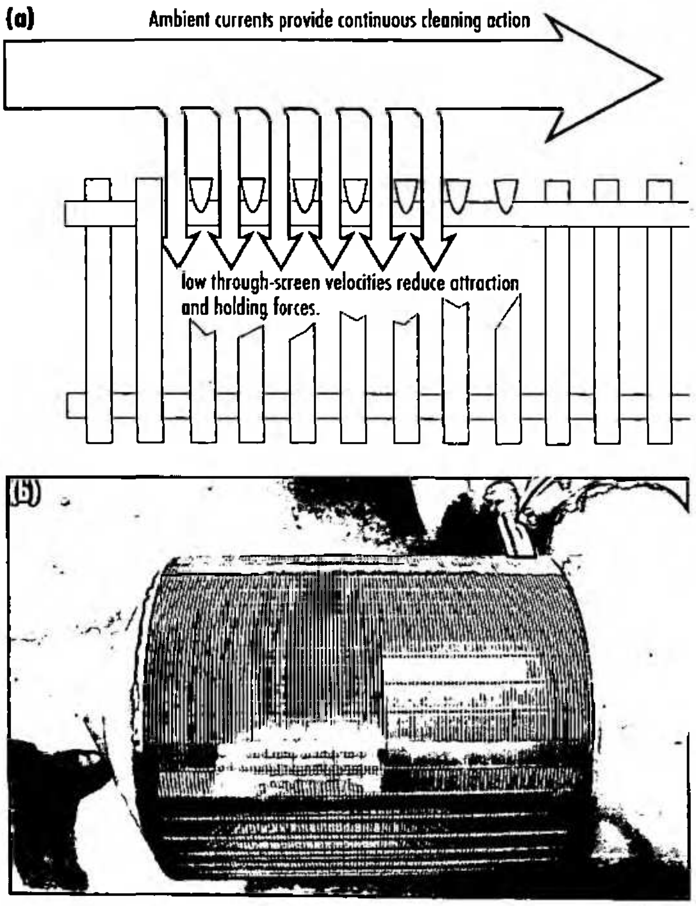



**Figure 4.8.**

**Johnson passive intake screens.(a) - diagram showing the section of the wedge wires (Johnson Filtration Systems). (b) - a screen on a public water supply abstraction at Gunnislake, River Tamar. The slot width is 3 mm.**

depth precludes the installation of a single screen of adequate dimensions to allow the desired abstraction, an array of smaller screens can be substituted (Figure 4.9). Ott et al (1988a) describe an array of eight vertically mounted cylindrical screens for a river intake for a hydro-electric scheme. The screens, each 168 cm tall and 84 cm in diameter can take a total of 3.54 m3/s (306 Ml/d) while maintaining a water velocity of 10.2 cm/s through 2.4 mm slots. The vertical mounting is claimed to have reduced screen costs to about $31 250 compared to over $120 000 for a more conventional tee arrangement of smaller screens. The former cost included the compressed-air backwash system. Another solution for shallow waterways is installation within a trough in the river bed. Although the trough tends to collect sand and other debris, it can be kept clear with an automatic water jet washing system. Such an arrangement has recently been installed at Restormel on the River Fowey in Cornwall (Figure 4.10). Successful operation of such a system in North America is described by Johnson and Ettema (1984).

Where river currents exceed the screen intake velocity the system is largely self-cleaning, but elsewhere clearing of impinged debris is easily effected by discharge of compressed air within the cylinder.

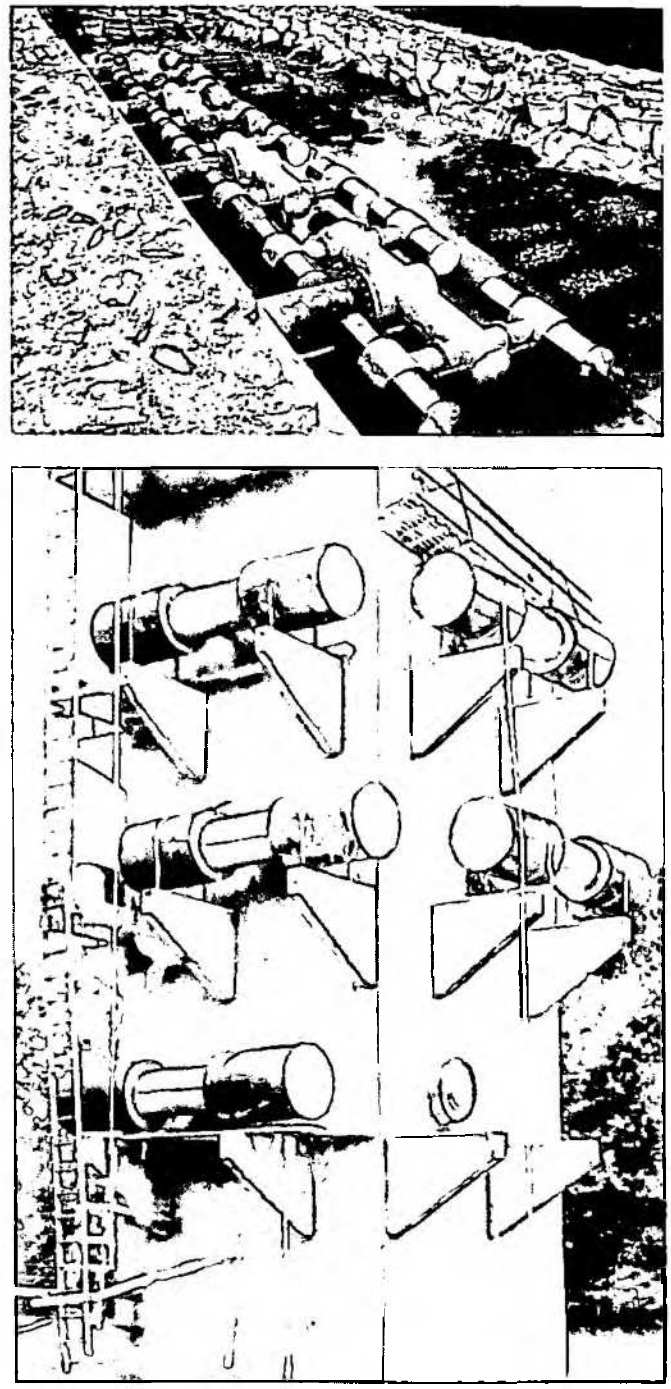


**Figure 4.9.**

**Arrays of Johnson passive intake screens. (Top) - Gunnislake, River Tamar. (The total licensed abstraction here is 148 Ml/d. ). (Below) - Multiple draw-offs in a reservoir in the US. (Reproduced with permission of Johnson Filtration Systems.)**

These intake screens are also suited to still-water draw-offs from lakes and reservoirs. At least three such installations are currently in use in England and Wales (Table 4.1). Multiple draw-off levels are readily arranged (Figure 4.9). Screens are installed in the two lakes used in the Blashford Lakes scheme in

Hampshire. Designed to pass a maximum of 50 Ml/d, each lake intake comprises two 700 mm diameter cylindrical screens, with slot width of 6.0 mm and an approach velocity of not more than 15 cm/s.

Salt water installations are also possible, though only one is currently in use in the UK (Tate and Lyle, Silvertown, Thames Estuary). Fouling by aquatic growth can be a problem in both salt and freshwater installations, but can be greatly reduced by choice of appropriate screen alloy. Turnpenny (1988b) records that a wedgewire screen constructed of a 70% Cu/30% Ni alloy operated on a 24 hour backwash cycle at Fawley Power Station for 16 months with only a 1.9% reduction in abstraction flow rate. No cleaning was carried out during this period; at the end of the trials, the limited biofouling was readily removed by scrubbing.

Although no specific studies could be identified in the UK to monitor fish impingement, all operators contacted expressed a view that operation was satisfactory in this respect. Numerous investigations in North America indicate a generally benign situation. Hanson et al (1977) tested a screen with 1 mm slot width in an experimental channel with a range of fish species and sizes, predominantly small striped bass *(Morone saxatilis)*. They found virtually no impingement of fish in excess of 20 mm, and that most potential entrainment was transformed to impingement. Many impinged fish were able to escape. They concluded that the avoidance of entrapment was facilitated by:-

- the "infinite" number of escape routes available;
- the flow dynamics that enable a fish to easily determine the direction of escape;
- the rapid decline in approach velocity as a fish leaves the screen;
- the small slot size;
- the ambient washing currents, which assist escape and avoidance.

Lifton (1979), in a pilot scale installation in Florida of screens with 1 mm and 2 mm slot width, concluded that impingement was virtually eliminated, and entrainment of fish larvae was reduced by more than 60% compared to unscreened inlets; there was little difference between 1 mm and 2 mm slot widths.

An investigation of entrapment of larval anchovy and gobies in Maryland showed that virtually no fish over 10 mm were entrained through a 1 mm slot width (Weisberg et al 1987). Widths of 2 and 3 mm were not so effective though the "effect of slot width on exclusion efficiency was small relative to the effect of fish size". The differences between the 1 mm, 2 mm and

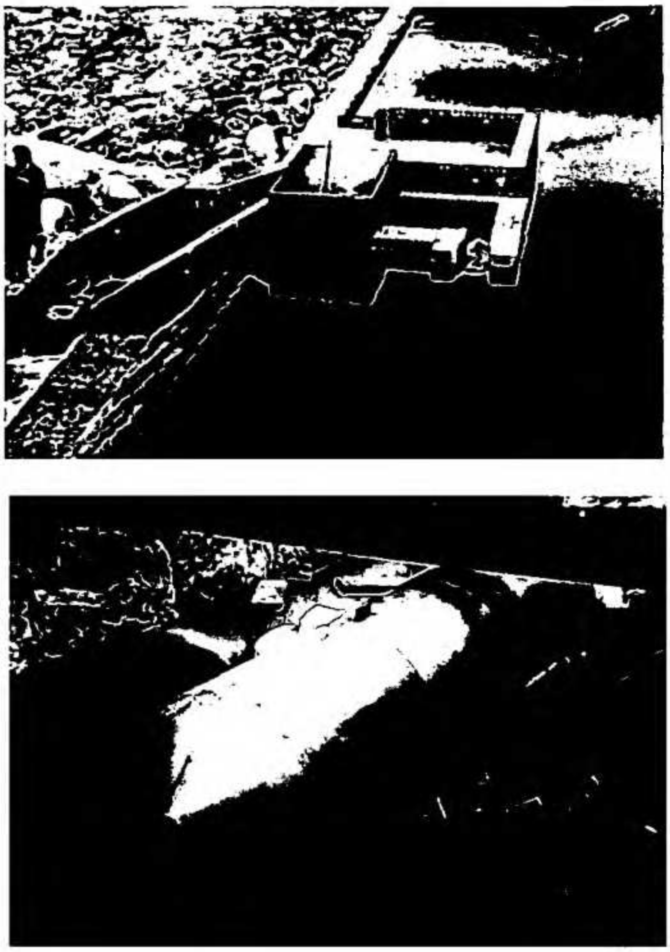


**Figure 4.10**

**Johnson passive intake installations. (Top) Watercombe, River Erme. (The single T screen can be seen submerged in the foreground. It has a capacity of about 9 Ml/d, and it has a 1.5 mm slot width.)**

**(Below) Restormel, River Fowey. Screens being installed in a river bed trough to ensure adequate depth. The trough will be kept clear of debris by water-jets. (Total capacity is about 83 Ml/d, through four screens with a slot width of 3 mm. (Photographs supplied by Johnson Filtration Systems.)**

3 mm slot width efficiencies were not statistically significant, due mainly to the small numbers entrained by all three. The conclusion was that entrainment of larval fish over 5 mm in length can be significantly reduced by the use of wedge-wire screens.

Heuer and Tomljanovich (1979) examined the effect of a range of variables on the entrapment of nine species of fish (including pike, *Esox lucius* and two species of zander *Stizostedion* pp). They used flat wedge-wire screens with slot widths of 0.5, 1 and 2 mm. They concluded that:-

- for optimal protection of very small fish larvae (<6 mm) a slot width of 0.5 mm and a slot velocity of 7.5 cm/s are needed;

- a 1 mm slot width probably precludes entrapment of fish over 10 mm;
- some species require a slot velocity of 7.5 cm/s for optimal avoidance, others can cope with 15 cm/s;
- 2 mm slot width gives substantial protection to all fish over 10 mm;
- species vary in other optimal parameters; for some a perpendicular slot orientation and lighting improve efficiency, for others not;
- provision of a refuge zone beneath the screen increases screen effectiveness.

Installation costs are a little difficult to establish as much of the cost of an intake concerns civil engineering rather than the screen itself. However, fitting an array of four Johnson screens with a 3 mm slot width to an existing intake abstracting 64 Ml/d cost of the order of £50 000. This intake is operated by the Bournemouth Water Company at Matchams on the Hampshire Avon. A screen to pass 8.6 Ml/d at a SWWS intake on the River Erme cost of the order of £12 000; slot width in this case is 1.5 mm (Figure 4.10). Each of the Blashford Lake installations, passing up to 50 Ml/d cost about £25 000 to install.

In conclusion, it appears that passive wedge-wire screens potentially offer a very high level of protection to all life-history stages of fish occurring in inland and estuarine waters in the UK. No investigation of the specific mesh size and approach velocity criteria for British species could be identified, but extrapolation from North American work would suggest that a 2 mm slot width and 15 cm/s slot velocity would afford substantial protection for all fish in excess of 10 mm, and total protection for fish over 20 mm.

