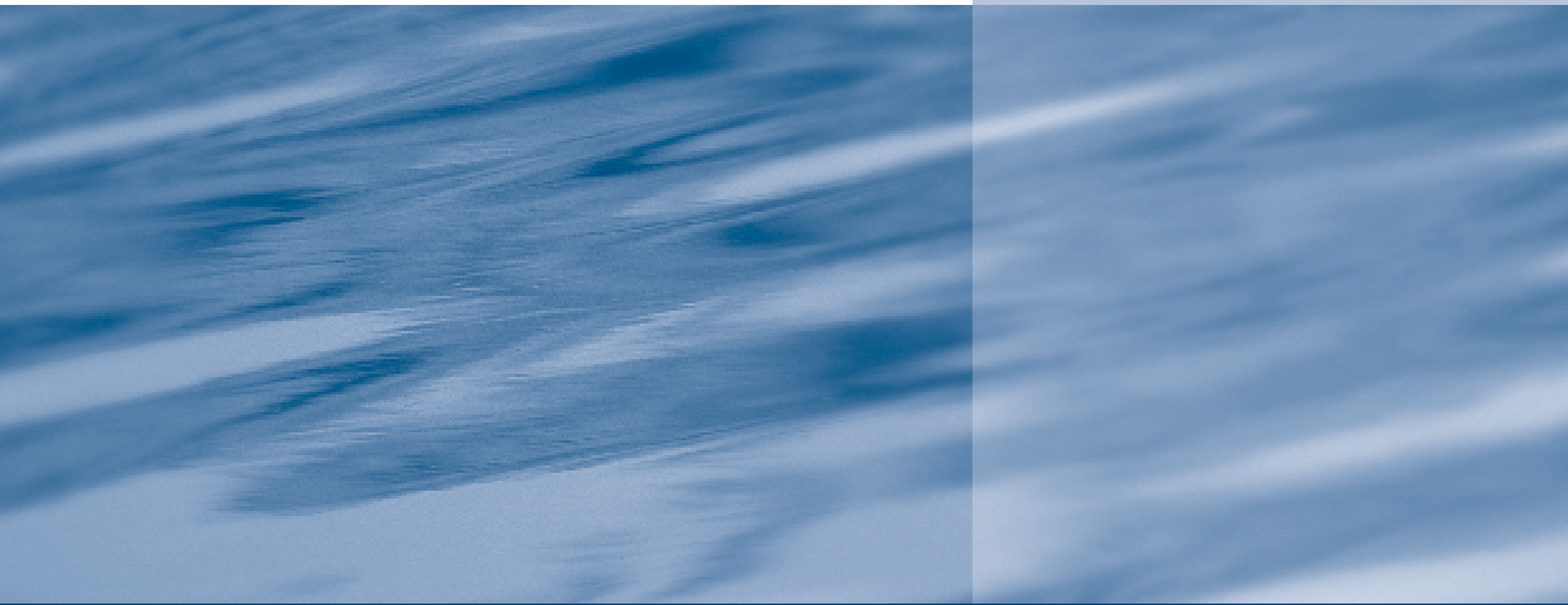

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Screening for Intake and Outfalls: a best practice guide

Science Report SC030231

ENGLISH NATURE

Cyngor Cefn Gwlad Cymru
Countryside Council for Wales

ENVIRONMENT AGENCY

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Professor Mike Depledge Head of Science

SUMMARY

The aim of this Guide is to provide a description of the legal responsibilities of operators of water intakes and outfalls and, from a review of current, worldwide examples, to present a synopsis of methods that are known to work best for different species and lifestages of fish in different situations. A review of the wide range of technologies that are in common use for fish screening is provided, including physical and behavioural screening technologies.

Effective screening must be targeted to the species and lifestages of fish that are to be protected. Given the diversity of screening applications and environments and the need to consider the protection of a much-enlarged list of fish species than perhaps in the past, the developer or operator is faced with a potentially bewildering array of options. This review will help to guide users towards current best practice to assist in the task of screen selection and specification. There remain a number of gaps, where the effectiveness of new techniques has not been fully evaluated or where methods for particular species or applications have yet to be identified or developed. Recommendations for further screen development and evaluation are made.

EXECUTIVE SUMMARY

Background and Aims

Intakes used for water supply and hydroelectric power generation may harm fish if not properly screened to prevent fish ingress and there is also a risk of fish injury at intake structures or gratings. The issues and their remedies were reviewed for the National Rivers Authority by Solomon (1992). Now, more than a decade later, there have been significant changes in the law relating to fish screening, in the regulatory framework, and in fish screening and diversion technologies. It is, therefore, timely to readdress the issues. The aim of this Guide is to provide a clear description of the legal responsibilities of operators of water intakes and outfalls and, from a review of current, worldwide examples, to present a synopsis of available methods, indicating those that are known to work best for different species and lifestages of fish in different situations.

Potential impacts of fish entrainment and impingement

The design, installation and operation of fish screens and barriers can add significantly to the capital and operating costs of facilities. It is important for operators to recognise the potential impacts on fish and fish communities, which justify the costs of the required mitigation measures, and consider undertaking cost-benefit analyses.

Migratory diadromous species are historically recognised as being at risk as they often have to pass numerous water abstractions, as well as weirs and other hazards, on their journeys between rivers and the sea. In recent years there has been increasing recognition of the risk of entrainment into water intakes of juvenile freshwater fish during their downstream dispersal phases. Unscreened intakes on water transfer schemes may cause the unwanted introduction of new species or different genetic stock. In estuarine and coastal waters, impacts can arise from refineries, docks, and shipping but especially from thermal power stations, which abstract large volumes of cooling water. Desalination plants may also be developed in the future.

Review of screening and guidance technologies

This section presents a review of the wide range of technologies that are in common use for fish screening, including both physical and behavioural types. For salmonids and larger fish there are six main types of physical screening techniques: 1) traditional passive mesh screens – the most common fish exclusion method; 2) vertical or inclined bar racks; 3) rotary disk screens – originally designed for sewage treatment works but with some merits for intake screening; 4) Coanda screens –wedge-wire spillway screens mainly for upland hydropower applications; 5) the 'Smolt-Safe™' screen – another type of spillway screen and 6) band- or drum-screens modified for fish return. For juvenile and smaller fish there are four main physical screen choices: 1) passive wedge wire cylinder (PWWC) screens – the most widely used method for juvenile and larval fish protection; 2) small-aperture wedge-wire panel screens; 3) sub-gravel intakes and wells – which use the riverbed as a filter; and 4) the Marine Life Exclusion System (MLES™) – a water permeable geotextile barrier currently being evaluated in the USA. Other physical screening technologies not currently available in the UK include the modular inclined screen which is a wedge-wire screen which is tilted up from the horizontal, the labyrinth screen, which is a compact arrangement of vertical bar racks arranged in chevron formation and the self-cleaning belt screen.

Behavioural technologies can be used where positive exclusion fish screening is impractical or as a supplement to more conventional screen types. The best of these can

be >90% effective against certain species when designed correctly and operated in suitable environmental conditions. As they do not provide a guaranteed barrier to fish passage, they are often used in less critical applications or where the alternative is to have no screening. There are five main types that have been used within the UK, comprising: 1) louvre screens – a semi-physical barrier; 2) bubble curtains – the most basic behavioural barrier; 3) electrical barriers – e.g. the 'Graduated Field Fish Barrier (GFFB™)'; 4) acoustic fish deterrents – which exploit the hearing sensitivity of fish; and 5) artificial lighting – either to illuminate physical structures or as an attractive or repellent stimulus (e.g. strobe lights). Behavioural technologies that are not known to have been used in the UK include: 1) turbulent attraction flow – which mimics natural river turbulence to guide fish into bywash structures; and 2) surface collectors – a bypass system which is based upon the natural tendency of salmon smolts to migrate to surface layers. Outfall screening may also be required to protect upstream migrating species. There are two main techniques suitable for screening outfalls: 1) mechanical mesh or bar screens and 2) electrical barriers.

Performance Criteria

While behavioural screens are expected not to achieve a complete barrier to fish, there is a common misconception that all positive exclusion fish screens, provided that they are designed with the optimum mesh size and velocity conditions, are 100% effective. In practice, this success rate is seldom achieved. Inspection surveys frequently reveal faults in the operation or maintenance of even the best designed screening systems. These can however, all be overcome with appropriate monitoring and maintenance. The effectiveness of screen measures should reflect the level of risk to the fish stock or fish community. The Environment Agency has adopted a 'Risk Assessment' approach, by which the required performance criteria for a screen can be determined according to such factors as the sensitivity of the fish stock or community and the other cumulative impacts upon it (e.g. other abstractions from the same watercourse, barriers to migrations, etc.).

Designing for Performance

Effective screening must, first of all, be targeted to the species and lifestages of fish that are to be protected. This will determine the method best suited, the critical times of the year and the specific design details for the fish screen (mesh size, etc.). Seasonal events may allow more focus in the design. Swimming performance of a species is strongly influenced by the length of the fish and by water temperature. The required criterion is that the fish approaching an intake should be able to swim fast enough and for long enough to ensure their escape via the bywash or any other route provided to return them to the main river flow. No statutory limits on escape velocities exist at present within the UK and the onus on the operator is to provide a system that avoids injury to fish. The chief purpose in hydraulics design is to avoid high velocity 'hot spots' that might cause fish to be impinged on the screen resulting in death or injury.

Selecting the Best Screen

Given the variety of screening applications and environments and the need to consider the protection of a much-enlarged list of fish species than perhaps in the past, the developer or operator is faced with a potentially bewildering array of options. Table 6.1 provides a summary of techniques that, from current knowledge, are likely to provide suitable screening solutions for different applications/environments and for the various categories of fish of concern.

It is stressed that screening is not always the best solution. It may be more economic and/or protective to modulate abstraction to avoid seasons, days or times of the day when fish are most at risk.

Monitoring for screen effectiveness: Recommendations for further work

From the review of screening technologies presented in section 3 of this Guide, it is clear that many different approaches exist and that there has been much innovation in recent years. The development of new techniques reflects the need to provide cost-effective solutions to suit an ever-widening range of circumstances. In practice, comprehensive scientific testing can be very costly and it makes sense to first answer basic questions on effectiveness from soundly designed generic studies. The number of techniques now in use could create an almost unlimited agenda for testing in order to cover the different environments, species and lifestages and the possible combinations of techniques. The Guide considers where resources would be best directed towards generic research to meet current needs. Fish screens usually form only part of an overall fish diversion or protection system and it is the performance of the entire system that needs to be proven. A variety of test methods is described, which can be used to assess screening efficiency, as well as for monitoring detailed fish behaviour in front of screens and bywashes. These include fish capture methods, biotelemetry, video monitoring, tagging, hydroacoustics and float-tagging. In addition to any generic research needs, site-specific commissioning trials may also be required to show that screening measures perform satisfactorily.

Knowledge gaps and future research needs

Solomon (1992) made a number of recommendations in respect of fish screening. The present Guide provides an indication of progress made since 1992 and comments on the current relevance of any outstanding issues. Key points arising from Solomon's recommendations are:

- A database of abstractions now exists but <u>there remains a need for details of fish protection stipulations and measures</u>.
- No significant advance has been made to investigate distribution and dispersion dynamics of coarse fish to aid in sympathetic siting and operation of intakes and <u>further research is required</u>.
- <u>There is a pressing research need to assemble life-history data sets for particular species</u> to investigate population control mechanisms to assess impact of losses at various life stages. Benefits of such research would no doubt spill over into other areas of fisheries biology and management.
- Screen slot and mesh sizes suitable for different species and lifestages are currently being researched in the USA and any new data from those studies should be investigated before commissioning new UK work. As the PWWC screen is one of the most important screening techniques currently available, good information on these aspects is essential and <u>work should be commissioned if data are not found elsewhere</u>.
- <u>As the main large-volume water abstractors, there remains a need to investigate potential impacts from power plant abstractions on fish entrapment at intakes</u>, either through commissioned R & D or owner-funded studies. Future work should concentrate <u>in particular on designated fish species, especially lampreys, on entrainment of fish eggs, larvae and fry</u> that are usually not fully represented in power station sampling, and on other species of conservation interest such as sea trout, smelt and eel.

- Wherever possible, through legislative provisions or voluntary cooperation, owners should be encouraged to ensure protection of all life stages of fish. This may be best achieved through screening measures, or through temporal modulation of flow to avoid abstraction during periods of high entrainment risk.
- Further, generic scientific testing of behavioural fish barriers is recommended.

CONTENTS

1 INTRODUCTION

1.1 Background

In England and Wales there are some 48,000 water abstractions licensed through the Environment Agency, for potable and industrial water supply, irrigation, flood defence, hydroelectric power generation and other purposes. Almost a third of these draw from surface waters containing fish populations, which may be harmed if the intakes are not properly screened to prevent fish ingress. Water outfalls can also present a hazard, where upstream-migrating fish may be attracted to the discharge and accidentally enter a works, a hydroelectric turbine or a fish farm, with a resultant risk of injury or delay to their migration. The issues and their remedies were reviewed for the National Rivers Authority by Solomon (1992). Now, more than a decade later, there have been significant changes in the law relating to fish screening, in the regulatory framework and in fish screening and diversion technologies. The consequences of fish entrainment are also better understood, as are the potential risks to fish populations. It is therefore timely to readdress the issues. It is also our aim to provide a clear description of the legal responsibilities of operators of water intakes and outfalls and, from a review of current, worldwide examples, to present a synopsis of which methods are known to work best for what species and lifestages of fish in different situations. The range of applications considered is as comprehensive as possible and the review includes estuarial and coastal, as well as inland waters. It is appropriate from a conservation perspective to widen the scope of review even further to include other nektonic organisms – notably crustaceans – that are potentially vulnerable to entrainment. Where relevant, these too are considered.

In preparing this document, the authors have drawn on a wide range of resources, including library holdings, material sourced from the Internet, contacts with scientists and other specialists in the field and contacts with operators of different technologies The starting point was the Solomon (1992) report. Other key guidance works consulted were:

- *Fish Passes and Screens for Salmon*. Report of the Salmon Advisory Committee (1997),
- *Notes for guidance on the provision of fish passes and screens for the safe passage of salmon*. Scottish Office Agriculture and Fisheries Department. (Anon., 1995a).
- *A UK Guide to Intake Fish-Screening Regulations, Policy and Best Practice with Particular Reference to Hydropower Schemes* (Turnpenny *et al*, 1998).

The present document summarises and updates the relevant information from these documents.

Prevention is better than cure and at the start of this guide we would urge that full consideration be given by operators to possible alternatives to fish screening: for example, modifying or ceasing the operational regime of the facility at crucial times of the year/ day/ tide, etc.

It can prove more cost-effective, for example to modulate periods of abstraction so that the risk to fish is minimised, rather than invest in costly fish screening measures. For new projects, such matters must be adequately addressed by *early* consultation with regulatory authorities, fisheries specialists and other interest groups, so that each can understand the others' constraints. Satisfactory fish screening or acceptable alternative arrangements must be provided which adequately address the level of risk to fish populations. The Environment Agency seeks to encourage improved engineering design, e.g. of pumps and turbines, or of fish rescue systems. While innovation must be the key to dealing with ever more challenging issues associated with new types of facility, different species and juvenile lifestages, there is an urgent need to make robust scientific assessments of new techniques. In this Guide, we will attempt to identify and prioritise research needs and gaps in available techniques.

For a variety of legal and historical reasons, many of our existing licensed intakes and outfalls have no protection or inadequate protection relative to present day needs. When considering screening technologies, the ability to retrofit equipment to existing facilities is therefore an important consideration.

The present Guide was commissioned by the Environment Agency, English Nature and CCW as a step towards improving the regulation of intakes and outfalls within the wider context of multi-species conservation across all aquatic habitat types.

1.2 Key drivers for broadening the requirement for fish screening

1.2.1 The developing legislative framework

1.2.1.1 The Salmon & Freshwater Fisheries Act (SFFA) 1975 as amended by the Environment Act 1995

The hazards of water intake and outfall structures were recognised in the fisheries law of England and Wales more than 80 years ago, with the introduction of screening legislation in the Salmon and Freshwater Fisheries Act of 18th July 1923[1] (revised 1975) (Howarth, 1987). Section 14 of the Act deals with the obligation of the owner or occupier of an undertaking to fit and maintain approved gratings, while s. 15 gives powers to the regulating authority to fit and maintain gratings at its own expense (gratings here may be interpreted as any device that prevents the passage of fish into the intake: Howarth, 1987). The most recent changes to SFFA s. 14 & 15 emanate from the Environment Act 1995, which made the Environment Agency the statutory authority in England & Wales. Key changes made at this time were the inclusion for the first time of fish farm intakes and outfalls as regulated structures, and the relinquishment of any regulatory approval mechanism: the latter important change effectively placed the onus of proof of effectiveness onto the owner or occupier; also, it became a requirement to provide a continuous bywash in any situation where screens are sited within a conduit or channel. The measures within SFFA s. 14 & 15 apply solely to the migratory salmonids, Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*) and technically apply to waters that are *frequented* by these species, a term which is interpreted to require demonstration that there is a self-supporting population of at least one of these species present, rather than one maintained by stocking. The Agency takes the view that this includes waters where there is a policy of reinstatement of migratory stocks.

The existing explicit law on fish screening may appear rather *Salmo*-centric in the present climate of fisheries and conservation, and even with regard to the protection of salmonids it is found to be wanting. Its powers do not for example extend to mills (including those operated as hydroelectric generation schemes) that have operated

[1] Schemes which have operated continuously since prior to this date have “licences of entitlement” and are exempt from provisions of the ACT.

continuously since prior to the 1923 Act[2]. Nevertheless, the Environment Agency and other regulators, including English Nature (EN) (for England) and the Countryside Council for Wales (CCW), have long held powers implicit within several Acts of Parliament that allow for the appropriate protection of any species of fish at water intakes and outfalls.

In England and Wales, powers emerge from the following statutes and amendments thereof:

1.2.1.2 The Wildlife and Countryside Act (WCA) 1981, as amended by the Countryside and Rights of Way Act (CRoW) 2000

The Wildlife and Countryside Act 1981 (WCA 1981) serves to implement the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention) and Council Directive 79/409/EEC on the Conservation of Wild Birds (Birds Directive) in Great Britain. It is complemented by the Wildlife and Countryside (Service of Notices) Act 1985, which relates to notices served under the 1981 Act, and the Conservation (Natural Habitats, & c.) Regulations 1994. Amendments to the Act have occurred, the most recent being the Countryside and Rights of Way (CRoW) Act 2000 (in England and Wales only). There is also a statutory five-yearly review of Schedules 5 (protected wild animals, including fish), undertaken by the country agencies and co-ordinated by the Joint Nature Conservation Committee. The Act, amongst other things, makes it an offence (subject to exceptions) to intentionally kill, injure, or take any wild animal listed in Schedule 5, although the accidental killing or injury of fish through failure to provide adequate fish screening may not come into this category. The Act also provides for the notification of Sites of Special Scientific Interest (SSSI) – areas of special scientific interest for their fauna or flora.

Amendments to the Act under CRoW place a duty on Government Departments and the National Assembly for Wales to have regard for the conservation of biodiversity and maintain lists of species and habitats for which conservation steps should be taken or promoted, in accordance with the Convention on Biological Diversity. Schedule 12 of the Act strengthens the legal protection for threatened species and requires the regulator to submit a formal notice to the relevant nature conservation agency if the activity to be granted a permission constitutes an “operation likely to damage” (OLD) the SSSI (whether within or outside a SSSI). This in particular could influence the granting of consents in relation to intakes and outfalls.

1.2.1.3 The Water Resources Act (WRA) 1991

Many abstractions that have been licensed in recent years have, irrespective of the limited powers of SFFA s.14, been required to fit fish screens as conditions attached to new abstraction or impoundment licences under the Water Resources Act, s. 158. The Environment Agency in this way exercises its statutory duty under s. 114 of the Act to ‘maintain, improve and develop salmon fisheries, trout fisheries, freshwater fisheries and eel fisheries’. Such conditions may require not only the installation of screening systems at the owner’s expense but also the installation of monitoring equipment and monitoring surveys where these may be required. In fact, the WRA provides for great regulatory flexibility in achieving the above statutory duty, for example through placing limits on the timing of abstractions to avoid critical fish migration periods (diurnal, tidal or seasonal) or

[2] But see Howarth (1987), p. 74, who proposes that this exemption applies only to the *occupier* of the mill, and not the owner.

through more complex formulae related to available flows and water levels. Operating conditions will normally be negotiated with the owners to achieve the most workable and effective solution.

1.2.1.4 The Conservation (Natural Habitats, & Conservation.) Regulations 1994

European Directives require the enactment of enabling legislation in the Member States prior to enforcement. The Habitats Regulations, as they are commonly known, provide for the application of the European Habitats Directive (92/43/EEC) in England and Wales.

The aims of the Directive are "…*to contribute towards ensuring biodiversity through the conservation of natural habitats and of wild fauna and flora in the European territory of the Member States to which the Treaty applies*" (Article 2.1); and

"…*to maintain or restore, at favourable conservation status, natural habitats and species of wild fauna and flora of Community interest*" (Article 2.2)

The Habitats Directive requires the protection of designated species and habitats within Special Areas of Conservation (SACs). In the case of fish, the Annex II species occurring in England and Wales whose conservation requires the designation of SAC sites include:

- River lamprey (*Lampetra fluviatilis*)
- Sea lamprey (*Petromyzon marinus*)
- Brook lamprey (*Lampetra planeri*)
- Atlantic salmon (*Salmo salar*)
- Bullhead (*Cottus gobio*)
- Spined loach (*Cobitis taenia*)
- Allis shad (*Alosa alosa*)
- Twaite shad (*Alosa fallax*)

Any plan requiring consents for the development of a new project or significant modification of an existing project that might impact an SAC site will be subject to the Habitat Regulations. It should be noted that this does not necessarily mean that the project must lie within the designated area of the SAC; if the project might indirectly impact the SAC, e.g. a pollution source upstream of an SAC or an abstraction on the migration path of a designated species attempting to reach the SAC, then it will also be subject to the regulations. In England and Wales, the Environment Agency, as the 'competent authority' with regard to water intakes and outfalls, can only agree to a plan or project having ascertained by an 'appropriate assessment' that there will be no adverse effect on the 'integrity' of the SAC. The appropriate assessment is thus precautionary, and does not include consideration of economic factors. Such decisions will be based partly on advice from other statutory consultees, including English Nature or the Countryside Council for Wales. If, following an appropriate assessment, the Agency cannot conclude that there will be no adverse effect on the integrity of the European Site (from the plan or project alone, or in combination with other plans or projects and in the context of prevailing environmental influences), alternatives and modifications to the plan would have to be evaluated. It may be appropriate to consider fish screening techniques for relevant sites at this stage, as a potential solution to achieve no adverse effect on integrity. The cost of installing such screening would be appraised with the overall aim of achieving no adverse effect, but in the context of alternative solutions and potential reasons of overriding public interest.

Interpretation of the Habitats Regulations is complex. Further information can be obtained from the Environment Agency via its website (www.environment-agency.gov.uk) and from the Joint Nature Conservation Committee (www.jncc.gov.uk).

1.2.1.5 The Environment Act (EA) 1995

This incorporates and amends the SFFA *s*.14 and 15 powers, as described above.