No specific studies on salmonids were identified. However, with newly-hatched fish being of the order of 30 mm in length, it is likely that a 2 mm slot width (and probably somewhat larger) would afford complete protection to even downstream-moving unfed fry. Migratory parr and smolts are likely to be afforded virtually complete protection by a larger slot width e.g. 6 mm.

## 4.6 Other wedgewire screens

The advantages of wedgewire material for intake screens have been detailed in Section 4.5. In addition to the cylindrical screen arrays described there there have been a number of other installations where effective self-cleaning has allowed the advantage of the material to be exploited.

Although no examples were identified from the questionnaires, a very effective design for small intakes is likely to be a horizontally-mounted wedge-wire screen with water falling into a sump. Such a design, though in this case using a conventional slotted screen, is described in section 4.2 (Brokenburrow).

Ott et al (1988b) describe an intake incorporating curved wedgewire panels with 1mm slot width into the downstream face of a small weir. Water falling through the slots is abstracted, and the remaining flow provides a constant cleaning action. The smooth face of the wedgewire ensures safe passage of fish. A potential problem arises because of the difficulty of regulating the take of water under conditions of varying stream flow. At times of low flow, all available water could pass through the screen, leaving the lower part dry. To avoid this, a V notch can be arranged at the top of the screen to concentrate the flow; thus some water always travel to the end of the screen, carrying fish and debris downstream. Installations providing flows from 10 to 300 Ml/d are described based upon weirs providing 8 to 12 Ml/d per metre of weir crest. The lower figure requires a weir head of about 0.9 m, and the higher figure about 1.2 m head. Cost of the screening material and supports is about US $200 per Ml/d, plus of course the cost of the weir. Design criteria for effective installation are provided by Ott et al (loc. cit.).

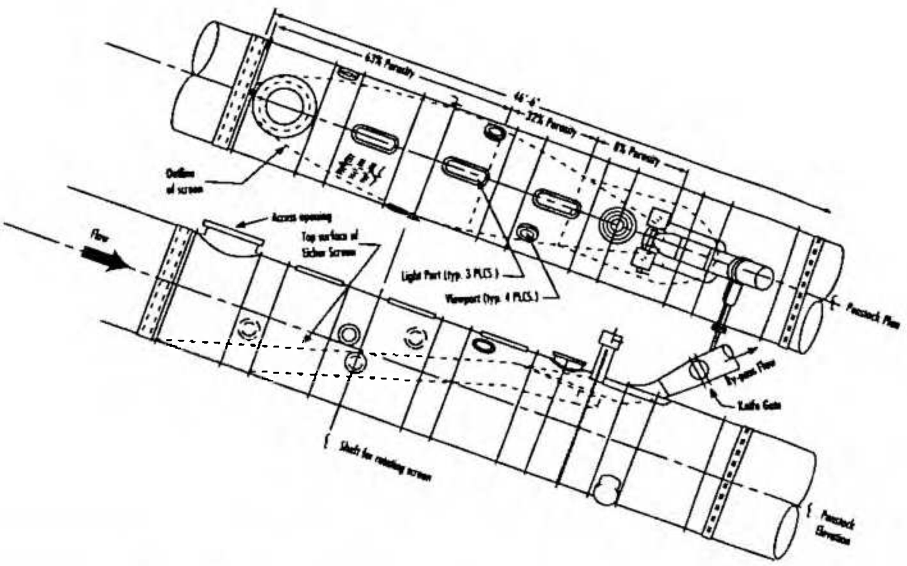
A more complex arrangement with specific application is the Eicher pressure screen. This uses a wedgewire screen at a shallow angle to the flow within an enclosed pipe or penstock, and is designed for use primarily at hydro-electric installations.

One installation has operated at TW Sullivan Dam on the Willamette River in Oregon since 1979. It comprises an inclined screen, 7 m in length mounted within the penstock. The penstock diameter is about 3.5 m, and the screen is inclined at about 19° to the axis of the flow. A later experimental installation at Elwha Dam (Figure 4.11) was improved by having an area of closer bar spacing for a panel close to the bypass entrance, where most impingement was found to occur. In tests involving passage of 5000 coho salmon smolts little or no injury was observed and only twelve fish died within three days of passage; eight of 5000 control fish also died. The screen appears to be virtually self-cleaning.

While clearly of application in only specific situations, the Eicher pressure screen appears to be an elegant and efficient answer to a particular problem. Costs are not readily available, but Eicher (1985) suggested a figure of the order of US $125 per Ml/d for large screens (of the order of 1000 Ml/d). Further details of design criteria, application and test results are given by Eicher (1982, 1985), Wert et al (1987), and Winchell (1990).

## 4.7 Sub gravel intakes and wells

A most appealing option for screens, from the viewpoint of fish protection is that of using the river bed or valley floor gravels as a screen, drawing water from beneath the bed or from an



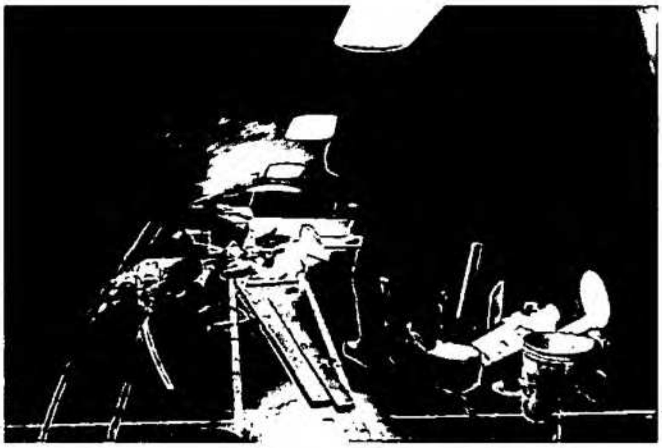


**Fig 4.11**

**Eicher pressure screen. (Top) - diagram of installation. (Bottom) - looking downstream to bypass entrance of screen installed at Elwha Dam, USA. (Illustration reproduced with permission of George Eicher.)**

unconfined aquifer. While situations where this might be realistic are limited, the filtration afforded to the abstracted water can considerably reduce treatment costs too.

Only one example of a sub-gravel intake in a river bed was identified by the responses to questionnaires sent to Regional fisheries officers. This is a recent installation at Ibsley on the Hampshire Avon, owned by Wessex Water Services. A maximum abstraction of 50 Ml/d will be taken via four stream bed intakes, each 2.4 m square internally. A section through one intake is shown in Figure 4.12. A wedgewire screen (supplied by Houston Well Screen International Ltd) with a slot width of 8.0 mm is supported by stainless steel beams over a concrete-lined chamber from which the water is pumped. Over the wedgewire screen is a 150 mm layer of 20-10, and a 300 mm layer of 200 gravel, making up to the existing surrounding bed level. A geomembrane sheet is laid between the two gravel layers.

Cleaning of the gravel will be effected by reverse pumping; the intakes have not yet been used operationally, so required frequency of backwashing is not known. Total cost of the installation was about £80 000. With the approach velocity of not greater than 10 cm/s, a high level of fish protection is envisaged.

A number of abstractions are made from river valley gravels, though some doubtless represent true groundwater abstractions. Where it is recognised that most of the abstracted volume is drawn indirectly from surface water flow in the adjacent watercourse, the abstraction can be considered as surface water abstraction. An example of such a situation is at the Littlehempston abstraction operated by South West Water Services, where it is assumed that 90% of water abstracted from two radial collector systems represents surface water.

Each collector system comprises a well of about 4 m diameter which reaches down to bedrock about 10 m below ground level. Twelve lateral pipes with a total length of about 250 m radiate from the well at two levels, about 8 and 9 m below ground level. The pipes are about 200 mm in diameter and are perforated along their length (Figure 4.13). The abstraction licence for the two collectors is for a maximum of 24.15 Ml/d. In addition to affording total protection against fish entrapment, these systems produce water of high quality requiring minimal treatment.

In conclusion, sub-gravel intakes and riverside wells appear to offer an excellent option for avoidance of fish entrapment where their installation and operation are viable.

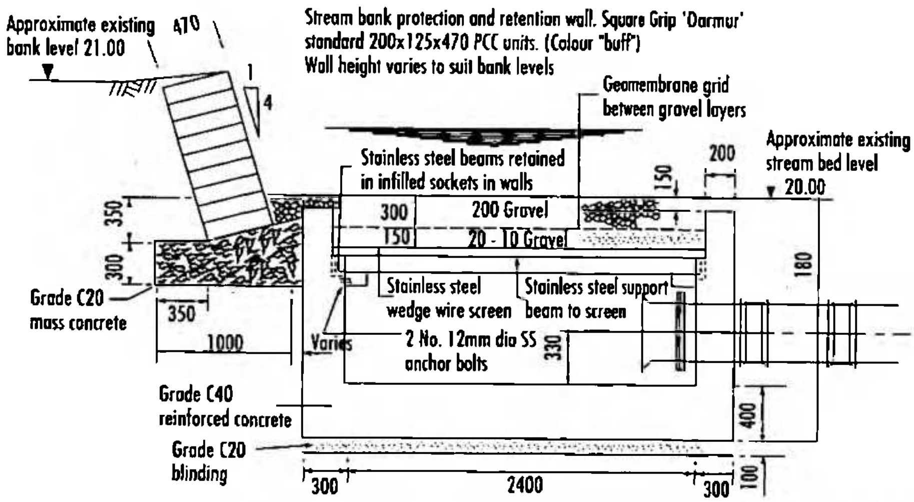



**Figure 4.12**

**Cross section of one of four sub-gravel intake chambers at the Wessex Water intake at Ibsley on the Hampshire Avon.**

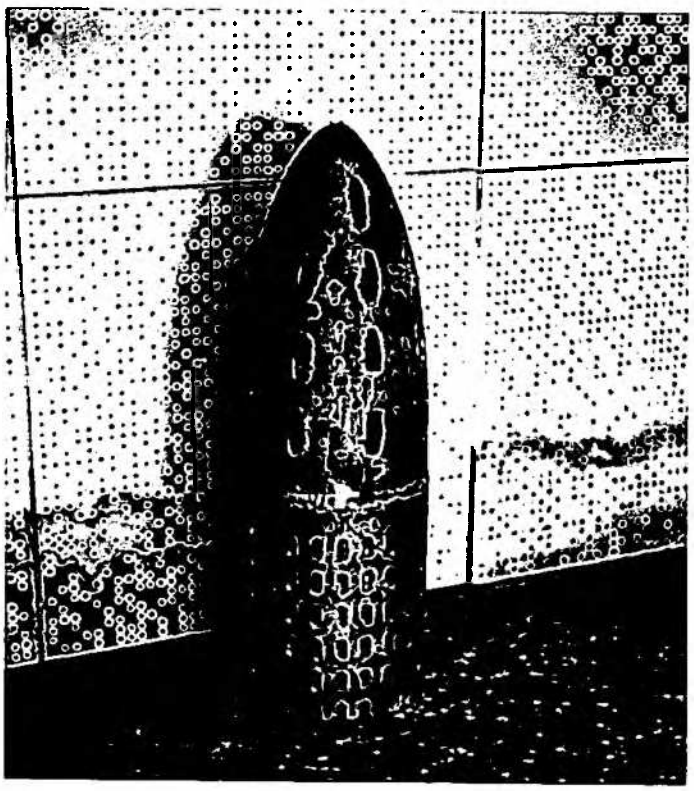


**Fig 4.13**

**End of a radial collector well arm as used at the Littlehempston abstraction by South West Water Services. Diameter of the pipe is about 200 mm.**

# 5. BEHAVIOURAL EXCLUSION SYSTEMS

## 5.1 Introduction

In this category come a wide range of systems that divert or exclude fish without the requirement for them to come into physical contact with any fixed or moving machinery. They exploit the reaction of a range of sensory systems including sight, hearing, awareness of currents and sensitivity to electrical fields. In some cases more than one sense is involved, and in others it is difficult to tell which sense is in fact predominant in eliciting a response.

Clearly, as long as the behavioural stimulus itself causes minimal trauma, such screens are to be preferred to those that involve physical contact and thus may cause damage to the fish. As already discussed however most physical screens that are truly effective at minimising entrapment and fish damage are in fact acting as behavioural barriers with most fish avoiding contact by appropriate responses. The overwhelming potential advantage of a pure behavioural barrier over a "physical-behavioural" barrier is that it is likely to involve less in the way of interference with flow and have a reduced problem with waterborne debris. Costs for both installation and maintenance are likely to be significantly lower.

The complexity of the behavioural responses to some systems and the "grey area" between behavioural and physical screens makes a valid and exhaustive classification system virtually impossible. What is undertaken in this section is a consideration of selected methods and approaches that appear to have promise for UK application. This includes all methods currently employed in the UK, along with details of appropriate developments in other countries. The categories considered are:-

- bubble curtains; often tried with mixed results. light; both illumination of other screens/stimuli and repellent action in its own right. Strobe lights most often employed;
- sound; generally dismissed until recently, some North American developments show considerable promise;
- louver screens; highly efficient for smolt diversion at appropriate sites;
- electric screens; often tried, rarely evaluated, with promise for exclusion of fish from outfalls.

Each of these categories is now considered in detail.