The Water Environment (Water Framework Directive) (England and Wales) Regulations 2003 &

1.2.1.6 The Water Environment (Water Framework Directive) (Northumbria River Basin District) Regulations 2003

Over-arching powers affecting the regulation of fish habitats will also emerge from the European Water Framework Directive (WFD) (2000/60/EC), introduced in the UK in December 2000, which is expected to be fully implemented in the UK by 2015. It requires all inland and coastal waters to reach 'good status' by this date. It will do this by establishing a river basin district structure within which demanding environmental objectives will be set, including ecological targets for surface waters. The above Regulations transpose the WFD into English and Welsh Law; the second set of Regulations is separated from those pertaining to the main body of England and Wales as the Northumbria River Basin District contains a small part of Scotland.

The full implications of the WFD with respect to fish screening have yet to emerge but it is clear that the requirement to achieve demanding ecological status objectives will strengthen rather than weaken existing powers. Essentially it is likely to mean that owners will be required to ensure that any new developments meet sustainability criteria and that they do not lessen the existing ecological status of a water body but if anything improve it.

1.2.2 Broadening scope of species to be protected

The consideration of species other than migratory salmonids goes beyond the statutory remit arising from the Habitats Directive. It comes from a modern perspective on the merits of holistic ecological conservation and the increasing recognition e.g. that many species of freshwater fish are much more mobile within the river continuum than was once understood. Thus the within-river ('potamodromous') movements of non-migratory trout and of coarse fish are now recognised, in addition to the more traditionally known migrations of diadromous species, such as salmon, eel, lamprey and shad, as are the migrations of euryhaline species such as smelt (*Osmerus eperlanus*), flounder (*Platichthys flesus*) and grey mullets. Any of these concerted movements or migrations within species put them at increased risk of entrainment. In some species, the risk of losses due to entrainment exacerbates an already declining trend in the status of stocks, for example in the eel, or may slow down the rate of recovery of returning species, such as smelt or shad.

1.2.3 Changing water resources perspectives

Recent years have seen an upsurge in interest in renewable energy development, including hydroelectric power (HEP) projects. HEP schemes generally use relatively large proportions of a river's flow (sometimes as high as 95% of the dry weather flow), which makes provision of effective fish screening a particular challenge. On some rivers the risk to fish populations is compounded by the cumulative effect of the need to pass two or more HEP schemes in succession. Risks arise from injury to fish in the turbines where they are able to pass through, from impingement on the screens where they are inadequately designed or operated or from delays to migration – with possible increased predation risk - where bywashes are not readily found by the fish (Turnpenny *et al.*, 1998, 2000). Anyone interested in this subject is also advised to refer to the Agency's publication "Hydropower – A handbook for Agency Staff" (May, 2003), available from Environment Agency offices.

1.2.4 Establishing 'green' credentials

A positive factor in fish screening is that many operators of intakes and outfalls want to be seen to be environmentally responsible and will do more than the law requires, provided that this does not impact too heavily on the viability of their operations. For example, a number of water companies who operate under 'licences of entitlement' or abstract from rivers not frequented by migratory salmonids have voluntarily provided fish screening. This is often to establish good relations with anglers or to meet internal environmental management objectives.

2 POTENTIAL IMPACTS OF FISH ENTRAINMENT, IMPINGEMENT & ATTRACTION TO OUTFALLS

The design, installation and operation of fish screens and barriers can add significantly to the capital and operating costs of facilities. It is important for operators to recognise the potential impacts on fish and fish communities, which justify the costs of the required mitigation measures.

2.1 Entrainment & Impingement

2.1.1 Diadromous Fish

Diadromous fish are migratory species that move between the sea and freshwater, or vice versa. These may be subdivided as follows (McDowell, 1988):

- *Anadromous*: spending most of the life in the sea but moving into freshwater to spawn (e.g. salmonids, shads, smelt, lampreys);
- *Catadromous*: spending most of the life in freshwater but moving into the sea to spawn (e.g. eels);
- *Amphidromous*: marine or freshwater species which spend a significant proportion of their life in the other (freshwater or marine) phase but not for the purpose of spawning (e.g. bass, but also numerous marine species whose early juvenile life is spent above the salt wedge in estuaries, e.g. sole, *Solea vulgaris*, see Coggan and Dando, 1988).

These migratory species are notably at risk as they will often have to pass numerous water abstractions, as well as weirs and other hazards, on their journeys between rivers and the sea. It is owing to the compounding risk of these multiple hazards that migratory species were the first to be explicitly protected in law. Although this explicit protection did not extend to the non-salmonid species prior to the introduction of the Habitats Directive, the Environment Agency (and NRA previously) has used its powers under the Water Resources Act to place protective conditions on abstraction and impoundment licences and land drainage consents.

While it might be tempting to assume that the salmonids are adequately catered for within present fisheries law, there remain many unscreened intakes and outfalls on salmonid rivers throughout England and Wales. A number of reasons account for this:

- Most commonly, the intakes/outfalls were built prior to the introduction of the 1923 Act and were not required to be screened.
- In other cases, salmonids were not present in significant numbers at the time when the intake/outfall was constructed (usually as a result of industrialisation) but have recovered or been reintroduced in later years (e.g. rivers Thames and Trent and many rivers in Wales, the North-East and North-West).
- In the case of fish farms, legislation was introduced only with effect from 1st January 1999.
- Subject to the Environment Agency's SFFA s.14 Risk Assessment procedure, intakes/outfalls where the risk is evaluated to be negligible may, at the Agency's discretion, be exempted from fish screening.

- The operator may not be complying with the requirements of SFFA s.14 under Agency policy.
- Predecessor agencies may not have enforced their powers rigorously.

There is little quantitative information on the risk to salmonids from unscreened intakes. The cooling water intakes of estuarine power stations have often been deemed a likely threat to salmon and sea trout runs but this has not generally been borne out by survey data from English and Welsh stations. Solomon (1992) refers to catch rates of up to 10,000 smolts per annum at Uskmouth A & B stations (R. Usk estuary, S. Wales). Records kept by Uskmouth B Power Station from the 1960s until its initial closure in 1994, recorded an annual impingement rate of 189 smolts (range 22-493: Fawley Aquatic Research, unpublished data), suggesting that it was mainly the A station or the combination of the two that was responsible; by comparison, the wild smolt population in the R. Usk was estimated to have varied between 8.4×10^4 and 3.0×10^5 over the years 1962-1987 (Aprahamian and Jones, 1989), indicating a loss rate of around 0.1% for the B station alone. Fawley Power Station (Hampshire), which abstracts from the migration path into the R. Itchen and R. Test, caught an estimated 203 salmon smolts and 42 sea trout smolts during a survey conducted from March 1978-March 1979, and records for the newly constructed Shoreham Power Station (R. Adur estuary) during three years of post-commissioning trials (2001-3) show an average catch of 18 sea trout smolts per year (Fawley Aquatic Research, unpublished data). An earlier survey at Fawley conducted daily from February 1973 to January 1974 found no impinged salmon smolts and 41 sea trout smolts (Holmes, 1975). On river intakes, where migratory fish may be forced to pass closer to the entrances, significantly larger proportions could become entrained in the absence of any screening. Solomon (1992) refers to a count of 1059 smolts entrained at a Hampshire fish farm intake, which was estimated to be around 5% of the run at that point. A model of smolt entrainment relative to potable water abstraction on the R. Thames indicated that, in wet years, about <5% of the sixty-thousand salmon smolts stocked annually might be entrained into water supply intakes, and around 15% in years of moderate rainfall. During extreme drought, it was predicted that this figure could rise to ≥80% (Solomon, 1992). As a result of this, Thames Water Utilities voluntarily installed acoustic fish deterrents on all of their intakes during the mid-1990s.

For the other migratory species, losses for the most part are not well quantified. While eels and elvers have been recorded as entrained at many water intakes around the country, there has been no concerted effort to quantify the impact of entrainment on stocks at a regional or national level. With recent evidence of the sharp decline in eel stocks internationally, and the conservation focus on lampreys, this has now become a concern. Perhaps the most difficult issue with these species is the potential conflict with run-of-river hydroelectric schemes. Being fine-bodied in cross-section, individuals of much greater length than a salmon smolt can pass through a conventionally sized smolt screen and will have a higher risk than a smolt of being chopped by a rotating turbine runner. For example, a conventional ½ inch (12.5 mm) square-mesh smolt screen will stop smolts of ≥12 cm in length and eels of ≥36 cm in length (Turnpenny, 1981): passing through a turbine, the eel would be three times more likely to be struck by the turbine runner. These species also seem less amenable to behavioural guidance methods. This therefore represents one of the major fish screening challenges as we look increasingly towards renewable energy sources.

An indication of the potential for lamprey entrainment is given by the results of an entrainment survey conducted by the former National Rivers Authority (NRA) at

Yorkshire Water's Moor Monkton pumping station on the R. Ouse (Frear and Axford, 1991). Over a 15 month period between January 1990 and May 1991, over 16 thousand lampreys were impinged. Most were recently metamorphosed down-migrating river lampreys (known as 'transformers'), along with some brook lamprey transformers, averaging about 100mm in length. The entrainment rate was very sensitive to the proportion of river flow abstracted. This risk has now largely been eliminated through new fine-screening measures (see section 3.2.1).

The shad species, of which the twaite shad greatly outnumbers the allis shad, also represent a significant challenge. Unlike the salmonids, juveniles return to sea at the end of their first summer. At this stage they are typically around 6 cm in length, compared with 12-25 cm for a 1-2 year old smolt, and will not be excluded by a smolt mesh. They also possess loosely attached scales and are particularly sensitive to any form of mechanical contact. As they migrate seawards in shoals they can be entrained in considerable numbers during the autumn migration period. Records from the Hinkley Point A & B Power Stations (Somerset) between 1981 and 2001 show catches on the cooling water intake screens of up to 42 juvenile shad in a 6-hour sampling period (Fawley Aquatic Research Laboratories Ltd, unpublished). The highest estimated annual catch (in 1990) was 17,000 shad, mostly 0-group.

2.1.2 Freshwater Fish

Little information on the entrainment and impingement of non-migratory freshwater fish was available in this country before the 1990s, primarily owing to a lack of interest. It was feared from overseas studies that large quantities of coarse fish fry were likely to be entrained at freshwater intakes. Hadderingh (1982) had reported daily entrainment rates of up to 25 million coarse fish fry during the peak season (May) at a coal-fired power plant on Lake Bergum in Holland.

Solomon (1992) described work carried out by Thames Water at Walton-on-Thames water treatment works (WTW) in the late 1980s. The project was intended to look at smolt entrainment and coarse fish fry were not fully quantitatively sampled. Solomon estimated that for the 1989 season, the numbers of 0+ fry entrained (excluding pinhead fry) might lie somewhere between 8.7×10^5 and 2.9×10^6, with ~20,000 fish of age 1+ being entrained in the same year. Fry appeared in samples from the end of May onwards, at lengths of 23-30mm, the largest growing to about 70 mm by the end of the season. The pattern observed elsewhere in other European rivers (e.g. Pavlov, 1989) is that newly hatched pinhead fry first occupy sheltered areas on gravel beds or in vegetation at the margins of rivers. Soon, they inflate their swimbladders and become buoyant, allowing them to be carried and redistributed downstream by currents. It appears to be at this time that they become most vulnerable to entrainment. Peak catches are generally reported at night and during periods of high flow.

Other freshwater fish entrainment and impingement work has since been carried out at UK power stations, including Didcot (R. Thames) and Ratcliffe-on Soar (R. Trent) and at Farmoor WTW (R. Thames). The Ratcliffe work was reported in detail by Smith (1998). Smith recorded peak fry capture rates in June and July of 10 fry per hour in daylight, rising to a maximum night-time rate of 4,500 per hour. Annual fry entrainment rates at the plant of $3.45\text{-}7.98 \times 10^5$ were recorded between the years of 1994 and 1997 (Table 2.1). The dominant species were roach (*Rutilus rutilus*), bream (*Abramis brama*), bleak (*Alburnus alburnus*) and chub (*Leuciscus cephalus*). Smith used an Equivalent Adult (EA) procedure (Turnpenny, 1988; Turnpenny and Taylor, 2000; Turnpenny and

Coughlan, 2003) to estimate the implied loss to the adult stock. The EA is a useful means of representing losses of fish of mixed ages by computing survival trajectories through to a standard age (the nominal age at first sexual maturation) based on life history data; it should be noted that it does not take account of possible density dependent factors that may operate within the population dynamics of a species. Table 2.1 shows the entrainment losses also expressed in EA terms.

Table 2.1 Estimated entrainment rates of coarse fish fry at Ratcliffe-on-Soar Power Station (R. Trent) and their Equivalent Adult numbers (after Smith, 1998).

Year of Sampling	1994-5	1995-6	1996-7	Average
Numbers of fry entrained	798,000	345,000	729,000	624,000
Numbers of Equivalent Adults	3,940	1,460	1,480	2,290

Smith (1998) estimated the loss to represent 4.1% of the stock size within the impounded reach.

Entrainment on the upper R. Thames was examined by Turnpenny (1999) on behalf of the Environment Agency. A potable water intake located at Farmoor (near Oxford) was monitored continuously between the months of June to August 1998 following the installation of an acoustic fish deterrent (AFD) system. It was found to entrain few coarse fish fry compared with the Walton intake: only 246 fry were entrained over the whole period, of which 80% were perch (*Perca fluviatilis*). This marked contrast with the Walton situation was attributed to a number of factors:

- a cold spring in 1998 led to poor spawning success and surveys of the river in the locality of the WTW showed overall low densities of fry to be present;
- intake velocities at Farmoor are very low compared with Walton (approximately 0.08 ms^{-1}, *cf.* 0.71 ms^{-1} at Walton);
- the AFD system was operated on alternate days for the testing and fry entrainment was reduced by 87% on days when the AFD was active.

Another Thames study reported in Turnpenny (1999) was carried out as part of the National Power/ PowerGen Joint Environmental Programme in May-June 1992, when samples of water were tapped off from the cooling water system of Didcot Power Station. The water was passed through a plankton net, allowing very small fry to be retained. Ten species of coarse fish fry were captured, starting at a length range of 8-13 mm in late May and reaching 12-26 mm by July. This work suggests that the Walton study may have missed a significant proportion of smaller fry, which is not surprising given that the sampling was aimed primarily at salmonids. The true catch rates at Walton may therefore have been considerably higher than the findings given above would suggest. The entrainment rate at Didcot was estimated at 1.2 $x10^3$ fry per day over this period. This yielded an annual entrainment estimate of around 1.9×10^6 fry, in this case including pinheads. However, Smith (1998) considered this likely to be an overestimate, perhaps by as much as a factor of ten, as it assumed uniform entrainment over the season, whereas entrainment tends to be patchy with time and decline over the season as the fish grow and are more able to resist entrainment.

The overall purpose of Turnpenny's (1999) Thames study was to assess the potential impact of entrainment from water abstractions on adult fish populations in the lower freshwater Thames (Hurley to Teddington). Based mainly on the Walton data, an estimate was made of the potential loss of fish if all the abstractions within this reach were operated at their maximum licensed capacity. It was shown that, in Equivalent Adult terms, the numbers of fry entrained per annum could equate to around 45% of the adult stock. While continuous operation of all of the intakes at their licensed limit is never likely to happen, and the figures are known to be very imprecise, the findings confirm that it is an issue that cannot be ignored, there or in other heavily abstracted rivers.

Land drainage pumping schemes are susceptible to fish entrainment issues, particularly where accumulations of fish overwinter in unscreened intake chambers. Fisheries staff in the Anglian Region of the Environment Agency have on occasions been called out to fish rescue operations in which tens of thousands of juvenile coarse fish have been recovered.

From the information reviewed on freshwater fish entrainment, benthic species such as bullheads and loaches seldom occur in survey lists. Presumably their benthic habit ensures that they are out of the reach of most types of intake and so are protected from the risk of entrainment.

2.1.3 Estuarine & Marine Fish

The main abstractors from estuarine and coastal water are thermal power stations, so located principally to take advantage of the large volumes of cooling water available. Intake flow rates for directly cooled generating plants are usually between 0.5 to 5 x 10^3 megalitres per day (Turnpenny and Coughlan, 2003). Other estuarine and coastal cooling water users include refineries and shipping. Various port and harbour operations require pumping of water, for example emptying of dry docks and operation of shipping locks, all activities which may incur fish mortalities. In other countries, tidal power generation and desalination plants may be added to this list but, while planned for the UK, none are known to the authors to date.

Much research into the effects of power station water use was carried out by the Central Electricity Generating Board (CEGB) of England and Wales and its successors, mainly prior to the privatisation of the industry in the late 1980s. An up-to-date summary of their research into the ecological effects of cooling water abstraction is given by Turnpenny and Coughlan (2003). Table 2.2 summarises the quantities of fish impinged on the cooling water intake screens of various stations that were monitored from the 1970s onwards, revealing that quantities amounted to tens of tonnes per annum in some cases; in the case of the French station at Gravelines, hundreds of tonnes. It is notable that the highest flow-standardised catch rates mostly occur at stations sited on the open coast. The data shown are raw catches, not equivalent adult-adjusted figures, and do not include entrained[3] fish eggs and larvae. For most stations, entrainment data were not collected but some idea may be gained from very detailed studies that were undertaken at the Sizewell A and B power stations over more than a decade (Turnpenny and Taylor, 2000): here, equivalent adult values calculated for impinged-plus-entrained fish of commercial species were higher by a factor of 14 in 1981-2 surveys and by a factor of 21 in 1992. The commercial value of fish lost to impingement and entrainment (as adult

[3] The term 'entrainment' refers to fish (including eggs and larvae) being drawn into the plant, as opposed to those that become impinged on filter screens.

equivalents) at the Sizewell A+ B sites was estimated at £0.5 million per annum (1994 Lowestoft market prices). While these figures may be seen as significant, it was also shown that the catches were minor relative to wastage in the fishing industry, for example several orders of magnitude lower than bycatch mortalities in the Wash shrimp fishery.

Table 2.2 Estimated annual fish impingement catches at various UK and French power stations (after Turnpenny and Coughlan, 2003).

Power Station	Location	Total quantity of impinged fish (tonnes/yr)	Catch per unit of CW flow (kg/10^6 m^3)
Dungeness A	Open coast	93	190
Sizewell	Open coast	43	73
Gravelines	Open coast	240	48
Dungeness B	Open coast	20.6	40
Hinkley B	Estuary	24	31
Dunkirk	Estuary	13	19
Fawley	Estuary	6.4	19
Wylfa	Open coast	2.4	5
Kingsnorth	Estuary	6.6	4.4
Shoreham	Estuary	0.68	3.8

Although the power industry sought to put these catch figures into the perspective of other causes of fish mortality, the overriding aim of the industry has been to improve intake technologies so as to reduce catches. Considerable progress was made and continues to be made in this regard. This point is illustrated by the history of the Sizewell sites (Turnpenny and Taylor, 2000). Prior to the construction of the Sizewell B pressurised water reactor, local fishermen lodged objections to the new plant on the grounds that fish stocks might be adversely affected. The fish catches at the A-station were monitored and quantified (see below) and much work was done to improve the intake design to reduce the fish catch. Design changes included:

- reduction of intake velocities;
- fitting a velocity cap to the intake to eliminate vertical flow components (see section 3.4.7);
- elimination of any intake superstructure (which tend to act as artificial reefs that attract fish);
- location of the intakes further offshore where juvenile densities are lower;

- installation of a fish return system.

Fish return systems collect the fish backwashed from the screens and return them to the wild. They employ various 'fish-friendly' design features that reduce the handling damage to fish (see section 3.1.5).

Table 2.3 shows for the key commercial fish species the benefit of these improvements. It is seen that for flatfish and cod, catches are reduced by >90% relative to the A-station for a unit of flow. Herring benefited least, being too delicate to be handled safely by the fish return system.

Table 2.3 Catch of fish per unit of cooling water flow at Sizewell B Power Station relative to catches at the A-station which does not have the intake design improvements (after Turnpenny and Taylor, 2000).

Species	B-Station / A-Station Mortality Rate		
	Due to Intake Design & Location	Due to Fish Return System	All Measures
Plaice	54%	0%	0%
Sole	63%	4%	3%
Cod	100%	6%	6%
Dab	46%	20%	9%
Bass	91%	11%	10%
Whiting	79%	52%	41%
Herring	74%	100%	74%

At newer estuarine/coastal power stations, additional improvements have been introduced, principally in the form of acoustic fish deterrent (AFD) systems (see section 3.4.5). AFD systems are especially effective against delicate pelagic species such as herring, sprat, smelt and shads and therefore complement fish return technology. Shoreham Power Station (Sussex), commissioned in 1999, incorporates AFD and fish return techniques and, as is seen from Table 2.2, has exceptionally low fish catch. The same technology pairing has recently been introduced at the new Great Yarmouth Power Station (Norfolk) and at Fawley Power Station (Hampshire). This is further discussed in section 3.

2.1.4 Non-Indigenous Species

Pumping large volumes of water from one location to another potentially promotes the risk of spreading invasive, non-indigenous species around and between catchments. Zander (*Stizostedion lucioperca*) provide an example of this. Having been introduced into the Fens in East Anglia many years ago, they have progressively spread into the river and canal systems of the Midlands by various means. British Waterways, operators of the canal systems, are concerned to avoid exacerbating the spread of the species via any of their water transfer schemes. For example at Napton in Warwickshire, a pumping station was installed some years ago to recharge a flight of locks. This involves pumping water from the bottom of the flight to the top, which is located within an adjacent watershed. Following advice, the pump entrance was retrofitted with a two-tier bubble curtain system, designed to reduce the risk of zander eggs and fry present in the downstream catchment from entering the pumps. A similar approach used in the Eastern Block was reported by Pavlov (1989), where 80% deflection efficiency was achieved with a single-tier bubble curtain. Zander have subsequently been found in the adjacent catchment but, as with the spread of any alien species, this may have been from one of a number of causes, such as angling activity, aquaculture, transfer by birds, and so on. The level of impact arising from catchment transfers by water pumping is therefore impossible to quantify but prevention of cross-catchment contamination through use of positive exclusion screens with appropriately small apertures is to be recommended.

2.2 Effects of Outfalls

2.2.1 Attraction of Fish to Outfalls

Seasonal upstream migrations are undertaken by a wide variety of species, including the spawning runs of salmonids, shads, smelt, lampreys and many coarse fishes, as well as the migrations of elvers towards river and lake habitats. Rheotactic reactions render these lifestages vulnerable to attraction into outfalls from hydroelectric schemes, fish farms, industrial waste discharges or other sources. Not only is this a distraction, which can delay upstream progress, they may also risk injury by attempting to enter the discharges. Distraction can be a particular problem where a discharge occurs near to the bottom entrance of a fish pass, and care must be taken to ensure that the discharge reinforces, rather confuses, the attraction flow from the pass.

Solomon (1992) conducted a questionnaire survey among NRA Regional Fisheries Officers to investigate the size of this problem. Three out of ten of the former NRA regions reported a ‘significant’ problem and four others a ‘minor problem’. Solomon estimated that there were a ‘few tens’ of problem sites throughout England and Wales. Most of the problems related to adult salmon or sea trout entering discharges, e.g. through poorly maintained screens. Where this is notified to the Environment Agency, the fish can be rescued by electrofishing. At a fish farm on the Hampshire Avon, such a rescue operation for adult salmon revealed that many coarse fish had also entered the outfall.

Solomon (1992) explained the significance of the problem in terms of possible truncation of the spawning distribution, increased risk of illegal exploitation of trapped fish and restricted upstream angling opportunities. Adult fish frustrated in their attempt to ascend the river may also injure themselves when attempting to pass outfall screens where there is no alternative route available to them.