## 5.2 Bubble screens

### 5.2.1 Introduction

Screens formed by a curtain of air bubbles released from pipes laid on the intake bed have been experimented with for over 50 years with variable results. Several of the replies to questionnaires by Regional Fisheries Officers referred to bubble screens currently operating at intakes; however, the great majority of these are installed for intermittent use to clear away floating debris. Any fish deterrent effect is incidental and unmeasured.

The unimpressive nature of the results obtained in a wide range of trials had led many previous reviews to dismiss air bubble curtains as an ineffective technique. However, they are worthy of further careful consideration in view of:-

- some good results obtained among the indifferent ones;
- improvements in effectiveness which appear to be achievable in conjunction with strobe lights;
- the potential medium installation cost, low running costs and minimal maintenance requirements;
- the lesson from acoustic screens (Section 5.4), that carefully specified equipment may work well where a less scrupulous approach has failed.

The nature of the stimulus that makes bubble screens effective at times is uncertain. Different authors suggest visual, auditory or shear-current clues, and the variable results under conditions of light and dark indicate that the effective stimulus may vary.

Critical aspects of screen design that are likely to affect performance include bubble size and spacing, volumes of air discharged, air pressure, water velocity, screen layout (access to bypasses etc) and illumination. A range of earlier investigations is now briefly reviewed with these aspects in mind. An unfortunate feature is the poor level of recording of these potentially critical aspects in many studies.

### 5.2.2 Summary of investigations

**Danish experiment (Bramsnaes et al 1942).**
Experiment conducted in still water in a flume. Carp and pike would not pass through the bubble screen even when chased, whereas rainbow trout passed freely. Bubble screen created "by means of perforated tube and compressed air" - no other detail provided.

**Californian experiment. (Warner 1956).**
Installation to deflect downstream migrant salmon and steelhead smolts in intake canal. Only one "control" night without screen, two experimental nights with screen; more fish

were caught on the latter two nights. However, the author did concede that the increased catches may have been due to a rise in water level causing more fish to migrate. This would appear to invalidate this experiment. The screen comprised a grid of vertical pipes, spaced at 30 cm centres, with air escaping through diaphragms (to create sound) at bottom end only.

**British Columbian experiments (Brett and Mackinnon 1953, Brett et al 1954).**

An experiment attempting to divert chinook salmon smolts appears to have been inconclusive. A perforated pipe (5/8" copper, 1/32" holes at 1/4" centres) was laid on the bed of channel, from one bank to the centre line, at an angle of 40° to the bank and axis of flow. Bubbles were created by connecting the pipe to the exhaust of a truck. Fyke nets were set downstream of the screen on each side of the channel. In three nights of tests, 22 fish were caught in the "control" net and 14 in the "screen" net; without the screen, catches tended to be equal. In addition to the inadequate numbers of fish to achieve any significance, it was possible for "deflected" fish to return to their original side of the channel between the downstream end of the screen and the "screen" net. Another installation of a similar screen gave good results with sockeye salmon; up to 98% (94% average) being caught on the "control" side in daytime, and 58% average at night. This screen did not present the possibility of deflected fish returning to the other side of the channel before being counted. The authors suggested that the shoaling nature of sockeye made them more amenable to deflection than the solitary chinook.

**Laboratory experiments, North Carolina (Bibko et al 1974).**

Used striped bass and gizzard shad. Demonstrated that bubble screens could be very effective, with no fish passing through a continuous screen. However, a 2"(5cm) gap in the curtain, or the bubbler pipe raised 2" from the bed of the tank, allowed passage of the fish almost without hesitation. The bubble screen was effective in the dark.

**Uskmouth Power Station (MAFF 1959, 1963).**

In an attempt to reduce heavy losses of salmon smolts in the Uskmouth A and B station (up to 10 000 pa) two separate bubble screens were tried. Disappointingly little detail has been recorded. The aim of the screen in 1958 was to create a curtain of turbulent water, with a screen "upstream of the intake and leading diagonally downstream clear of the danger", with a length of 150 feet. Compressed air was blown through the pipe for alternate hours, but small numbers of smolts rendered the trial of little validity; "fewer salmon smolts were caught when the bubble-screen was being blown, but numbers are not large enough to show whether or not this as a mere chance effect". In 1962, a longer screen (800 feet) was laid, but bad weather conditions prevented the distal end being installed; it therefore consisted of two arms converging (but not meeting) at the outer end of the intake channel. It proved ineffective. The conditions at Uskmouth are bad for smolt impingement, with a high-speed flow through a relatively small intake which is short of water at low tide, when most smolts are drawn in. Up to 15 million gallons of water per hour (360 mgd) pass through the screens. The poor performance of the inadequate bubble screens is probably inevitable; the poor degree of recorded detail (complete absence of constructional detail) is unfortunate. Reference is made in a CEGB research programme of an intended trial of a bubble-screen at Oldbury-on-Severn Power station in 1966, but no results appear to have been published. Bainbridge (1964) reported that a bubble screen was tried for two seasons at Uskmouth without success. The minutes of the "Supervisory group on methods of excluding fish from water intakes" (later the "NERC screens committee") record Mr Pentelow as considering that the poor results at Uskmouth justified the discontinuation of the use of the bubble screen.

**Power station on Lake Michigan (Devereaux Barnes, 1976).**

This is an important observation, as it concerns a successful application with full details of the installation. The intake is up to 18.3 m/s (1616 Ml/d) and the bubble screen extends across the mouth of the intake in 3.6 - 4.0 m of water. The system consists of 2.5 cm diameter PVC lines with holes at 4" centres. Total air flow is 100 cfm at 60 psi. Optimal airflow was measured at 0.01 $m^3/s$ (0.36 cfm) per 0.3 m of air pipe at 60 psi. Although some fish did still get through the screen was equally effective at night. The fish involved were mainly alewife.

**Indian Point Station, New York State (Alrevas 1974, Devereaux Barnes 1976, Lieberman and Muessig 1978).**

A complex and expensive screen gave poor and conflicting results. Two screens were installed, 3ft and 6ft (some reports say 18" and 3ft) in front of a fixed screen. Each screen was like a ladder leaned against a wall, with the "rungs 4ft apart and being the diffusers. Air was discharged through 0.8 mm (1/32") holes at 13 mm (1/2") centres (one report says 25 mm centres). Total volumes used in two tests were 900 cfm and 400 cfm, but this means little in the absence of other dimensions of the screen. The main species involved were striped bass, white perch and tomcod, and most impingement took place at night in turbid water - conditions not ideal for a bubble screen. No details of water flow rates or "bypass" or "escape" arrangements are available. At one stage the screens appeared to work effectively with just the bottom row ("rung") bubbling, but at other times the whole screen seemed ineffective.

**Washington State experiment (Hanson, White and Li 1977; Liebermann and Muessig 1978).**

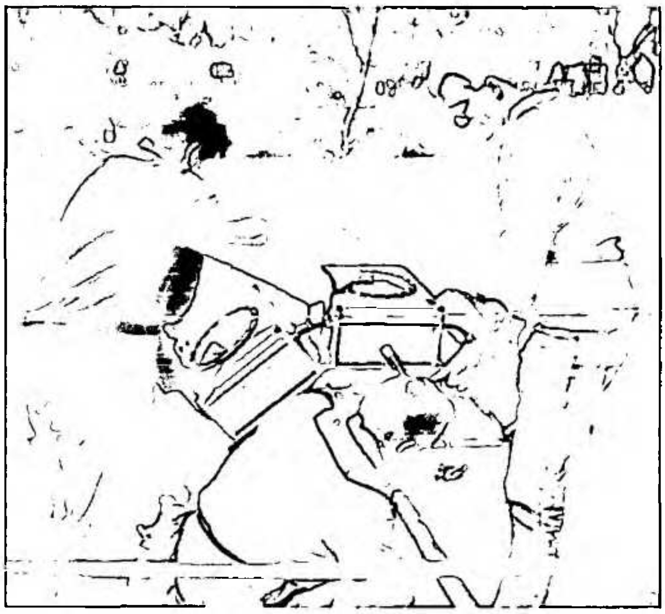
Unfortunately little detail of these experiments is available as the original reference (Bates and Van der Walker 1969) is an internal report and unavailable; the results appear to have never been formally published. Using juvenile Pacific salmon (species not stated), a bubble screen was reported as giving 90% deflection (95% in one report) in daylight with an approach velocity not exceeding 0.6 m/s. As the effect was less at night (28%) it was assumed to be operating visually.

**Ontario Hydro experiments (Patrick et al 1985).**
A bubble curtain was created using a "bubble wand", perforated plastic tube filled with sand. Bubbles could be generated O (continuous), 5, 10, or 20 cm apart; the bubbles were less than 1 mm in diameter. At low light levels in clear water, 98% of gizzard shad, 70% of alewife and 92% of smelts that would otherwise have entered a chamber with the current were deflected into adjacent chambers. In full darkness, efficiency dropped to 80% for shad and 51% for alewife. Optimal bubble spacing appeared to be 5 and 20 cm for shad and 0 and 5 for smelt. In turbid water conditions the effectiveness of the bubble curtain for alewife was reduced to 59% at a current velocity of 0.15 m/s and to 38% at 0.32 m/s. Effectiveness was increased when the bubble screen was illuminated with a strobe light; the range of efficiencies observed for alewife increased from 38-73% for bubbles alone, to 90-98% with strobe illumination under various conditions of water turbidity and current speeds.

**Thames experiments (Gough 1991; G Armstrong, pers. comm.).**
A bubble screen, used with and without strobe light illumination, was used in trials to reduce entrainment of salmon smolts at the entrance of the intake channel at Walton on Thames Waterworks (Figure 5.1). The effectiveness of the installations was measured using a louver screen trap installed in the channel, described in section 5.5.4.

The air was supplied to the screen by a blower delivering 348 $M^3$/hour at 1 bar. The screen comprised four 6 metre lengths of 50 mm diameter galvanised steel pipe, with 2 mm diameter holes drilled at 25 mm centres along the length. The strobe light illumination was provided by an array of nine lights in waterproof enclosures, which operated at 440 flashes per minute.

Actual catches in the louver-trap in the channel while the screens were operating were compared to catches predicted from a model that was validated from catches made while the screens were not operated. On four of six occasions when the bubble screen



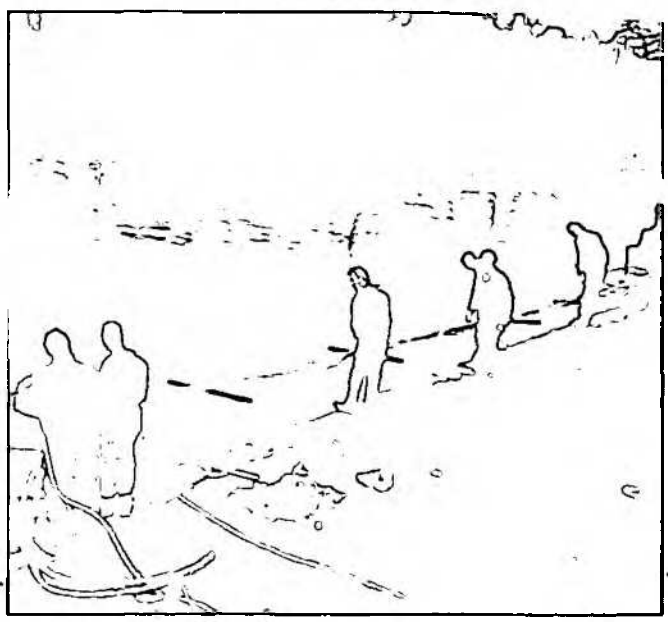


**Figure 5.1.**

**Experimental behavioural screen system at the intake at Walton on Thames Waterworks, River Thames. (Above right & right) - strobe lights and air line being installed. (Above) - Bubble screen in operation. (Photographs reproduced with permission of Mr Greg Armstrong, Thames Region NRA.)**

operated without strobe illumination catches were less than predicted; while both bubble screen and strobes were operated, nine out of ten trials showed reduced catch. Operation of the bubble screen with strobe illumination is estimated to have reduced entrainment by 62.5%, from 14.4% to 5.4% of the total run of smolts down the river. Application of the "expected catch" model to the five main water intakes on the lower Thames suggests that employment of bubble/strobe screens at each could reduce overall losses from 80% to 41% in a very low flow spring such as 1976, and from 15% to 5.9% in a high flow year such as 1981.

Some preliminary laboratory experiments with juvenile roach and chub indicated the potential for bubble screens for diversion from intakes, with fish being reluctant to cross the screen when first encountered. Habituation eventually occurred, suggesting that such screens may be less effective for protection of local resident populations than for fish migrating past. Differing efficiencies of diversion for the two species highlights the need for definitive investigations for a range of species.

#### 5.2.3 Conclusion.

The variable results of attempts at fish diversion with bubble screens suggest that the approach has potential, but that we cannot yet specify optimal design criteria for different situations and species. The promise justifies further investigation, for use with both salmonids and coarse fish. The observations that a combination of a bubble curtain and strobe lights is more effective than either operated singly is encouraging. There is a requirement for a series of laboratory tank and field experiments to establish a range of criteria with different species.

## 5.3 Light

Light has been used in two distinct ways to reduce entrapment of fish at intakes; first for illumination of screens to facilitate avoidance, and second as an attracting or repellent stimulus in its own right.