It is important that outfall screening remains effective even when the outfalls are not discharging. Otherwise, fish may enter them during quiet periods, subsequently risking becoming trapped or injured. Hydroelectric tailraces, which often operate intermittently, are prone to this problem. A run-of-river plant at Beeston on the River Trent, has electric outfall screens. When initially commissioned, the power to the screens was switched off when the plant shut down. After two large bream were found severed below the plant, probably as a result of collision with the runner blades, the operating regime was altered to keep the electric barrier continuously energised. Since that time no further problems have been reported (Fawley Aquatic Research, unpublished report).

There are similar, anecdotal reports of adult salmon mortalities at other British hydroelectric schemes where the velocity of flow exiting the turbine draft tube has been relied upon as an alternative to screening. It appears that actively migrating fish become attracted to the residual flow emanating from the draft tube when the turbine is not running. At start-up, they then become at risk of blade strike from the turbine.

2.2.2 Losses from Fish Farms and Reservoirs

Amendments under the Environment Act 1995 to *s*.14 of SFFA 1975 were partly in recognition of the potential environmental impacts caused by losses from fish farms and stocked reservoirs when inadequate outfall screening allows fish to escape. Losses may be of indigenous species of different genetic origin than the native river stock, but often involve non-indigenous fish such as rainbow trout (*Oncorhynchus mykiss*). Problems most often occur during flood events when reservoirs overtop unscreened spillways or when fish farm outlet screens are damaged or not set sufficiently high to cope with flood water levels. Fish stocks in the rivers Exe in Devon or Test in Hampshire, and others that support large numbers of fish farms, are heavily contaminated by rainbow trout, to the potential detriment of native species.

3 REVIEW OF SCREENING & DOWNSTREAM GUIDANCE TECHNOLOGIES

This section presents a review of the wide range of technologies that are in common use for fish screening. Where experience allows, best practice is identified. Later sections discuss where the different techniques may be of benefit. More promising ‘cutting-edge’ techniques are also described, some of which are still under development or may require further evaluation.

3.1 Positive Exclusion Screening Methods for Salmonids and Larger Fish

3.1.1 Traditional Passive Mesh Screens

Static screens constructed of mesh are presently by far the most common method of fish exclusion. A standard smolt-screening arrangement, as found at many hydroelectric stations, as well as drinking water and industrial water supply intakes, uses flat panels of mesh, fixed to a stiffening frame (Plates 3.1 & 3.2) (Aitken *et al*., 1966). One or more such panels are inserted into vertical slots in a fixed supporting structure, which may have an overhead walkway and lifting gear to facilitate removal and replacement of individual panels for cleaning and maintenance. Alternatively, the panels can be made to pivot, so that debris can be back-washed off by the water flow, but this may lead to a risk of fish passing through while the screens are being turned and is therefore not ideal. Suitable systems can be designed for any size and most configurations of intake. Ideally, the screen should be aligned flush with the riverbank, or else at an angle to the flow to assist in guiding fish towards a bywash positioned at the downstream end of the screen. The angle is calculated such that the flow vector normal to the screen face is below the required escape velocity for the target fish species and sizes (see Section 4). The size of individual panels used is determined by the overall screening area and by practical considerations of handling.

Plate 3.1 Fixed panel screen installed on the R. Afan, Port Talbot in 2003, to prevent salmonid smolts from entering the docks feeder.

The mesh can be made from one of a number of materials, including plastics but stainless steel is the norm. The ease of cleaning and extended life expectancy outweigh the initially higher capital costs. Weldmesh is easier to clean and cheaper to produce than e.g. a woven mesh. Plastic meshes, used on the band- or drum-screens of some continental power stations, are probably not sufficiently robust for use in open water. Stainless-steel wedge-wire is very effective, particularly where it is required to exclude juvenile fish also (see section 3.2.2). The amount of debris reaching the fish screen may be lessened by placing a coarser trash rack in front of it, without affecting fish passage. In this case a bywash entrance must also be provided upstream of the trash rack as well as by the smolt screen, so that larger fish (e.g. kelts) can bypass the structure. An example of this is found at Scottish Hydroelectric's Dunalastair Dam (see Aitken *et al.,* 1966). Alternatively, a larger bar spacing can be used (e.g. 15 cm) or gaps can be left at intervals to allow larger fish to pass.

Plate 3.2 Fixed panel screen installed on the R. Plym, Devon in 2003, protecting the entrance to an industrial supply offtake.

Selection of a suitable mesh aperture for a standard square mesh screen design is discussed in section 5.7.

3.1.1.1 Design Best Practice for Panel Screens

The main design requirements are as follows:

1. the mesh size should be selected to ensure exclusion of the minimum target fish size based on preventing penetration of the fish's head (see equation 1);
2. the screen should be flush with the riverbank for a lateral river intake or, when placed across a channel, angled (in plan view) relative to the channel to guide fish into a bywash;

3 a suitable bywash should be provided where the screen is placed across the channel;

4 the velocities ahead of the screen should be low enough to allow fish to escape without injury.

For shallow water applications (typically <1 m), it may be practicable to operate fixed screens with manual raking or brushing. For deeper water designs, screens will need to be removable for cleaning. For this purpose they are normally dropped into vertical slots from which they can be hoisted out for cleaning. In this case best practice will also include:

- provision of two sets of slots, one behind the other, allowing a cleaned screen to be inserted before the soiled screen is removed;
- provision of adequate seals around the screen to prevent fish passage or injury;
- provision of a datum mark on the screen which aligns with a mark on the slot rails to show when the screen is fully seated and sealed.

3.1.1.2 Applications

Passive mesh panel screens are suitable for a wide range of applications provided that the above criteria are met. Limiting factors may include required frequency of cleaning in order to avoid risk of blockage, structural strength in relation to flood damage risk and hydraulic head loss where small mesh sizes are used. These factors tend to become more significant with larger abstraction flows. Factors favouring this type of screen include no necessity for electrical power and relatively low capital cost, especially on small installations.

3.1.1.3 Fish Species/Life Stages

Suitable for all fish species and life stages, subject to meeting design requirements 1-4 above.

3.1.1.4 Ease of retrofitting

Retrofitting of this type of screen is possible but depends largely on site characteristics. A common problem with retrofitting fixed fish screens as a replacement for simple trash racks is that water velocities may be too high. In this case it may be necessary to widen or deepen the intake.

3.1.2 Vertical or Inclined Bar Racks

Vertical or inclined bar screens have in the past been used mainly as trash racks for debris exclusion; many are fitted with moveable tines or raking systems that keep the screens clear of rubbish. Back- and front-raked systems are available, but the former necessarily lack horizontal braces and are not recommended for closely-spaced bars. Conventional trash rack spacings may be anywhere between 38 mm and 150 mm, depending on the application. Inclining the bars by 10^{o} to the vertical assists in maintaining the weight of the rake against the bars. Mild steel (with or without galvanization) is commonly used as the construction material, or stainless steel. One north-American manufacturer[4] offers robust plastic trash racks.

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[4] (Structure Guard Inc., Maine, USA www.structureguard.com)

Currently there is interest in replacing two-tier systems comprising trash racks followed by mesh fish screens with a single-tier bar rack using a smaller bar spacing that can act as a fish screen. This provides a self-cleaning alternative to the traditional manually cleaned mesh panel screen described above. Scottish and Southern Energy plc (SSE) have been investigating this approach for a number of years. Clough *et al.* (2000 unpublished) undertook controlled trials in a test flume constructed within a large fish pass at Gaur (R. Tummel system), in which hatchery smolts were released upstream of test bar racks of 10 mm or 12.5 mm spacings. The aim was to assess whether the risk to fish was any different when compared with a regular 12.5 x 25 mm steel mesh screen. The screens were presented either at 75^{o} or parallel to the flow and provided with an adjacent bywash at approach velocities of up to 0.4 ms^{-1}; bywash entrance velocities were 1.5 times the approach velocity. Fish reactions were observed by video camera, using infra-red lighting at night. It was concluded that:

- there was no evidence that 10 or 12.5 mm spaced bar screens were any more likely to impinge smolts than the 12.5 x 25 mm mesh traditionally used: no fish were impinged on either type during the tests;
- smolt behaviour was similar for both screen types, irrespective of screen alignment and whether light or dark, at all velocities tested.

Plate 3.3 Experimental apparatus used in bar rack trials at Gaur (Clough *et*. 2000).

In 2001, SSE installed vertical bar screens at a small hydroelectric intake. Bars were spaced at 12 mm and cleaned automatically by a raking machine once a specified pressure differential was measured across the screen. This has performed satisfactorily, except under extreme flow conditions when the raking system has been hampered by gravel shoals accumulating at the base of the screens (Dr Alasdair Stephen, SSE, personal communication. SSE plans to install a raked bar screen for smolt exclusion on one of its larger schemes in 2004.

Other UK examples of automatically raked bar screens designed specifically for fish exclusion include a pair of screens with 10 mm spacings located at a small (2 m^3s^{-1}) hydroelectric intake at Dolanog on the R. Vyrnwy in Wales, and a larger 15 m^3s^{-1} capacity smolt screen at Innogy Hydro's recently refurbished Stanley Mills plant on the R. Tay (Perthshire). The Dolanog screens (New Mills Hydro Ltd) have individual hydraulically powered rakes; the river does not contain migratory fish at the abstraction and the screens are aimed primarily at excluding brown trout. The Stanley screen is a large angled bar rack, some 33 m long and 2.4 m deep, with a single travelling rake supported on an overhead rail. It was installed in 2003 and is intended primarily to protect the Tay salmon run.

3.1.2.1 Design Best Practice

The main design requirements are as for mesh screens, but in this case the bar spacing should be set to prevent the penetration of the fish's head. It should be noted that equation 1 is based on penetration of a square or rectangular opening and may not be accurate for calculating bar spacing. Rectangular section bars or perforated plates are preferable to round-section bars, which are prone to 'gill' fish.

While conventional design practice demands that bar spacing should be calculated in this way for the target fish, smaller fish will not necessarily pass through screens that have spacings exceeding the fish's body width. Travade and Larinier (2001), who investigated a bywash adjacent to a 25-mm-spaced vertical bar screen at St Cricq hydroelectric plant in France, estimated that >90% of salmonid smolts were successfully diverted into the bywash even though they were small enough to pass through the screen. The screen in this case was aligned perpendicular to the flow, which is not recommended in practice, but the width of the channel was small (11m) so that fish readily found the outlet.

Angled bar racks are used quite widely on small hydroelectric plants in north America but Simmons (2000) noted that their performance has rarely been examined. He reported a study of the bypass efficiency of an angled bar rack at the Lower Saranac Hydroelectric Project at Plattsburgh New York, which also used 25 mm spacings. In this case the rack was aligned at 45^{o} to the flow (in plan). In an experiment in which 52 Atlantic salmon smolts were released upstream, 29 passed the Project; none passed through the trash rack. Of 23 steelhead trout (*Oncorhynchus mykiss*) passing the Project in a similar experiment, 3 (13%) passed through the trash racks. These results were obtained under the optimal conditions tested, in which high bywash entrance velocities were maintained ($\geq$1 ms^{-1}, *cf.* velocity perpendicular to the screens of $\leq$0.6 ms^{-1}). Both this and the French study mentioned above emphasise the importance of good hydraulics and bywash attraction flow in achieving high bypass efficiencies with over-spaced bar screens. These aspects are discussed further in Section 4. Where over-spaced racks are used, observational trials will be needed to check efficiency.

Solomon (1991) referred to the possible 'louvre-screen' effect of trash racks placed tangential to the main channel flow; the implication of this is that vortices generated by flow hitting the bars will act as a deterrent to fish. Unfortunately, this is not consistent with this author's (AWHT) observations of flow at tangential trash racks, where the dominant flow at the trash rack face during periods of abstraction tends to be near-parallel to the bars.