At intakes with physical screens, the great majority of entrapment may take place at times of low visibility. Pavlov (1989), considering a range of sites, recorded that 60-97% of young fish enter intakes during the hours of darkness. In turbid water conditions, this diurnal variation is much less marked. He recorded that the effectiveness of artificial illumination at reducing entrapment during the hours of darkness was greatly enhanced by provision of stationary visual clues e.g. reeds or tree branches near the intake. Under such conditions, entrapment of young cyprinids and percids was reduced by 84-91% at a site with an intake of 1 $m^3$ /s. Hadderingh and Kema (1982) achieved a reduction of 54-70% reduction in nocturnal impingement by provision of illumination at Bergum Power Station in the Netherlands. Effectiveness varied with species; it was almost 100% for perch *(Perca fluviatilis)* and ruffe *(Gymnocephalus cernua)* but entrapment of three-spined-sticklebacks *(Gasterosteus aculeatus)* increased with illumination. The use of strobe illumination to improve the effectiveness of bubble curtains has already been discussed (Section 3.2).

Constant illumination alone has not proved an effective deterrent for most species though Lowe (1952) was able to divert migrating silver eels by illumination. In some situations, as mentioned above, illumination proves positively attractive to some fish. However, experiments with flashing lights (strobe lights) have showed some promise. Patrick et al (1982) used strobe lights to successfully discourage upstream migration of eels, when researching a problem of adult eels entering a turbine unit during shut-down. Numbers of 30-50 cm eels were reduced by 65-92%. Sager et al (1987) found avoidance of strobe lights by a range of estuarine species including white perch *(Morone americana)* spot *(Leiostomus xanthurus)* and Atlantic menhaden *(Brevoortia tyrannus)* though effectiveness varied with species. It also varied with frequency of flashes (120, 300 and 600 flashes per minute). Effectiveness was considerably enhanced when used in combination with bubble curtains (Section 5.2), with which 300 flashes per minute proved most effective. Patrick et al (1985) also found that a number of North American freshwater species also avoided strobe lights and bubble curtain including alewife *(Alosa pseudoharengus)* smelt *(Ocmerus mordax)* and gizzard shad *(Dorosoma cepedianum)* Taft (1986) also reported other work by Dr Patrick which showed that several salmonids including Atlantic salmon were repelled. However, Taft (loc. cit.) also pointed out that strobe lights had so far only been used in experimental situations, and that while the technique showed promise, more robust and appropriate light units would be required for operational use.

## 5.4 Acoustic methods

#### 5.4.1 Background

The concept of generating repellent underwater sound stimuli to divert fish from intakes is one that has appealed to numerous experimenters over many years. Most attempts produced results that were indifferent at best, and until recently it was generally assumed that acoustic systems were unlikely to represent a viable way ahead. In a comprehensive review of screening technology (Section 3.5), Taft (1986) discussing the use of sound concluded that "further investigations of this fish protection measure are unwarranted".

However, in the last few years two independent initiatives in North America have indicated that acoustic methods may have distinct possibilities for fish diversion. It appears that progress has been made where earlier attempts gave poor results because greater attention has been paid to the species specific differences in anatomy, frequency range and sensitivity of the auditory system. Further, rapidly developing underwater technology has made available more effective transducers for radiating signals.

### 5.4.2 Development by Ontario Hydro

A group of scientists at Ontario Hydro have investigated a range of devices for generating underwater sound (Haymes and Patrick 1986; McKinley et al 1988; Patrick et al 1988a, 1988b). The first tests used a pneumatic popper, a type of air gun which emits a high pressure air bubble used in seismic surveys. These were used to repel adult alewife *(Alosa pseudoharengus)* from nets set in the cooling water intake channel at Pickering Nuclear Power Station on Lake Ontario. Numbers fell by 71-99% when the devices were operating. Other tests indicated less impressive results with some other species, however.

In subsequent experiments two other sound generating devices were used. The "popper" was replaced by another "hammer" device referred to as a fish pulser. It is described as a "spring mass impulse device which produces a repetitive sharp sound, with a relatively high energy level and low frequency, by exciting resonant modes of a structure which is in direct coupling with the surrounding water". The duration of the pulse is about 200 ms. It offered distinct advantages over the "popper" because the frequency characteristics of the pulses can be readily adjusted. The device was tested in the forebay of Seton Creek hydro dam in British Columbia. Two trap nets were deployed, one with the hammer near its mouth and the other as a control. Operation of the Hammer reduced catches of juvenile sockeye salmon *(Oncorhynclus nerka)* in the experimental net by over 75%. Again, however, evidence of critical inter-specific differences is shown by poor results with juvenile coho salmon *(O. kisutch)* in laboratory tests.

The "fish drone" used sonic vibrations to excite a metallic structure at a selected resonance, and is adjustable to generate fundamental frequencies from 20 to 1000 Hz. It can also produce continuous sounds or pulses, allowing development of the most effective mode of operation. Although some repellent effect was achieved in tests this device appeared generally less effective than the fish pulser.

The Fish pulser is now manufactured commercially by FMC of Canada Ltd. Their address is given in Appendix B.

### 5.4.3 Development by American Electric Power Corporation

This initiative is described by Loeffelman (1987), and Loeffelman et al (1991a, 1991b), and has its origin in an investigation of fish passage through a bulb turbine at Racine on the Ohio River. Sonar monitoring of fish movements indicated definite avoidance of the immediate intake area, with fish gathering near the shores and surface, and further out in the forebay area. This zone of avoidance corresponded to the area of greatest sound-intensity created by the operating turbine; sound levels immediately upstream were calculated to be 79 000 times more intense than in the tailrace area. Trials then followed with sound generators to reproduce this effect to attempt to guide and divert fish movement.

Very aware of the species-specific responses of fish to sound, Loeffelman and his co-workers examined the sounds produced by a range of fish species. On the assumption that these sounds were used for communication, they hypothesised that the frequencies would lie within the more sensitive zone of detection of the species. They also used the results of published research on audiograms (description of frequency/sensitivity relationship) of fish, e.g. Hawkins and Johnstone (1978) on Atlantic salmon.

Results in a range of situations have been promising. Of particular interest are results with salmonids, generally considered to be of low auditory acuity and thus challenging subjects for acoustic guidance. Tests were conducted in a fish pass with steelhead trout *(Oncorhynchus mykiss)* and chinook salmon *(O. tshawytscha)*. One sound signal referred to a as a "two frequency crescendo" signal effected a 71% reduction in steelhead passage, but no statistically demonstrable effect on chinook. A "three frequency crescendo" signal proved to have an influence on chinook also. The scientists involved feel that more effective diversion or exclusion may be achievable in situations where the ambient noise level is less than the 130 dB recorded in the fishpass (P.Loeffelman, pers. comm.). Smolt diversion tests were conducted on the two species by attempting to divert downstream-migrating fish from capture in a trap net. Diversion efficiencies of 94% for steelhead and 81% for chinook were achieved. A new signal developed specifically for chinook smolts was more effective. It was found that the most effective signal for smolts was different to that which proved most effective for adults.

### 5.4.4 Conclusions

In view of the observations on the critical definition of sound signals required for effective diversion, and the observation that this can be different not only for related species but also for different age classes of the same species, the indifferent results of earlier a hoc ests is hardly surprising. However, these recent positive results from North America indicate great potential for this approach. Clearly more trials are required on a range of species, and further development of the optimal layout of intake and signal sources is needed.

There may be an important difference between sounds that may temporarily deflect fish and those that, by virtue of frequency or intensity, are inherently repellent. The latter could clearly be useful for intake screening even for fish residing or lingering in the area. On the other hand, some sound signals may be temporarily repellent when first experienced, but fish may become used to the stimulus or habituated. Such sound sources may still be a most effective behavioural diversion system for fish migrating past the intake, and are thus unlikely to have a chance to become habituated. They may be less effective for exclusion of more sedentary fish.

Unfortunately no cost figures are available at present, but installation and maintenance costs are likely to be considerably lower than for mechanical screens.

## 5.5 Louvers

### 5.5.1 Introduction

Louver screens are considered by many to be the most effective of potential behavioural barriers for juvenile salmonids, with consistently good results being obtained. They feature in the "promising short list" of most earlier reviews (Section 3.5).

Louver screens operate by creating a sharp change in direction of flow near the screen, which fish find disturbing; by careful orientation of the array to the flow, fish are readily led to the alternative "bypass" route. They comprise a diagonal series of flat slots, each of which is orientated at right-angles to the flow (Figure 5.2). The earliest reference to louvers being installed for reduction of fish entrapment is Bates and Vinsonlhaler (1957) with further major contributions from Ruggles and Ryan (1964) and Ducharme (1972).

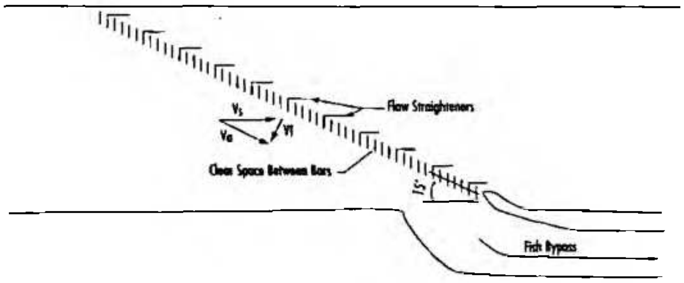



**Figure 5.2.**

**Features of a louver screen.**

### 5.5.2 Design criteria for effective operation

These appear to be a number of critical features for optimal operation of a louver screen for salmonid smolts, but if these can be satisfied efficiencies in excess of 90% can be achieved. The critical features are:-

(a) Channel width and screen length.
Optimal efficiency of louver screens appears to occur with the screen at an angle of 10-15° to the axis of flow. This dictates a screen length of 3.86 to 5.76 times the effective channel width (ie less by-pass width). There is no recorded evidence of the screen length adversely affecting efficiency - it appears that most "penetration" of the screen by fish occurs in the last few feet before the bypass, presumably as a result of the narrowness of the remaining channel or unattractiveness of some other feature of the by-pass. Good results have been obtained using large inter-slat widths (up to 12") at the upstream end of a long screen, narrowing to say 2" near the bypass. In some situations, it may be advantageous to reduce the overall length of the installation by using a V arrangement of two louver screens with a central bypass though the overall length of louver panelling will remain the same.

(b) Water depth.
Within reasonable limits, water depth appears not to influence the efficiency of louver screen operation. The "tallest" screen reported in the literature was 4.27 m, operating in 3.96 m of water; this was effective at diverting smolts of Atlantic salmon (Ducharme 1972). Clearly installations in deep channels will require a greater degree of engineering, but the screen will be much shorter than one screening a similar discharge in a wide, shallow channel. Bypass width (see below/above) is important - for a given bypass width and overall discharge, increasing depth will increase the volume (proportions) taken by the bypass. This may be unacceptable if the bypass water is not returned to the channel, and also will make removal/retention of fish more difficult.

(c) Waterborne debris.
Although less vulnerable to debris problems than traps which "sieve" the whole flow of the channel, keeping the screen clear is a significant task when the river is carrying large amounts of "rubbish". Debris build up, both of large items lying across several slats and small items impinged upon single slats, will increase the head-drop and, with the disintegration of the regular flow pattern may reduce efficiency to some extent. Mechanical clearing is simple by access across the top of the screen, but does of course require manpower presence, or manpower "on call", in case of head-loss build-up. Slats which can be lifted from the screen frame make effective clearing a fast job. Where the screen lies in an off-cut channel, the entrance to the channel can be protected with a screen with gaps equivalent to the louver gaps (e.g. 50 mm), though this screen itself will also of course require cleaning. Many mill leats and other intakes have such screens anyway; it is then just a matter of installing the fish (louver) screen downstream of the trash rack, or re-siting the latter to make this possible. In a situation where protection of salmon smolts is the only concern, the screens need only be installed for the duration of the smolt run e.g. April - May. This avoids operation during the seasons of greatest problems with waterborne debris.

(d) Current speed.
A range of current speeds have been used in experiments

described in the literature, for a range of species, with the following broad observations being made:

Ruggles and Ryan (1964). Species - chinook fry, 37-62 mm and steelhead smolts 74-198 mm. Current speeds 0.6 - 1.1 m/s with no discernible difference in guiding efficiency.

Ruggles and Ryan (1964). Species - Sockeye smolts 60-90 mm, Coho smolts 80-120 mm. Current speeds 0.4 - 0.9 m/s with little discernible change in efficiency. With wide louver spacing (300 mm) peak efficiency at 0.73 m/s for sockeye, no variation with coho.

Ducharme (1972). Species - Atlantic salmon smolts, 152-177 mm. Current speeds 0.24-1.03 m/, with a weak positive correlation between current speed and guiding efficiency.

Munro (1965). Species - Atlantic salmon smolts, size not stated. Current speed 0.75 - 1.1.5 m/s, with no difference except with 300 mm louver spacing when the efficiency was lower at the lower speed.

Thus with a wide range of fish sizes, there appears to be little variation of efficiency with changing velocities within the range 0.3 - 1.2 m/s, except with large louver spacings. The conclusion of all authors is that there is an "optimal" approach velocity within this range which minimises the effect of other variables such as louver spacing and poor bypass design. Current speeds can of course be accelerated at times of low flows by "blanking off" part of the upstream end of the screen.

(e) Head loss.

Ruggles and Ryan (1964) presented the following equation for calculating head losses:-

$$H = \frac{KV^2}{2g}$$

H = head loss
V = water velocity
g = acceleration due to gravity
K = loss coefficient

The loss coefficient is of course installation and site-specific, but Ruggles and Ryan found it to be between 1.89 and 1.62 for 3 m to 6 m channel widths with a 50 mm louver gap, screen angle 11.5° and bypass width of 15 cm. They suggest these figures would be appropriate for similar installations elsewhere. Using the upper figure for K, the formula then gives the head losses for a long screen, clear of debris:-

| Approach velocity | Head loss |
|---|---|
| 1.5 m/s | 21.6 cm |
| 1.0 m/s | 9.6 cm |
| 0.5 m/s | 2.4 cm |
| 0.3 m/s | 0.9 cm |

(f) By-pass requirements.

For all species and situations tested, an acceleration into the bypass is essential for a high guiding efficiency. Bypass velocities of 110-300% of screen approach velocities have been utilized, with 140% appearing ideal. In many situations this is easily achieved, as the louver screen itself restricts the approach velocity; an open channel bypass, leading directly to the channel downstream of the screen, will present an accelerating flow. The problem arises when it is desired to remove the fish from the bypass flow, still returning the water to the main channel; one has very little effective head to utilise and still maintain "bypass acceleration". Hopefully it is just a matter of careful trap design. The ideal is where the bypass water can be led to a lower level, as in the case of a high-level carrier, or the water and fish can be returned directly to the main river. A potential minor problem is the volume of water the bypass will take; an ideal bypass will of significant dimensions (e.g. 45 cm wide) and flow. If this flow is to be lost to the intake, it could be critical to restrict its extent. Smaller bypasses, down to 15 cm width have been used with success, but such an option makes other parameters such as slot spacing and approach velocity more critical.

### 5.5.3 Floating louvers

An effective variation of a louver screen is described by Ruggles (1990). For a specific site at a hydro-electric dam at Holyoke on the Connecticut River a floating louver array screening only the surface layers was specified. Based on observations that salmon smolts tend to migrate in the top metre or two of water, only the upper 2.4 m of the 5.5 m water column was screened. The louver slats were constructed of polypropylene, and were suspended at 76.2 mm (3") centres from floating wooden beams. The array was fitted at 15° cross the 44 m channel, giving a total screen length of 176 m. Total flow was about 150 m3/s. Tests with batches of radio-tagged smolts released upstream indicated that over 90% were successfully guided into a 4 m wide bypass channel that led to a surface spillway over the dam. Further tests are proposed for shad. For such a high volume intake with a suitable alternative spillway route to which fish can be guided the floating louver array is clearly a very realistic option. No installation costs are available.

### 5.5.4 Installations in the UK

Very few louver screens appear to have been installed in the UK. The best monitored is an experimental installation in the intake channel for Walton Waterworks on the lower Thames, installed by Thames Water Authority in 1987 (Figure 5.3). It is of standard design, with slot spacing of 300 mm at the upstream end, reducing to 50 mm near the bypass entrance. Two aspects worthy of mention are a lack of flow straighteners, and a problem with achieving adequate acceleration into the bypass; this is discussed below.

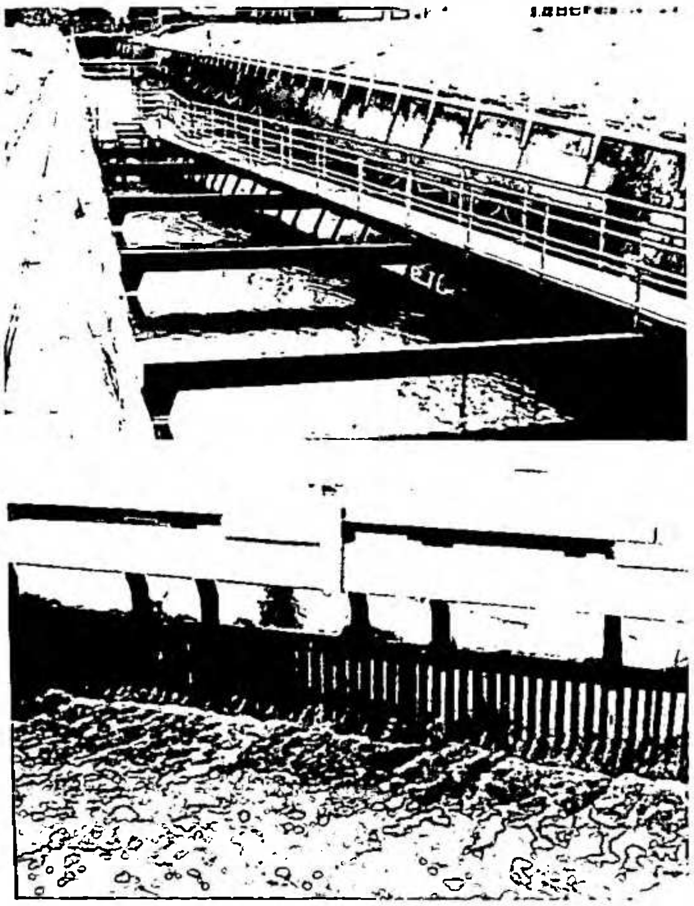


**Figure 5.3.**

**Experimental louver screen installed in the intake channel at Walton Waterworks, River Thames.**

Early hydraulic trials are described by Solomon (1987) and fishing trials by Clarke (1988). As the aims of the screen were basically to provide a sampling method for assessing the entrainment of smolts (and thus to test the efficiency of any other screen device installed at the mouth of the intake channel) it was necessary to trap the fish in the bypass. A makeshift cod-end trap tested in 1987 gave acceptable bypass acceleration between 130 and 136%. However, finer-mesh cod ends used in trials in 1988 produced a nett deceleration into the bypass. Screen efficiency trials with this unsatisfactory arrangement indicated about 67% at maximum intake rate, falling to 40-45% at half maximum rate. While clearly unsatisfactory performance as a fish protection device, these results nevertheless allowed achievement of the primary aim of the installation. Very much higher diversion efficiencies are likely to have been achieved with optimal acceleration into the bypass.

Responses to the questionnaire sent to Fisheries Officers indicated louver screens installed in two other Regions. In Welsh Region, a screen for a canal abstraction on the River Tawe at Ystradgynlais is reported to be under evaluation and improvement by BWB. A screen at the intake for the Montgomery Canal (Severn Trent Region) is said to be of poor design.

#### 5.5.5 Conclusion

As concluded by earlier reviews, the louver screen appears to be a well established and effective technique for salmon smolt diversion at sites where appropriate installation can be achieved. The potential for a floating louver array is of great interest.

## 5.6. Velocity cap.

The velocity cap represents a simple modification to unscreened intakes in open sea or lake situations which can significantly reduce entrainment. As described by Hocutt and Edinger (1980), a number of North American power stations on the coast or on the Great Lakes had offshore cooling-water intakes comprising a vertical pipe projecting well above the sea bed, drawing in water vertically downwards. Fish apparently are much less able to detect and resist vertical currents than horizontal ones. The velocity cap, comprising a flat plate mounted horizontally above the open end of the intake pipe, ensures that water is drawn in horizontally; a situation that fish are able to better detect and avoid. Hocutt and Edinger (loc cit) describe that entrainment rates at a power station in California were reduced by 46-49% by installation of a velocity cap; they describe further modifications to the lower lip of the intake (ie the top of the vertical pipe) which reduced entrainment further. However, Mussalli et al (1980) point out that stations on the Great Lakes fitted with velocity caps may still entrap millions of fish per year.

The fact that velocity caps are generally associated with intakes in the open sea or offshore in large lakes suggests that they are likely to be most effective in situations where ambient currents are low. Their use in rivers and estuaries with strong tidal currents is likely to be less effective. In appropriate situations they would appear to represent a great improvement over a totally unprotected intake, but would appear to have little to offer for use in UK fresh waters. There may be scope for their deployment in some estuary situations, though more information would be required on the effect of tidal currents on the effectiveness of this approach.

## 5.7 Electric screens

Electric screens for excluding or diverting fish appear to have had an uncertain history of effectiveness, particularly for downstream migrants. Hocutt (1980) recorded that the US Fish and Wildlife Service discontinued research on the subject in 1965 after 15 years of concentrated effort. Unsatisfactory results had been obtained for diverting downstream migrants, particularly of mixed sizes and species. There was also concern about the potential risk to humans and other animals. Taft (1986) highlighted the problem of fish size and stimulus characteristics; a field strength suitable for diverting small fish may result in injury or death of larger individuals. He gave details of a screen at a power plant which reduced entrainment of catfish and eels over 15 cm long by 68-82%. However, equally good results were obtained with the screen switched off! It appeared that the array of aluminium electrodes was acting as a visual behavioural barrier.

Electric screens have been installed at numerous sites in the UK over many years, but their effectiveness appears to have been monitored in few cases. In several instances fisheries officers are unable to say whether screens are working at all! Many have been removed or their operation discontinued for a variety of reasons.

Three sites are listed for South West Region. Two are at outfalls from leats (Tiverton and Pynes on the Exe) and one at an intake (for Morwellham Canal, River Tavy, Tavistock). All three are no longer in use. In at least one case (Pynes) this was as a result of concern by the Health and Safety Inspectorate. One site is listed for Yorkshire, at Moor Monkton, a PWS abstraction on the Nidd. No information on its effectiveness is available. Three sites were listed for Welsh Region: W. Cleddau at Canaston Bridge, River Teifi at Llechryd and R. Dee at Huntington. The efficiency of the first two "is very much in doubt and may be the subject of investigation". A comprehensive response to a request for information on the Huntington screen was provided by North West Water (NWW). A memorandum from the Technical Support Manager (Cheshire), Mr A H Jones states:-

> "From discussion with personnel at Huntington WTW it is apparent that in the period prior to the installation of the screen problems were experienced with "large numbers" of fish entering the the intake sump. When I recently visited the site however the fish screen was not operational and yet no fish ingress was reported. I suspect that the screen was out of action for a considerable period. In the past also, I have noted that when the screen was out of action for a prolonged period no fish ingress was reported.
>
> The whole subject appears to be surrounded by an aura of mystique and rumour, and getting accurate information on the performance of the screen is extremely difficult."

Mr Jones also discussed human safety concerns. Connecting himself across the terminal outlets with wet hands caused a shock that made him conclude that "I can muster no confidence to say that the Huntington installation is operating at a level which would be tolerable to bathers in the vicinity of the intake."

NWW also made available notes of meetings with the Health and Safety Executive some years ago which showed that there was very little reliable information on "safe" levels of electric fields in water. Despite experiments with a volunteer bather, the Health and Safety Executive considered that proposed electric screens for intakes on the Lune and Wyre should be fitted with "bather screens" to prevent swimmers from approaching the intakes; in the event the screens were not installed. The brochure for a manufacturer of electric screens states that "...it is our belief that a person or animal would not be fatally shocked with our design. However, it is imperative that all personnel, general public and animals be kept clear of the electrified zone for obvious liability reasons."

The MAFF Fisheries Laboratory at London (subsequently Lowestoft) had an active research programme on electric screening some years ago, but most of the remaining installations were removed in about 1982; the existing installation at Huntington (see above) is said to be a "MAFF Mk 8 Electric Fish Screen". Little of this work was published but further information is likely to be available from MAFF.

An electrical screen system for intakes and outfalls is marketed by Keipe Electric Gmbh of Vienna. It operates via pulses of a few milliseconds duration at 0.3 - 3 Hz, 100 - 1000 V. They list several installations in Austria and Finland, but none in the UK.

Smith Root Inc of the United States manufacture a range of pulsed electric screen units. All use short pulses of DC current introduced to the water by a range of electrode arrays. Three units are for exclusion of upstream migrants from outfalls, and one for the diversion of downstream migrants.

Considering the history of installations in the UK the poor level of knowledge of performance and design criteria is surprising. Taft (1986) concluded that the potential for screening hydro-electric intakes was poor, and no other recent review expresses great enthusiasm. However, it is suggested that the potential for excluding fish from outfalls is significant and further investigation for this application is recommended. Clearly Health and Safety requirements will have to be borne in mind.

# 6. CONSIDERATIONS IN INTAKE SITING AND OPERATION

## 6.1 Introduction

Several times so far in this report reference has been made to the scope for the siting, and method and timing of operation of an intake, to have a considerable effect upon its potential for entrapment of fish. Consideration of the factors involved in some detail is justified as they can have a fundamental influence on the impact of both screened and unscreened intakes. There are a number of cases where care over intake siting, or modulation of abstraction in diurnal or seasonal terms can have as great an effect in reducing entrapment as provision of an efficient screen.

## 6.2 Siting of intakes

Fundamental to the effective operation of any intake screen is the appropriate siting with respect to the fish being able to locate without problem or delay a safe route as an alternative to entrapment. This is discussed in some detail in sections 3, 4 and 5. However, there is also evidence from the discontinuous nature of the three-dimensional distribution of fish in rivers and lakes that there is scope for careful intake siting to reduce the numbers of fish at risk. Most of the useful information on this comes from the Russian literature and is reviewed by Pavlov (1989). He noted that intakes which draw water from shallow marginal areas entrap more young fish than those sited away from the margins. In June 1965, during each 24 hours about 200 000 young fish entered the Olinskaya irrigation system on the Volga delta. When the intake was moved from the river to a shallow bay (June 1970) up to 3 million fish were entrained each day. Location within lakes can have an equally significant effect. Numbers of young roach entrained daily by a near-bank intake at one site were about 2313/m³/s, while only 390/m³/s were drawn into a deep water intake. At another reservoir site entrapment was reduced two-hundred-fold by resiting a shoreline intake to a depth of 6 m.