Additional points in bar rack design are:

- inclining the screen by 10^o to the vertical facilitates raking;
- the bars need to be sufficiently stiff to maintain the design spacing throughout the screen; this may require horizontal tie-bars to be fixed across the back of the screen;
- manual raking of bar screens is probably only safe and practicable in water depths of <1.0-1.2 m

3.1.2.2 Applications

Vertical bar racks can be considered a suitable alternative for most applications that would otherwise use mesh screens.

3.1.2.3 Fish Species/Life Stages

Vertical bar racks are potentially suitable for screening most fish, subject to the bar spacing being small enough to exclude them. At present the UK user base for this type of screen is quite restricted and therefore there has been little feedback on the relative performance with different species. It could be expected that eels and other anguilliform species would tend to get trapped lengthwise between the bars but this is purely speculative. There is evidence also that eels, when confronted with a bar screen, try to force their way through, rather swimming along the face of them (Richkus, 2001).

3.1.2.4 Ease of retrofitting

Retrofitting issues are similar to those for fixed panel screens.

3.1.3 Rotary Disc Screens

3.1.3.1 Description of Screens

Rotary disc screens were originally designed for the use in sewage treatment works but may also be applied to intake screening. They are based on a series of plastic, stainless steel or high impact glass-reinforced polypropylene discs stacked in a column with spacing between the discs suitable for its specific usage, such as preventing the entrainment of fish or other debris. The discs within each column rotate in the same direction with adjacent columns interleaving. The discs are driven via motors with the direction of rotation matching that of the direction of water flow. Debris and fish will be passed from one column to another until carried away by the flow. There is also a possibility that vibration of the discs may discourage fish to enter the area but this has not been investigated (Turnpenny, 1998).

Within the UK Mono Pumps Limited[5] produce Discreens™ with apertures of 2.5, 5, 9, 13 and 18mm. They have a capacity range of 0-3.7m^3s^{-1} in depth ranges of 200 to 1750 mm. The screens are fitted with comb bars to eject screened solids back into the main flow.

There have been numerous rotary disc screen installations throughout the UK over the past decade with only one or two being used for fish intake screening applications,

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[5] Mono Pumps Ltd. – Martin Street, Audenshaw, Manchester, M34 5JA (0161 339 9000).

www.mono-pumps.com

others being mainly in water and sewage treatment applications. One at Testwood raw water intake, Hampshire (Mr R. Edbury and Mr M. Bridges, Southern Water Services Ltd, personal communication) comprises four disc columns per screen unit. The units are approximately 1 x 1.2m in area and have a handling flow rate of 40MLd^{-1} (0.46 m^{3}s^{-1}) with an approach velocity of 0.35 m.s^{-1}. The screens were designed to prevent the entrainment of smolts and have a gap size of 9mm. The installation was completed in 1997 at a cost of £200k; the installation still consists of the same number of units although one has been rebuilt during this time. The power consumption is fairly low at 4.4 kW resulting in relatively low operating costs. The screens have experienced some problems with weed becoming wrapped around the spindles of the disc, which has resulted in the need for periodic removal and refurbishment of the screens.

An upgrade at the Knapp Mill WTW by Bournemouth and West Hampshire Water resulted in the update of the existing drum screens with six Mono L series Discreens. The Discreens are designed to prevent entrainment of both debris and aquatic wildlife. Four fourteen shaft screens were placed on the lagoon intake and two ten shaft screens on the upper intake. The screens have a handling flow of 0.76 m^{3}s^{-1} and a power consumption of 3.7 and 4.4 kW. The screen is believed to benefit from self-cleaning abilities.

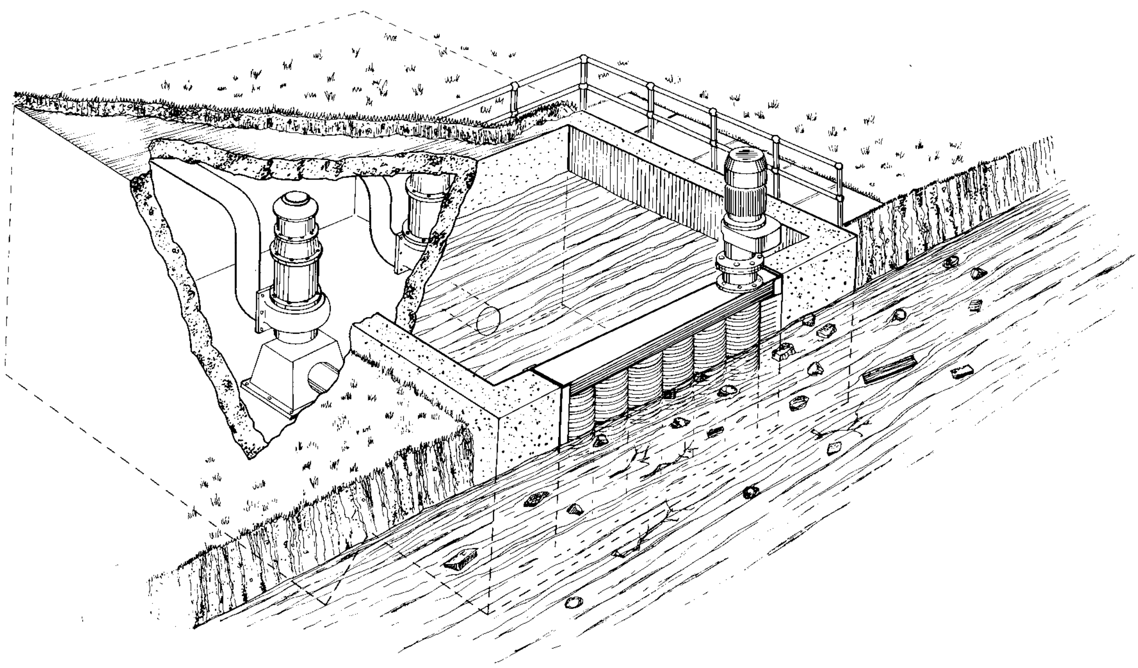

Figure 3.2 Schematic of Rotary Disc Screen

3.1.3.2 Design Best Practice

For any single unit there is a maximum screen depth of 1m. This can be overcome for greater depths via stacking units in a stepped format.

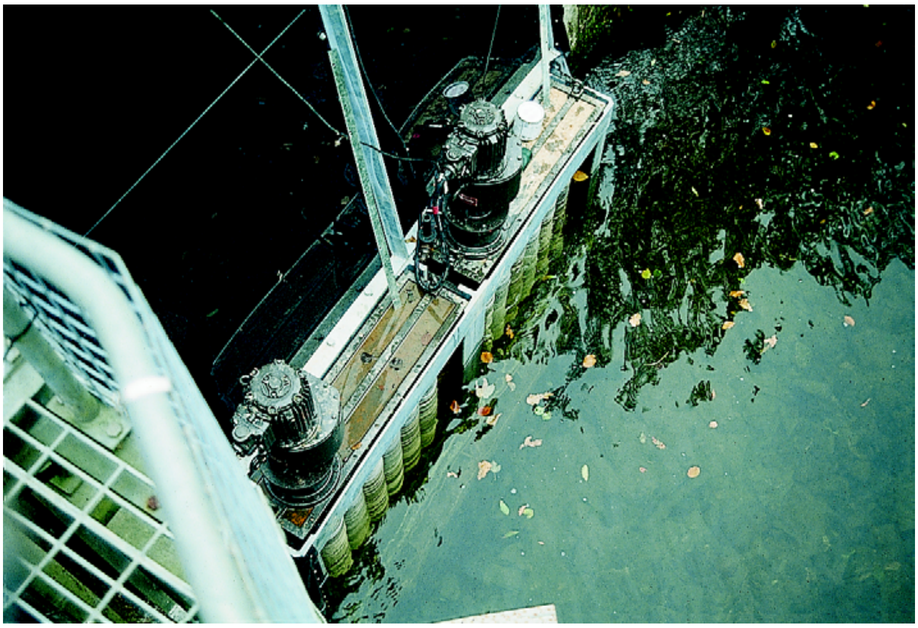

Plate 3.4 Rotary Disk Screen at Testwood Raw Water Intake, R. Test, Hants

3.1.3.3 Applications

The screen is suitable primarily for the screening of smolts and larger fish on rivers with a strong sweeping flow. High leaf and filamentous/stranded weed loads may cause problems. This screen is not economical for large intakes owing to the high surface area required to achieve low approach velocities, and consequent high costs.

3.1.3.4 Fish species/life stages

Depending on the spacing between discs this screen should be suitable for screening salmonid smolts and adults of most species.

3.1.3.5 Ease of Retrofitting

The main attraction of the rotary disc screen is that it is compact and a relatively straightforward retrofit option. It may, as at Testwood, be suitable as a direct replacement for trash racks, provided that these are flush with the riverbank or projecting out into the flow. It can also serve as a replacement for drum screens as at the Knapp Mill WTW. Approach velocities need to be set according to the species and sizes of fish involved.

3.1.4 Spillway Screens

The principle of a spillway screen is that a grid of some sort replaces part of the downstream face of a weir and water falling through the grid enters a channel beneath, from which it is conveyed to the turbine or other application. Meanwhile, fish and debris larger than the screen openings are flushed by surplus flow across the surface of the grid to the downstream side of the weir (Turnpenny, 1998).

3.1.4.1 Coanda Screen

The Coanda screen is based on the 'Coanda-effect', the principle of how fluids follow a surface, a phenomenon first identified by Henri-Marie Coanda in 1910. In this case the surface is that of a wedge-wire screen with the bars running from side to side across the width of the weir (Figure 3.3, Plates 3.4, 3.5). Water then follows the surface of the V-profile wires and runs into the collecting chamber (penstock) below. The wedge-wire screen is contoured to form an ogee-shape curved to a 3m radius. A curved 'acceleration plate' is positioned at the top to stabilize and accelerate the flow. The spacing between the wedge-wire bars is designed to be small enough to exclude all fish including young fry. Depending on the spacing of bars the screen can also be used to exclude silts, sand and gravel (Turnpenny, 1998).

The Coanda screen has been used mainly for small, upland hydro intakes but there is no reason why it should not be used in other applications where the topography is suitable. Within the UK Coanda screens are sold and installed by Dulas Hydro Limited[6] and are manufactured by Optima International[7], Doncaster. The screen is available in a range of designs for varying installation sizes:

Screen A: A full height screen with removable screen material – suitable for flows from 210 $l.s^{-1}$ upward in 70 $l.s^{-1}$ steps.