Pavlov (loc. cit.) also described differential distributions of young fish along river bends, where in some cases 50-70% of drifting fish become aggregated into 25% of the river cross section. Many more fish enter an intake sited on the outside of a bend than one sited on the inside bank. More complex patterns were noted in a series of bends on the Ural River, where careful intake siting was calculated to have reduced entrapment by 81.5% compared to a potential site 200 m upstream.

Heuer and Tomljanovich (1979), investigating factors affecting entrapment on vertical screens found that provision of a bottom refuge made by blanking-off the bottom 9 cm of the screen significantly reduced impingement of two demersal species. They concluded that provision of a bypass area below the screen would probably increase avoidance for nearly all species.

The extent to which the approach of careful siting of intakes could be a valid one in the UK depends upon the patterns of behaviour of our fish species in the rivers or lakes of concern. It would appear that the Russian examples quoted above, while clearly significant, are generally based on larger rivers and reservoirs than are typical in the UK. This again highlights the need for more information on the ecology and behaviour of juvenile coarse fish.

## 6.3 Temporal modulation of abstraction

There would appear to be scope for temporal modulation of abstraction on three levels to reduce entrapment:-

- seasonal e.g. avoid April and May for salmon smolts;
- daily; avoid days of peak migration;
- diurnal; avoid abstraction at night, for example;

These are now discussed in turn.

It is well known that smolts of salmon and sea trout migrate downstream in the spring - predominantly during April and May in England and Wales. While for many intakes a shut-down for several weeks would be impractical, there is nevertheless some scope. For example, large-volume takes for winter filling of pump-storage reservoirs are becoming marginal in April; a formal acceptance of a March 31 deadline could protect smolts for little operational inconvenience. Similarly, the greatest potential entrapment of 0+ cyprinids is likely to take place between June and September (Section 3.4.1; Figure 6.1). An abstraction with a prescribed flow rule is likely to be marginal at such times, and again an acceptance of a no-abstraction period may well cost little in lost yield.

In the case of both salmon smolts and cyprinid juveniles it may be possible to pinpoint more accurately the peaks of migration, and achieve effective protection with a shut-down of much more limited duration. For example, number of smolts entering Uskmouth Power Station were recorded on a daily basis by CEGB. In 1985, for example, 48.5% of smolts were caught on seven days (not consecutive) (CEGB, 1985). On the Elle in Northern France in 1973, 62.5% of the smolt run occurred in seven days (Bagliniere 1976) and on the Piddle in Dorset in 1974-1977, 67%, 65%, 89%, and 53% of the recorded run occurred in four days in each year (Solomon 1978, and unpublished data). Although these days are not necessarily consecutive and do not of course occur on the same dates each year, they are likely to be predictable at short notice from water temperatures, and identified at the time by monitoring fish movements.

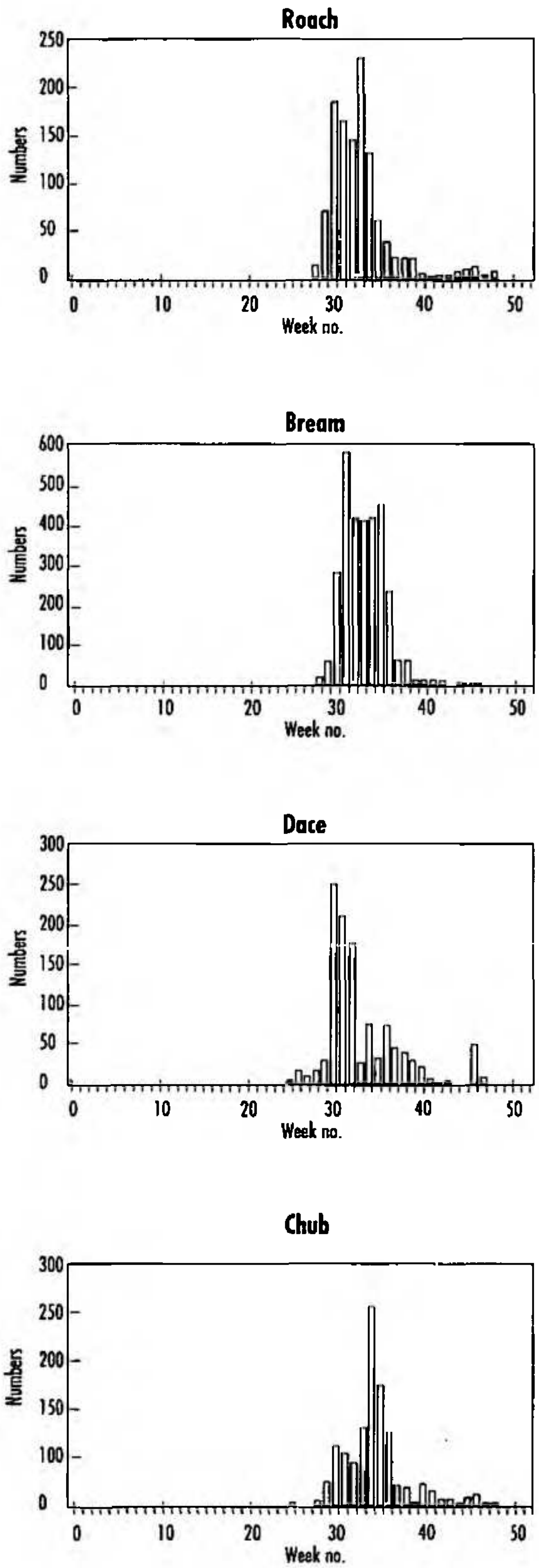



**Figure 6.1.**

**Weekly numbers of 0+ roach, dace, chub and bream observed entrained in a fish farm abstraction on the Hampshire Avon in 1986. This represents only a part of the total entrainment, so the figures are presented as an index of weekly losses. (Data from Dr G Lightfoot, Wessex)**

Pavlov (1989) noted that 65 - 91% of all potential entrapment of juvenile common bream, silver bream and bleak occurred in a period of 5 to 8 days at one site in the Southern Ukraine. Abstraction ceases during these peaks of abundance. In an investigation of the numbers of young cyprinids drawn into a fish-farm intake on the Hampshire Avon the period of vulnerability appeared to be more spread in time, though most activity was concentrated in a very few weeks (Figure 6.1; Dr G Lightfoot, pers. comm.) It is apparent that the species peak at slightly different times; in 1986, roach and dace peaked in week 30, bream in week 31, and chub in week 34 (Figure 6.1). In the investigation at Walton on Thames described in section 2.2. peaks of 0+ fish were rather earlier than this, albeit in a different year (1989). Over 77% of entrainment occurred in the three weeks between June 15 and July 6 (Figure 6.2). This period approximates to week numbers 25 to 27 in Figure 6.1. About 89% of entrainment of chub (6304 out of a years total of 7086) occurred on June 28. The much smaller numbers of 1+ fish entrapped were more widely spread through the sampling season of April to September (Mr G Armstrong, pers. comm.). If the peak days of potential entrapment of species considered to be particularly vulnerable can be reliably identified, there may be scope for temporary cessation of abstraction as occurs in the Southern Ukraine situation described above. Many abstractions which have a prescribed minimum flow must fall back on alternative sources at times, and addition of a few days of no abstraction is likely to prove only a minor imposition in non-drought years.

The scope for diurnal modulation of abstraction may be even greater. Pavlov (1989) reported that the major period of entrapment of juvenile cyprinids occurs at night. In relatively clear water, 60 - 97% of young fish entering intakes did so during darkness. This diurnal pattern was obscured under turbid conditions. In many situations salmon smolts also migrate by night or under conditions of turbid water. However, in some situations peaks of migration can occur in daylight (Solomon 1978) so local information is required before such operating rules are set.

Once again, the need for detailed information regarding behaviour patterns of juvenile coarse fish is highlighted.

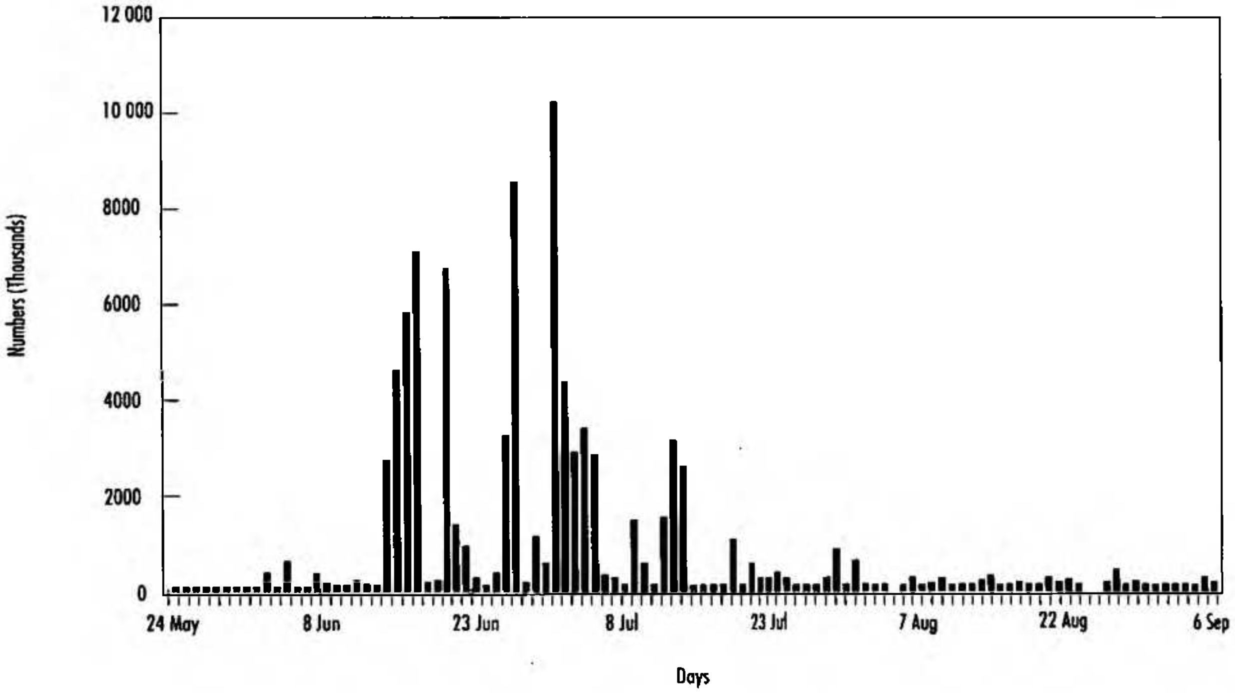



**Figure 6.2.**

**Daily catches of 0+ coarse fish in the louver screen trap in the intake channel at Walton Waterworks between May and September 1989. (The efficiency of capture is low, so the numbers are an index only. Predominant species are roach, dace and chub, with numbers of bleak, minnows, perch, bream, gudgeon and ruffe also represented. Total sample 87,408 fish.**
**(Data from G Armstrong, Thames Region NRA.))**

# 7. CONCLUSIONS AND RECOMMENDATIONS

## 7.1 Conclusions

### 7.1.1 Introduction.

The aim of this section is to summarise the findings of this study, in relation to the terms of reference stated in section 1.1. Recommendations are referred to, where appropriate, but are detailed in section 7.2.

### 7.1.2 Nature and extent of impact

Very little work appears to have been undertaken on the nature and extent of damage to fish and fisheries caused by intakes in the UK fresh waters. The Fawley Laboratory of National Power have studied the situation at coastal and estuarine power station and have concluded that, even if a 100% mortality is assumed for entrapped fish, the impact on stocks of marine species is minimal (Section 2.2.5).

For fresh water it is concluded here that mortality of fish entrained or impinged at intakes is likely to be high, especially as the species/life history stages most at risk (including salmonid smolts and 0+ cyprinids ) are very delicate. It is suggested that a 100% mortality of entrapped fish should be assumed unless there is good evidence to the contrary. Even if not killed directly, fish abstracted with flows pumped to reservoirs represent a total loss to the river (Sections 2.2.2, 2.2.4).

The impact of such mortality on fish stocks has been little studied. Loss of salmon smolts is likely to lead to a proportionate loss of adults returning and thus a loss to both catches and spawning stock. The situation with 0+ coarse fish is less certain, as the population control mechanisms are little studied. There is little information by which to judge whether the loss of tens of thousands of young cyprinids estimated to be entrapped at a fish farm on the Hampshire Avon in a year represents a major, minor or insignificant loss to the local populations. This highlights the first major R&D requirement, for more information on the population dynamics and migrations of coarse fish. There is considerable evidence that many cyprinid species for example undertake migration, or at least functional redistribution, at specific times in the life cycle of greater magnitude than is widely recognized. This has a fundamental effect on the risks represented by intakes (Sections 2.2.5, 2.1).

Fish being attracted to outfalls, particularly where the outfall channel is fairly lengthy and unscreened or inadequately screened, can pose a significant problem. This arises particularly with adult salmonids, but local problems also occur with coarse fish (Section 2.2.3).

In the absence of detailed studies, regional fisheries staff were asked to suggest whether the extent and impact of fish losses at intakes in their area were:

(a) catastrophic,
(b) major,
(c) significant,
(d) minor, or
(e) insignificant.

No Regions suggested the first two; for migratory salmonids all returns were "insignificant" or "minor". For non-migratory species returns varied from "significant" to "insignificant". NRA records show of 14 346 licensed surface-water abstractions totalling 38 372 Ml/d. Only about 500 of these licenses are for more than 10 Ml/d, with over 12 000 being for 1 Ml/d or less. It is not possible to suggest what proportion of these intakes represent a significant danger to fish; NRA Regions are even unable to provide details of how many are fitted with any sort of screen. There is clearly a need for an evaluation of the extent to which a range of intakes represent a danger to fish populations. A register of screens fitted in each Region would also be of considerable value. The legal framework for requiring the installation of screens is somewhat confusing, and powers available to the NRA and MAFF appear to have been little used. A review of this area is recommended (Sections 2.3, 2.4).

### 7.1.3 Potential solutions.

In section 3 the basic criteria for screen arrangements were discussed, with specific approaches considered in detail in sections 4 and 5.

For small-scale abstractions (say less than 1 Ml/d) a fixed bar or mesh screen remains the most practical solution. A submerged horizontal screen of wedgewire would appear to be an excellent option which is largely self-cleaning (Section 4.2). Appropriate mesh sizes and approach velocities for avoidance of entrapment are considered in section 3.4.

For larger abstractions a range of options become available. Where water is drawn into a leat, a louver screen (Section 5.5) or "Econoscreen" (Section 4.4) would appear to offer a high degree of protection for salmon smolts. With appropriate mesh and water velocities the "Econoscreen" is also likely to provide a high degree of protection for cyprinids and other coarse fish. Other available types of drum or band screens cannot be recommended as offering an acceptable degree of fish protection (Section 4.3). For intakes in both rivers and lakes the Johnson passive screen (wedge-wire) appears to be a near-ideal (Section 4.5). The Eicher pressure screen and other wedge-wire screens would appear to be highly effective (Section 4.6). Where feasible, sub-gravel intakes and riverside-gravel wells offer virtually total protection for fish (Section 4.7). It is considered that the above screening technologies are well enough developed for consideration of installation without further

R&D, though monitoring of effectiveness would be a most useful contribution to future decision-making.

From a wide range of behavioural diversion systems that have been tried in the past one can draw a short-list of promising approaches (Section 5.1). Bubble-screens, particularly in combination with strobe lights are worthy of further examination (Section 5.2). Perhaps the most promising system however is that of acoustic diversion; current developments appear most encouraging (Section 5.4). Electric screens would appear to have promise for excluding fish from outfalls, but have generally been dismissed in past reviews for diverting fish from large-scale intakes (Section 5.6). Recommendations for appropriate R&D on these methods are made in section 7.2.

A major contribution to the reduction in fish entrapment appears to be possible by a careful approach to intake siting and the regulation of timing of abstraction (Section 6). This applies to both unscreened intakes and those with less than totally-effective screens (ie the great majority!). More work is needed on the distribution and movement of coarse fish to fully exploit this potential (Section 6.2), though enough information is available for migratory salmonids.

There would seem to be great scope for reducing potential entrapment by avoiding abstraction at times of peak abundance of fish in the zone of the intake (Section 6.3). Periods of weeks, days or even hours may be identifiable when the risks are very much greater than at other times. Again, more information on juvenile coarse fish is needed in this respect.

## 7.2 Recommendations and R&D requirements

#### 7.2.1 Introduction.

The following recommendation for R&D requirements and other matters arise from the consideration in the body of this report. The numbers of the sections discussing the relevant matter are given, but the recommendations are made only here and are not specifically repeated earlier in the text.

#### 7.2.2 Intake screen database

A surprising result of the questionnaire survey of the NRA Regions was the problem of identifying which abstraction licences contained a requirement stipulating intake screens, and which intakes actually had screens of any sort fitted. It is understood that databases of abstraction licences are being developed in several Regions, and that a national database is being considered. It is recommended that details of fish protection stipulations, and screens actually fitted, be included in these databases. (Sections, 2.3, 2.4).

#### 7.2.3 Fish screen legislation

The legal framework for imposition of a screening requirement on existing and new licensed abstractions and discharges is unsatisfactory and little used. Regions would benefit from a concise legal summary of the existing legislation. It is strongly recommended that the existing provisions are rigorously applied, and that changes in legislation are sought to cover all types of abstraction and all species of fish as recommended by the Bledisloe Report (1961) (Section 3.1).

#### 7.2.4 Stipulation of a fish screening requirement

Subject to the legal considerations mentioned in Section 7.2.3, it is recommended that a requirement for appropriate fish screens be made whenever possible on both new and existing licensed abstractions and discharges, whenever the Regional Fisheries Officer considers this desirable. The state of screening technology is such that a suitable and effective method is likely to be available for any situation and conditions. (Section 7.1.3.).

#### 7.2.5 R&D on biology of juvenile coarse fish

There appears to be a considerable lack of knowledge concerning the ecology and behaviour of young coarse fish in their first few months of life in the UK. The three main areas of interest here are:-

- timing, mechanisms and extent of migrations of 0+ and older fish. Critical for assessing the overall problem of potential entrapment, and for considering the scope for short-term discontinuation of abstraction to reduce entrapment;

- distribution and dispersion dynamics - important for maximising scope for sympathetic siting of intakes. Includes diurnal patterns, swimming depths etc;

- population control mechanisms of 0+ fish. Critical to assess the impact of losses at various life-history stages.

One further specific area where information could be gathered concerns the physical dimension of small fish and the mesh size/slot size that is appropriate for their protection.

It is recommended that:-

(a) a desk study be considered to locate all published information on these aspects and to identify current work on the subject;

and

(b) if (a) suggests, a programme of R&D be commissioned to provide the information. It is suggested that this information will be relevant to a much wider range of fishery management matters. (Sections 3.4, 6.2, 6.3).

#### 7.2.6 R&D on fish entrapment

As there appears to be only very limited information on the extent of fish entrapment in intakes in England and Wales, it is recommended that an R&D programme be commissioned to obtain more. If a suitable site could be identified it could also be used to assess a range of screen/barrier types. Although at first sight an existing operating abstraction might appear a correct choice, it is suggested that a purpose made or disused abstraction might be more suitable because:-

- experiments might interfere with operation of an existing abstraction;
- the requirements of the abstraction might preclude manipulation desired for the study;
- the operators of the abstraction may be unwilling to cooperate with a project aimed at identifying the harm they are doing.
- A disused leat abstraction, with full control of flow and a good head-loss available is recommended. Matters that should be addressed are:-
- how many fish of which species are drawn into the unscreened intake under various conditions of flow and other environmental variables?
- what is the diurnal and seasonal pattern of entrapment?
- how effective are a range of behavioural barriers at reducing entrapment? (Section 2.4).

#### 7.2.7 R&D on bubble screens/strobe lights

It is concluded that a full evaluation of bubble screen/strobe light combinations for UK applications is justified. Developments should be based upon the successful experiments recently undertaken in North America and by the Thames Region. Areas justifying particular attention are the scope for diversion of juvenile coarse fish (perhaps commencing with laboratory experiments), and establishment of critical criteria for bubble size, spacing, air flow rates, strobe light frequencies etc. (Section 5.2).

#### 7.2.8 R&D on acoustic diversion methods

The promising results obtained in N.America with acoustic diversion systems suggest that evaluation of this technology for UK application warrants immediate attention. In the first instance, consideration should be given to trials involving the North American signal development systems and sound system hardware. The currently-available equipment represents the results of considerable R&D programmes, and basic research in the UK would be difficult to justify until currently-available technology had been evaluated. Field trials, possibly using fish held captive in nets in the first instance, are suggested as it is likely to prove difficult to simulate appropriate sound-field conditions in a laboratory trial (Section 5.4).

#### 7.2.9 Electric barriers

All information on the considerable development and installation of electric screens in the UK should be gathered and evaluated. If the results justify, a field investigation of electric screens to exclude fish from outfalls should be undertaken. (Section 5.7).

# 8. REFERENCES


Aitken P L, Dickerson L H and Menzies W J M (1966). Fish passes and screens at water power works. Proc. Inst. Civil Eng., 35: 29-57.

Alveras R A (1974). Status of air bubbler fish protection at Indian Point station on the Hudson River. In: Jensen L R (Ed) Second workshop on entrainment and intake screening. Rept 15, Electric Power Research Institute, Palo Alto, California, pp 289-292.

Bagliniere J L (1976). Etude des populations de saumon Atlantique (Salmo salar 1766) en Bretagne-Basse Normandie. II Activite de devalaison des smolts sur l'Elle. Ann. Hydrob. 7: 159-177.

Bainbridge R (1964). The problem of excluding fish from water intakes. Proc. Ass. Appl. Biologists. 53: 505-508.

Bates D W and VanDerWalker J G (1969). Exploratory experiments on the deflection of juvenile salmon by means of air and water jets. Freshwater and estuarine research programme. US Bureau of Commercial Fisheries, Seattle, Washington. 11pp.

Bates D W and Visonhaler (1956). Use of louvers for guiding fish, Trans. Am. Fish Soc., 86: 38-57.

Bell M C (1973). Fisheries handbook of engineering requirements and biological criteria. Fisheries-engineering research program. Corps of Engineers, North Pacific Division, Portland Oregon.

Bibko P N, Wirtenan L and Kueser P E (1974). Preliminary studies on the effects of air bubbles and intense illumination on the swimming behaviour of the striped bass *(Morone saxatilis)* and the gizzard shad *(Dorosoma cepedianum)* I:.Jensen L D (Ed) Second workshop on entrainment and intake screening. Rept 15, Electric power Research Institute, Palo Alto, California, 193-304.

Blaxter J H S (1969). Swimming speeds of fish: In: FAD Fisheries Report no 62. vol2. Proceedings of the FAO conference on fish behaviour in relation to fishing techniques and tactics. 1967. FRm/R6.2 (Tri), 69-100.

Bramsnaes F, Morgens J an d Otterstrom C V (1942). Barriers against fishes by means of electricity or veils of air. Rept Danish Biol. Stn, 47: 39-.

Brett J R and Mackinnon D (1953). Preliminary experiments using lights and bubbles to deflect migrating young spring salmon. J. Fish. Res. Bd Canada, 10: 548-559.

CEGB (1983-1985). Uskmouth Power Station - Reports on smolt migration. Central Electricity Generating Board, South West Region, Bristol.

Clarke M (1988). Walton Water Works smolt trap. Efficiency and Entrainment April - June 1988. Report to Thames Water, Nugent House, Vastern Road, Reading Berks. RG1 8DB.

Devereaux Barnes P E (1976). Development document for best technology available for the location, design, construction and capacity of cooling water intake structures for minimizing adverse environmental impact. Environmental Protection Agency, Effluent Guidelines Division, Washington DC. Rept no. EPA 440/1-76/015-a. 270pp.

Ducharme L J A (1972). An application of louver deflectors for guiding Atlantic salmon (Salmo salar)smolts from power turbines. J. Fish. Res. Bd Canada, 29: 1397-1404.

Eicher G J (1982). A passive fish screen for hydroelectric turbines. Paper presented to ASCE Hydraulics Division Symposium, Jackson, Mississippi, August 1982. 6pp.

Eicher G C (1985). Fish passage; protection of downstream migrants. Hydro Review. Autumn 1985, 95-100.

Gough P J (1991). An assessment of the potential of a bubble screen and a strobe light system as behavioural barriers to reduce the entrainment of Atlantic salmon smolts (Salmo salar ) at a water abstraction intake on the lower Thames. National Rivers Authority, Thames Region, Reading.

Hadderingh R H and Kema N V (1982). Experimental reduction of fish impingement by artificial illumination at Bergum power station. Int. Rev. ges. Hydrobiol. 67; 887-900.

Hancock R S, Jones J W and Shaw R (1976). A preliminary report on the spawning behaviour and nature of sexual selection in the barbel, Barbus barbus . J. Fish Biol. 9: 21-28.

Hanson C H, White J R and Li H W (1977). Entrapment and impingement of fishes by power plant cooling-water intakes: an overview. Mar. Fish Rev., 39(10): 7-17.

Haymes G T and Patrick P H (1986). Exclusion of adult alewife, Aosa pseudoharengus,using low frequency sound for application at water intakes. Can. J. Fish. Aquat. Sci. 43(4); 855-862.

Hawkins A D and Johnstone A D F (1978). The hearing of the Atlantic salmon Salmo salar. J. Fish Biol. 13: 75-87.

Henderson P A, Turnpenny A W H and Bamber R N (1984). Long-term stability of a sand smelt *(Atherina presbyter uvier)* population subject to power station cropping. J. Appl. Ecology 21; 1-10.

Heuer J H and Tomljanovich D A (1979). A further study on the protection of fish larvae at water intakes using wedge-wire screening. Technical Note B33, Division of Water Resources, Tennessee Valley Authority, Norris Tennessee 37828.

Hocutt C H and Edinger J E (1980). Fish behaviour in flow fields pp 143-18. In: Power Plants. Academic Press.

Johnson J C and Ettema R (1984). Passive intake system for a shallow sand-bed river. Paper presented at Joint Power Generation Conference, Toronto. 9pp.

Jordan D R and Wortley J S (1985). Sampling strategy related to fish distribution, with particular reference to the Norfolk Broads. J Fish Biol. 27(Suppl A), 163-174.

Lieverman J T and Muessig P H (1978). Evaluation of an air bubbler to mitigate fish impingement at an electric generating plant. Estuaries. 1: 129-132.