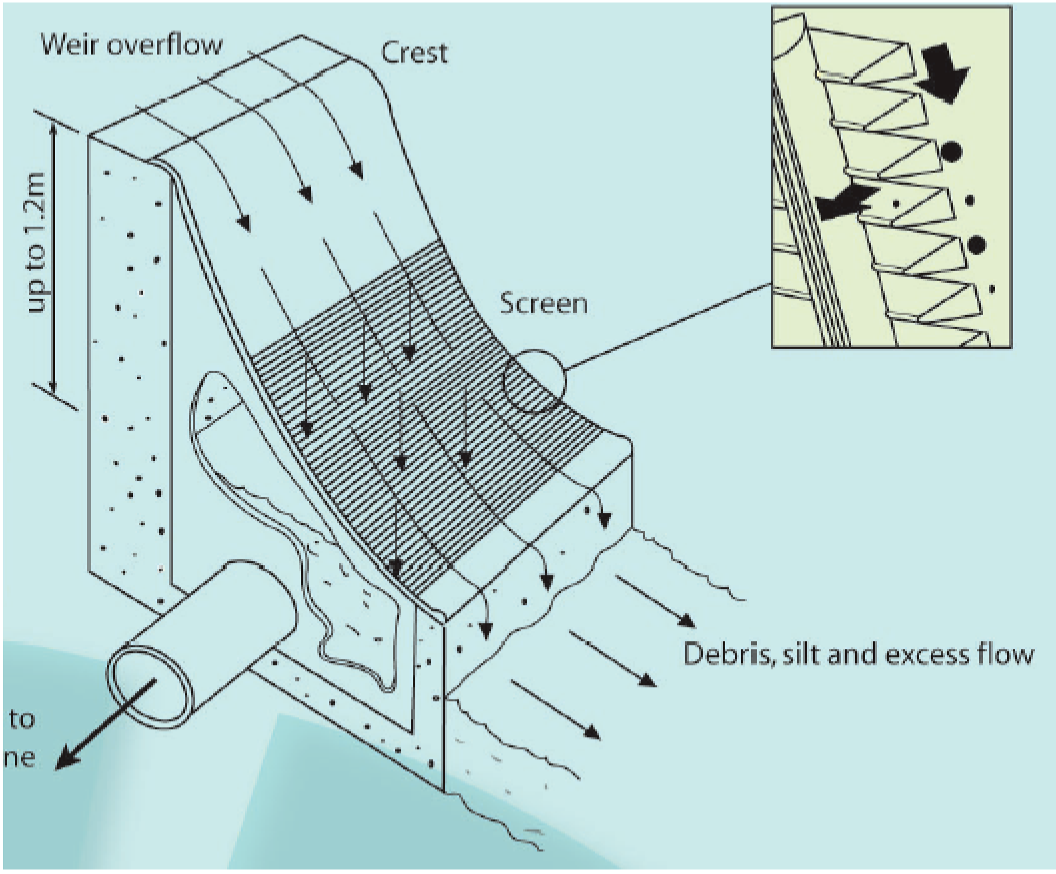

Figure 3.3 Diagram of an Aquashear™ Coanda screen, showing detail of the V-profile of the wedge-wire (Dulas)

[6] Dulas Hydro Ltd. – Dyfi Eco Parc, Machynlleth, Powys, Wales, SY20 8AX.

[7] Optima International – www.optima-international.co.uk.

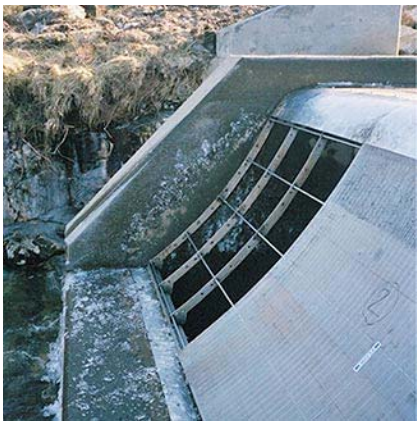

Plate 3.5 Example of a Screen A Coanda installation (Dulas Hydro)

Screen B: A full height one piece small screen – suitable for flows of 80, 100, 120, 140 and 160 ls^{-1}.

Screen C: A half height full width one piece screen – suitable for flows from $100ls^{-1}$ upwards in steps of 50 ls^{-1}.

Screen D: A half height, one-piece small screen:- suitable for flows of 20, 30, 40, 50 and 60 ls^{-1}.

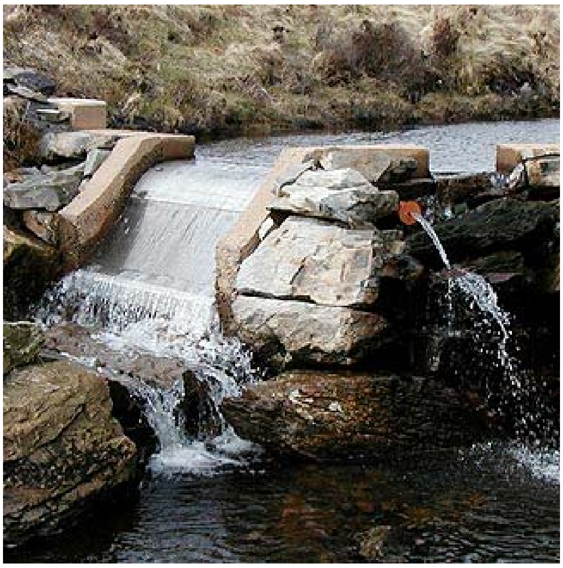

Plate 3.6 Example of a Screen B Coanda installation (Dulas Hydro)

Full height screens have a head loss of 1,270 mm and half height screens have a 705mm head loss. Thus there must be a minimum of 705 mm sacrificable head loss available before a Coanda screen can be used. The maximum flow of the screens is dependent on the weir width. A full-height screen has a capacity of 140 ls^{-1} per metre width, therefore 1 m^3 flow would require a weir just over 7 m in length.

The recommended screen materials are 304 stainless steel in freshwater, or 316 grade for marine environments. The acceleration plate is a circular arc similar to a parabolic 'ogee' shape, which matches the path of an unsupported jet of water. The plate acts to speed up the water, helping the shearing effect, which improves abstraction efficiency.

Coanda screens are designed to be low maintenance although during low flows some debris build up may occur, which will be washed off in subsequent high flow periods. Brushing with a stiff broom clears the majority of any remaining debris. Most screens require periodic visual checks and brushing approximately quarterly.

There was a reported total of 22 Coanda screen installations within the UK by 2003. Most are at small-scale private hydropower installations with capacities ranging from 10 to 1,300 ls^{-1}. One of the larger installations was commissioned by Innogy Hydro south west of Fort Augustus in the Scottish Highlands. The screen is a full height design with a flow capacity of 1300 $l.s^{-1}$. Although there were initially some concerns over fouling by algae it has been found that the screen self-cleans during periods of high flow and the overall opinion of the screen at this location is good (personal communication W. Langley).

The effectiveness, suitability and cost benefit of the screen was evaluated at a small hydropower scheme near Keswick in Cumbria (Howarth, 2001). A screen with 1mm bar spacings was commissioned in April 1999. It was capable of excluding all debris greater than 1mm and 90% of particles >0.5mm. Performance evaluation was carried out over a 15 month period with monitoring of screen capacity, silt exclusion performance, self cleaning operation, slime and algae growth, operation and maintenance requirements, integrity and resistance to damage and cost benefit analysis. After the 15-month period there were no noticeable signs of wear and at high flows up to 94% of suspended silt particles between 0.41 and 1.17mm. There had been no records of blockages by debris although it was believed that very thin strands of weed may pass through the wedge-wires. After the 15 months, a thin film of algae had developed over the screen, resulting in some loss of capacity, although it was readily cleaned with a stiff brush. Overall the screen was found to be consistently robust, resistant and has a high performance rating.

Fish Protection Performance

No assessment of fish exclusion efficiency or fish condition after passing the screen was undertaken in the Keswick study. Elsewhere, Bestgen (2000) reported tests carried out at the Colorado State University Larval Fish Laboratory on the exclusion and survival rates of fathead minnow passing over a Coanda screen. Out of 150 trials releasing and recapturing fish downstream of five different lengths (5, 7.5, 12.5, 22.5 and 45mm) an exclusion rate of “nearly 100%” was obtained for fish greater than 12.5mm.

3.1.4.2 The ‘Smolt Safe™’ Screen

The Smolt Safe™ screen (Figure 3.4) is manufactured by Rivertec of East Sussex. The principle is broadly similar to that of the Coanda-effect screen. In the configuration shown, the weir is constructed flush with the bank of the river and water is carried off sideways from below the screen. Water falling through the screen is collected in a take-off channel, while a further debris channel is provided to carry fish and trash back to the river. There is no reason, however, why the screen should not be constructed as part of a transverse weir, as in the Coanda-effect example.

The example shown in Figure 3.4 was constructed at a distillery where there is a large amount of waterborne debris. Screen mesh size in the example is 10 mm, but this can be varied as required. The manufacturers claim the screen to be 100% safe for passage of smolts and other fish but this has not been verified by trials. A similar screen built at Heltondale in Cumbria has been found not to be suitable for screening pre-smolts (G. Armstrong, personal communication. The problem was due to fish becoming trapped among debris at times when there was insufficient washover flow. Potentially, this can be overcome by blanking off part of the screen at low flows but the degree of washover is difficult to control with variable river flows, particularly at remote sites. The fact that the screen is flat rather than inclined (as e.g. in the Coanda screen) does not help debris clearance.

As for the Coanda-effect screen, there are constraints on operation. The manufacturers specify an operating flow range of 0.5 to 5 m^3s^{-1}. However, there seems no reason in principle why larger flows should not be accommodated, given suitable space and arrangement of the civil works. A second constraint is that at least 25% of flow is required for washover. Thus, for a 5 m^3s^{-1} draw-off, at least 6.25 m^3s^{-1} initial river flow would be required.

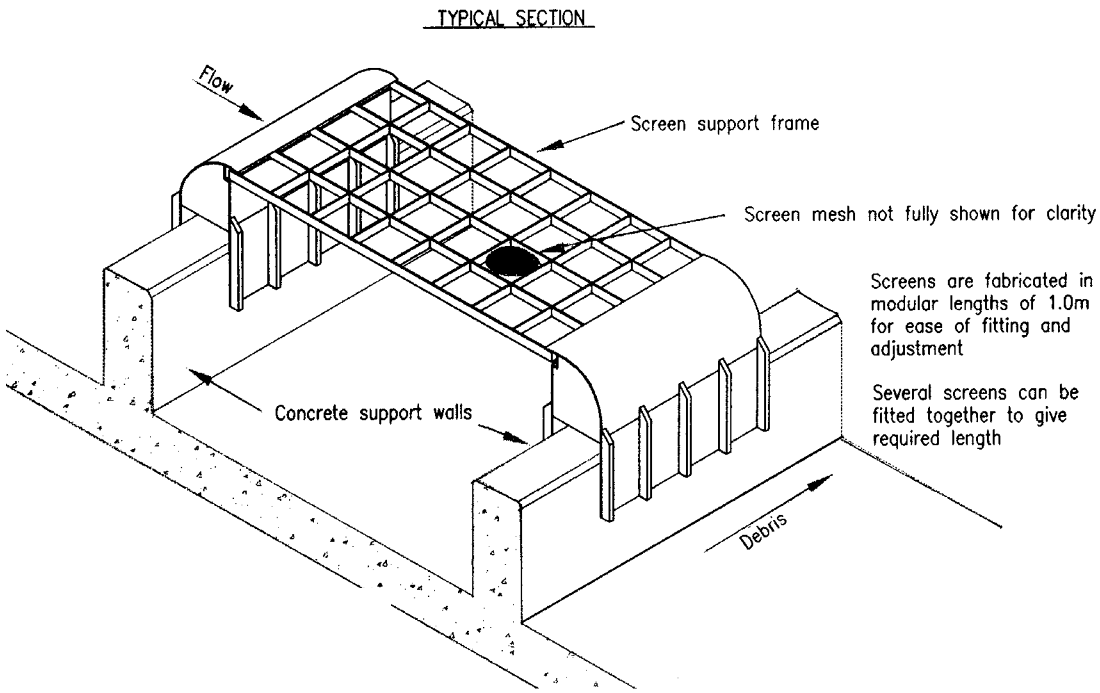

Figure 3.4 The Smolt Safe™ Screen (Rivertec Ltd)

3.1.4.3 Design Best Practice

For spillway screens, the manufacturers recommendations must at present be regarded as best practice. An important consideration is the relationship between abstracted flow rate and the surplus washover flow. If the screen is over-sized, then there may be a risk of not leaving sufficient ecological flow in the river downstream of the offtake and of there not being sufficient surplus flow to flush fish and debris safely off the screen in the downstream direction. It may be necessary to provide a means of blanking off part of the filtration area during dry weather flows. This problem is likely to be greater on flashy upland streams than e.g. in chalk streams having a stable flow regime.

Debris should not be allowed to accumulate on the screen owing to the risk of causing fish injuries.