Lifton W S (1979). Biological aspects of screen testing on the St Johns River, Palatka, FLA. Proceedings of passive screen intake workshop. Johnson Division. UOP Incorporated. St Paul, Minnesota.

Lightfoot G W and Jones N V (1976). The relationship between the size of O group roach *(Rutilus rutilus)*, their swimming capabilities, and their distribution in a river. Proc. of the First British Freshwater Fisheries Conference. University of Liverpool.

Linfield R S J (1985). An alternative concept to home range theory with respect to populations of cyprinids in major river system. J. Fish Biol. 27 (Suppl. A), 187-196.

Loeffelman P H (1987). Underwater turbine sound diverts fish from hydro intakes. A E P Search. Winter 1987, 6-7.

Loeffelman P H (1991). Fish Protection: The sounds of success. Search. Vol XI, Winter 1991.

Loeffelman P H, Klinect D A and Van Hassel J H (1991). Fish protection at water intakes using a new signal development process and sound system. In: Waterpower '91. Proceedings of the International Conference on Hydropower sponsored by the American Society of Civil Engineers July 24-26 1991 in Denver Colorado.

Lowe R H (1952). The influence of light and other factors on the seaward migration of the silver eel *(Anguilla anguilla)*. J. Anim. Ecol. 21: 275-309.

MAFF (1959-1974). Annual Reports of the Salmon and Freshwater Fisheries Laboratory, Ministry of Agriculture Fisheries and Food.

McCleave J D and Stred K A (1975). Effect of dummy telemtry transmitters on stamina of Atlantic salmon *(Salmo salar)* smolts. J. Fish. Res. Bd Canada, 32:559-563.

McKinley R S, Patrick P H and Mussali Y (1988). Controlling fish movement with sonic devices. Water Power and Dam Construction, March 1988, 13-17.

Munro W R (1965). The use of louver screens as a means of diverting salmon smolts. ICES CM 1965, Salmon and Trout Committee.

Mussalli Y G, Taft E P and Larsen J (1980). Offshore water intakes to protect fish. J. Hydraulics Divn., Am. Soc. Civil. Eng., 106 (HYII), 1885-1901.

Ott R F, Boersma P E and Strong J J (1988a). Innovative static self-cleaning intake screen projects both aquatic life and turbine equipment. In: Proceedings: Fish Protection at Steam and Hydroelectric Power Plants. CS/EA/AP-5663-SR Proceedings, Micheletti W C (Ed) March 1988. Electric Power Research Institute. Palo Alto. California 94304.

Ott R F, Strong J J and Finch H E (1988b). Arbuckle mountain hydro vertical-axis fish screens. In: Proceedings: Fish Protection at Steam and Hydroelectric Power Plants. CS/EA/AP-5663-SR Proceedings, Micheletti W C (Ed) March 1988. Electric Power Research Institute. Palo Alto. California 94304.

Pagano R and Smith W H B (1977). Recent developments in techniques to protect aquatic organisms at the water intakes of steam-electric power plants. MITRE Technical Report 7671. METREK Division of the MITRE Corp. 1820 Dolley Madison Blvd. McLean, Viriginia 22101.

Patrick P H, Sheeham R W and Sim B (1982). Effectiveness of a strobe light eel exclusion scheme. Hydrobiologia 94, 269-277.

Patrick P H, Christie A E, Sager D, Hocutt C and Stauffer J (1985). Responses of fish to a strobe light/air-bubble barrier. Fish. Res. 3: 157-172.

Patrick P H, McKinley R S and Micheletti W C (1988a). Field testing of behavioural barriers for cooling water intake structures - test site 1- Pickering Nuclear Generating Station. In: Proceedings: Fish Protection at Steam and Hydroelectric Power Plants. CS/EA/AP-5663-SR Proceedings, Micheletti W C (Ed) March 1988. Electric Power Research Institute. Palo Alto. California 94304.

Patrick P H, McKinley R S, Christie A E and Holsapple J G (1988b). Fish protection : Sonic deterrents. In: Proceedings: Fish Protection at Steam and Hydroelectric Power Plants. CS/EA/AP-5663-SR Proceedings, Micheletti W C (Ed) March 1988. Electric Power Research Institute. Palo Alto. California 94304.

Pavlov D S (1989). Structures assisting the migrations of non-salmonid fish: USSR. FAO Fisheries Technical paper 308. UN Rome.

Ruggles C P (1990). A critical review of fish exclusion systems for turbine intakes with particular reference to a site on the Connecticut river, USA. Proc. Int. Symposium on Fishways '90 in Gifu Japan, October 8-10; p151-156.

Ruggles C P and Hutt R (1984). Fish diversionary techniques for hydrolectric trubines intakes. Canadian Electrical Association, Report 149 G 339.

Ruggles C P and Ryan P (1964). An investigation of louvers as a method of guiding juvenile Pacific salmon. Can. Fish Cult., 33: 1-68.

Sager D R, Hocutt C H and Stauffer J R. Estuarine fish responses to strobe light, bubble curtains and strobe light/bubble curtain combinations as influenced by water flow rate and flash frequencies. Fish. Res. 5: 383-399.

Solomon D J (1978). Migration of smolts of Atlantic salmon *(Salmo salar)* in a chalkstream. Env. Biol. Fish. 3: 223-229.

Solomon D J (1987). Louver screen smolt trap, Walton Waterworks. Report to Thames Water on design, construction, installation and testing 1987.

Solomon D J (1981). Migration and dispersion of juvenile brown sea trout. Salmon and Trout Migratory Behavior Symposium. In: Brannon E L and Salo E O (Eds), University of Washington, 136-145.

Solomon D J (1988). Fish passage through tidal energy barrages. ETSU TID 4056, Department of Energy.

Taft E P (1986). Assessment of downstream migrant fish protection technologies for hydroelectric application. Electric Power Research Institute, Palo Alto. EPRI AP - 4711.

Thorpe J E and Morgan R I G (1978). Periodicity in Atlantic salmon Salmo salar Lsmolt migration. J. Fish Biol., 12: 541-548.

Travade F (1985). Comment sauver poissons et crevettes dans les prises d'eau? In: Electricite de France, direction des etudes et recherches, extrait du no.5 Janvier 1985.

Turnpenny A W H (1981). An analysis of mesh sizes required for screening fishes at water intakes. Estuaries 4(4); 363-368.

Turnpenny A W H (1988a). Exclusion of salmonid fish from water intakes. CEGB Research report RD/L/337/R88.

Turnpenny A W H (1988b). The behavioural basis of fish exclusion from coastal power station cooling water intakes. CEGB Research report RD/L/3301/R88.

Turnpenny A W H, Langford T E and Aston R J (1985). Power stations and fish. CEGB Research April 1985, 27-39.

Wardle C S (1977). Effect of size on swimming speeds of fish, In: Scale effects in animal locomotion (Ed. Pedley T J), New York, Academic Press, 299-313.

Warner G (1956). Report on the air-jet fish-deflector tests. Prog. Fish Cult., 18: 39-41.

Weisberg S B, Burton W H, Jacobs F and Ross E (1987). Reduction in Ichthyoplankton entrainment with fine-mesh, wedge-wire screens. N. Am. J. Fish. Management 7: 386-393.

Wert M A, Casey D W and Nece R E (1987). Hydrauilic model evaluation of the Eicher passive pressure screen fish bypass system. Electric Power Research Institute, Palo Alto. EPRI AP - 5492.

Winchell F C (1990). A new technology for diverting fish past turbines. Hydro Review, December 1990; 32-42.

# APPENDIX A TEXT OF QUESTIONNAIRES SENT TO REGIONS.

## NRA RESEARCH PROJECT ON DIVERSION AND ENTRAPMENT OF FISH AT WATER INTAKES AND OUTFALLS.

**Request for information on surface water abstraction from NRA Regions.**

1. What is the total licensed surface water abstraction in your Region?

2. Does (1) include licences of entitlement ? If not, can you suggest how much extra they are likely to include?

3. How many licences are involved in the above total abstraction?

4. Are you able to break down the numbers of licences by total volume? If so, could you say how many of the licensed abstractions are for

   a) More than 10 Ml/d

   b) Between 5 and 10 Ml/d

   c) Between 1 and 5 Ml/d

   d) Less than 1 Ml/d.

5. Are you able to make any estimate of how many of the above abstraction points are likely to incorporate screens to prevent entrainment of fish?

6. Does your abstraction licence database contain information on intake screening requirements or provisions? Could this be readily accessed?

7. a) What is the total surface-water run-off from your Region?
   b) Can you propose a reasonable estimate of the proportion of (a) that represents a Q95 (e.g. 1/4, 1/8 or 1/16 th) for the Region?

(The idea here is to try to relate the total licensed surface-water abstraction to an estimate of dry-weather flow for the Region as a whole).

Form completed by ........................................................................................

Region.................................................................... Date...............................

Please return completed form to Dr D J Solomon, Foundry Farm, Kiln Lane, Redlynch, SALISBURY. Wiltshire. SP5 2HT.

Queries to Dr Solomon Tel 0725 22523, Fax 0725 22964.

## NRA Research Project on Diversion and Entrapment of Fish

### REQUEST FOR INFORMATION AND VIEWS FROM REGIONAL FISHERIES OFFICERS.

Please use this form for your response where possible, but feel free to continue on separate pages as appropriate.

Form completed by:-

Region:-

**Extent and significance of losses at intakes.**

1. Do you have any quantitative information on fish losses at individual intakes (including estuary sites)?

2. In your Region as a whole, do you feel that fish losses at water intakes are:-

   (a) catastrophic
   (b) major
   (c) significant
   (d) minor
   (e) insignificant

(Please separate for migratory salmonids and other fish as appropriate. I apologise for the range of subjective categories but I suggest it is as close as we will get. Please add any comments or suggestions).

3. Are you aware of any studies in your Region of the fate of fish drawn into intakes? (e.g. injuries, death)?

**Extent and significance of problems at outfalls.**

4. Do you have any specific information about problems with fish entering water outfalls, tailraces etc?

5. In your Region as a whole, do you feel that problems with fish entering outfalls, tailraces etc are:-

   (a) catastrophic
   (b) major
   (c) significant
   (d) minor
   (e) of no significance.

(Again please separate for migratory salmonids and other fish as appropriate.)

**Extent of existing screening arrangements.**

6. Are some/many/most of the major surface water abstractions in your Region fitted with what you consider to be adequate screens or other fish diverting devices?

7. Do you feel that more could readily be fitted ie that adequate technology exists?

8. As far as you are aware, are any intakes in your Region protected by:-

(a) drum or band screens
(b) wedge-wire screens
(c) other fixed fish-proof screens
(d) sub-gravel intakes
(e) electric screens
(f) bubble screens
(g) acoustic deterrents
(h) strobe lights
(i) louver screens
(j) other (please specify).

It would be very helpful if you could give a location and intake purpose of any examples of the above apart from (a) and (c).

9. Any comments you can offer on the efficiency of the above would be welcomed.

**Protection at outfalls/tailraces etc.**

10. As far as you are aware, are any outfalls or tailraces in your area protected by:-

(a) physical screens
(b) electrical screens
(c) any other mechanism

(Again, interesting examples would be welcomed).

**Areas and sites for further investigation.**

11. a) Do you feel that your Region would be a useful candidate as one the three or so to be examined in more detail?
b) Would you and/or your staff be willing to give some time (a day or so) to going through things in some detail with me?

12. Can you suggest sites that would be good candidates for specific consideration? In particular, examples of the more unusual types in questions 8 and 10 would be appreciated. Please give a few details e.g. type, location, intake/outfall purpose, owner etc.

13. Please feel free to make any further comments you feel might be useful, including ideas for R&D requirements, and areas you feel I may have so far overlooked.

Many thanks for your time and trouble.

Please return completed form to Dr D J Solomon, Foundry Farm, Kiln Lane, Redlynch, Salisbury, Wilts SP5 2HT.

Tel 0725 22523 Fax 0725 22964

# APPENDIX B
# LIST OF MANUFACTURERS AND SUPPLIERS

This list comprises all manufacturers and suppliers where products are mentioned in the body of the report. The inclusion of a supplier in this list does not necessarily imply endorsement of their products, neither does absence of names of other suppliers imply any criticism..

Econoscreen Environmental UK
Crosshills House
Southwaite
Carlisle
Cumbria CA4 OLB
UK
Tel: 0697-473295
Fax: 0228-514575

FMC of Canada Ltd
(Material Handling Operation),
650 Hood Road
Markham
Ontario L3R 4S7
CANADA
Tel: (416) 474-7500
Fax: (416) 474-7542

Houston Well Screens International
Unit BT 507/1 Thornhill Industrial Estate
Hope St, Rotherham
South Yorkshire S60 ILH
UK
Tel: 0709-829521/2
Fax: 0709-367309

Johnson Filtration Systems Ltd
Johnson House
Browells Lane
Feltham
Middlesex TW13 7EQ
UK
Tel: 081-751-4424
Fax: 081-890-1533

Keipe Electric GmbH.
Engerthstrasse 59
A-1201 Wien
Postfach 131
AUSTRIA
Tel: (0222) 35 36 36

Loeffelman, Paul H.
1270 Clubview Boulevard, North
Worthington, Ohio 43235,
USA
Tel: 614-436-8761
Fax: 614-451-9221

Eicher Associates Inc.
Ecological and Environmental Analysis and Planning
8787 SW Becker Dr.
Portland
Oregon 97223,
USA
Tel: 503-246-9709