3.1.4.4 Applications

In the UK, Coanda screens have chiefly been used at medium to high head hydropower screens in upland areas. However, there is no obvious reason why either Coanda or

Smolt Safe screens should not be used for other types of application where sufficient head of water exists, e.g. fish farms located on upland rivers.

3.1.4.5 Fish Species/Life Stages

Although used in this country mainly for trout and salmon exclusion, spillway screens would be equally suitable for exclusion of eels, lampreys and other upland river species. The sizes of fish excluded would depend on the wire spacings but, for example, a ≤3mm spacing should be suitable for salmonid fry exclusion.

3.1.4.6 Ease of Retrofitting

Coanda or Smolt-safe™ screens are likely to be suitable mainly for new-build applications or replacement of existing spillway screens.

3.1.5 Band or Drum Screens Modified for Fish Return

Many power stations intakes and potable water abstractions are fitted with mobile band screens or drum screens for debris filtration. These are usually set somewhere within the pumphouse and not at the intake point. Fish-handling modifications have been developed for both types which can reduce the risk of injury, at least to the more robust species. The modifications relate chiefly to the design of the ledges or ‘buckets’ which are used to lift fish and debris out of the water, and to reduced-pressure backwash sprays that are used to flush material off the screens and out of the buckets. Thereafter, instead of discharging the filtered material into trash baskets for disposal, a return gully or pipeline puts them back into the water body. Such a system is commonly known as a ‘fish return’ or ‘fish rescue’ system.

Fish return systems have been used at power stations in the UK for many years. The earliest ones were constructed at CEGB estuarine sites in the 1960s for the return of salmon *(Salmo salar)* and sea trout (S. *trutta)* smolts (e.g., Uskmouth and Oldbury-on-Severn power stations) but for various reasons these were never fully utilised or evaluated. A number of other stations (e.g. Dungeness 'B', Sizewell 'A') have operated simple trash return systems which involve periodic discharge to the sea of the biological and other debris that has accumulated in trash baskets, with no deliberate attempt to promote the survival of living organisms; in fact, the system at Sizewell ‘A’ macerates the debris prior to discharge. Sizewell 'B' power station incorporate a facility to direct trash either to baskets or into the CW discharge, along with a number of other engineering measures to reduce stress effects on fish. The Sizewell ‘B’ system is licensed to operate in fish-return mode, provided that quantities of fish are below a certain level, otherwise fish must be collected in trash baskets to avoid possible wash-up of dead fish (notably sprats) on beaches. Barking Power Station (Thames Estuary) has a fish recovery system based on modified band screens, which returns fish to the estuary via the cooling water outlet.

Fish return is practiced widely overseas. In the United States, the prospect of compensation being levied against fish losses and the requirement under Section 316(b) of the Federal Water Pollution Control Act to implement effective environmental protection systems has encouraged the development of fish return systems. In Europe, the French power industry, as part of its nuclear expansion during the '70s and '80s, investigated a wide range of fish protection systems and has implemented a fish and shrimp recovery system on at least one estuarine site, Le Blayais, on the Gironde (Travade *et al.,* 1983). A new power station at Doel in Belgium is also being fitted with a fish return system, following the demonstration of good fish and shrimp survival rates on the bandscreens (Maes *et al*., 1999).

Plate 3.7 Fish Return System at barking Power Station, Thames Tideway. Insert shows screen panel with fish buckets inverted.

3.1.5.1 Operating Principles of a Fish Return System

The main changes to a standard band or drum screen are to add water-containing scoops or 'fish buckets' at the bottom of each mesh panel, and to use a low-pressure (≤1 bar) backwash spray to flush fish off into the return gullies. A high-pressure spray (≥3 bar) can be deployed at a later point in the cycle to remove the more persistent debris. Rotation speed is also an important factor. Where fish are not a concern, bandscreens are rotated intermittently, either at preset time intervals or when sufficient material has accumulated to cause a head differential across the screen mesh; this save on bearing wear. With such an arrangement, fish may become impinged on the screens for hours before being lifted out by the screens, and may become asphyxiated or exhausted. During rotation, conventional bandscreens operate at one of two speeds, the low-speed setting being used for normal levels of trashing, switching into the faster setting when inundated with trash. To optimise fish survival, the screens are rotated continuously, switching to the higher speed setting if a head loss develops (usually >100 mm) across the screens.

After being washed off the screens by the low-pressure spray jets, the fish and other organisms are flushed into open troughs, and from there to a discharge pipeline that returns them to the water. Handling stress is minimised in these stages through careful design and construction of the gulleys and pipes, ensuring that tight bends are avoided and that smooth surfaces are provided. Swept bends are used throughout with either stainless steel, fibre-glass or PVC materials, with joints ground smooth. The recommended radius for swept bends is 3 m when a trough or pipe diameter of ≤0.3 m is used (Turnpenny *et al*., 1998), although space constraints do not always allow this. Where smaller-radius bends are used, fish tend to find shelter and epibenthic species in particular may accumulate; also, tight bends are susceptible to blockage, hence access for cleaning is required. Where larger pipe or trough diameters are used (≥0.4 m), the bend radius may be reduced to ≥1.5 times the pipe diameter, as there will be less risk of blockage. The chief requirements are that blockage and hold-up of debris should be avoided and that access for maintenance should be provided in case of blockage. The screen wash pumps supply flow for the backwash sprays to ensure that the fish are kept moving through the system and to reduce the risk of blockage.

The use of chlorine or other biocides can, potentially, reduce survival in fish return systems. Fortunately, in the UK, typically 80% of the annual fish take occurs outside the season (approximately May–September, or when water temperature is >9^{o}C) when biocides are applied. The toxicity of chlorine, the most common biocide used at power stations, depends on the concentration and the exposure time. For biofouling control purposes, chlorine is normally injected in the intake at around 1 mgL^{-1}, decaying to about 0.2 mgL^{-1} at the CW pumps. The exposure time in the intake forebay and screenwell can be kept to an hour or less in a purpose-built system. The toxic risk is generally low under these conditions. However, unless a detailed analysis of the toxic risk can be undertaken, taking into account the local water quality conditions, mixing dynamics and species and life-stages exposed, it is preferable to ensure that chlorine is injected downstream of the screens.

3.1.5.2 Fish Protection Performance

The survival rates of the returned fish can depend on a number of design and operational factors. Design variations revolve mainly around the shape and construction material of the fish buckets and the backwash arrangements. Older designs often had incorrect bucket geometry, so that fish fell back into the water and were recycled several times or were not washed out from the optimum point of the cycle. Table 3.1 shows the typical survival rates measured at older fish return systems, ranging from >80% for robust epibenthic species to virtually nil for delicate pelagics.

Table 3.1 Typical fish survival reported from studies of drum-or bandscreens with simple modifications for fish return (e.g. with fish buckets, low-pressure sprays and continuous screen rotation) (Turnpenny, unpublished data).

Fish Group	Survival Rate >48 h After Impingement
PELAGIC	
e.g. herring, sprat, smelt	<10%
DEMERSAL	
e.g. cod, whiting, gurnards, etc	50-80%
EPIBENTHIC	
e.g. flatfish, gobies, rocklings, dragonets, etc., and crustacea	>80%

In the USA, requirements to reduce fish impingement mortalities have led to renewed research into fish return techniques. Recent developments have benefited in particular from the use of CFD flow analysis to optimize the fish bucket design, which can greatly improve the fish retention and reduce damaging turbulence. There have also been improvements resulting from use of non-metallic buckets, smoother screening materials and improved methods of washing off the fish. One company (Beaudray USA) claims to improve fish survival by removing fish before the screen lifts them out of the water. It is now claimed to be possible to return >90% of even delicate pelagic species alive.

3.1.5.3 Design Best Practice

With recent developments in the USA, this is clearly an area where improved designs shortly may become more widely available. Some of the innovations are likely to be protected by patents and therefore available only through certain screen manufacturers. It is important when specifying band or drum screens which are to be used for fish return to ensure that the design of the fish buckets in particular has been optimized for fish handling and evidence of this should be sought from the manufacturer. Other key points in fish return system design are:

- The screens should be capable of long-term continuous operation: intermittent operation is unsuitable for fish return. This means, in particular, that bearing life should be considered.
- The screen meshes should be smooth and ‘fish-friendly’. Certain types of woven stainless mesh are commonly used for this purpose.
- The mesh size should be as small as is practical, and of no more than 6 mm aperture.
- Low-pressure backwash sprays (≤1bar) should be used for fish removal; higher pressure jets may be used at a later point in the cycle to wash off debris.

- The geometry of the collecting hoppers should be checked to ensure that fish that are washed off the screens cannot fall back into the screenwell (an issue mainly on drum screens).
- Biocides should be applied downstream of the screens unless it can be shown that the toxic risk is negligible.
- Fish return gullies should be smooth, with any joints properly grouted and finished. They should be a minimum of 0.3m diameter; 0.5m diameter or larger is preferred for long runs (>30m).
- It is beneficial to enclose or cover fish return lines to avoid algal growth. Suitable access hatches or rodding points should be provided to facilitate maintenance.
- Where bends are required, swept bends of radius >3m should be used.
- Dedicated fish return lines which discharge well blow the low water mark are preferred. Return on power plants via the heated water discharge should only be used where it can be demonstrated that survival rates will be acceptable.
- A continuous washwater supply should be provided that will ensure sufficient depth to keep fish immersed and moving along the return line.
- At coastal sites where there is a risk of occasional inundation by schools of pelagic fish, provision may need to be made for diverting the catch to collecting baskets. This can be necessary to avoid the risk of discharging large quantities of dead fish onto neighbouring bathing beaches.

Plate 3.8 A sharp bend in this fish return gulley demonstrates the issue of biofouling where uneven joints have encouraged algal growth, causing a flatfish to take cover there. A smooth surface or exclusion of light would have prevented this.

3.1.5.4 Applications

Fish return systems are presently used mainly at estuarine and coastal power stations, although the technique is potentially suitable for fish protection at potable water intakes where band screens are often used.

3.1.5.5 Fish Species/Life Stage

In the past, fish return systems have been suitable mainly for more robust epibenthic species, such as flatfishes and reef/rock-pool species, with moderately good results for demersal fishes such as cod and whiting but with very poor survival prospects for delicate pelagics (Table 3.1). With improved designs, some systems may also be suitable for pelagic species. Fry are normally too delicate to survive handling in this type of system.

3.1.5.6 Ease of Retrofitting

In most cases, a system designed without fish return facilities will require substantial modification of civil works to accommodate larger buckets, as well as fish return ways. Careful analysis of the system by a specialist in this field may suggest modifications that would substantially improve fish protection, however.

3.1.6 Econoscreen

The 'Econoscreen', a self-powered rotating drum screen as described in Solomon (1992), appears to be unavailable at the time of writing. This is unfortunate, as results have appeared promising at the few sites where it has been used. They include Shotton steelworks (R. Dee) and an abstraction in Port Talbot (D. Mee, Environment Agency, personal communication).

3.2 Physical Screening for Juveniles and Small Fish

Of the screening techniques described above, other than the Coanda screen the methods are generally unsuitable for screening juveniles and alternatives should be considered. The methods described below are, of course, highly effective against larger fish as well, but (mainly on cost grounds) would not generally be used where it was not also necessary to screen out small fish. These methods, with appropriate design, can be used to screen fish even down to larval or egg size.

3.2.1 Passive Wedge-Wire Cylinder Screens

Passive wedge-wire cylinder (PWWC) screens are a tried and tested solution and are generally regarded in Britain as the best available technology for juvenile and larval fish protection.

3.2.1.1 Basic Form of the Screen

Figure 3.5 illustrates the basic form of the PWWC screen. It comprises a cylinder, formed of the wedge-wire material around its circumference, one end being blanked off and flow being drawn off through the opposite end. The blanked end may be closed off either with a flat plate or, where facing into a flow, with a conical cap for streamlining.

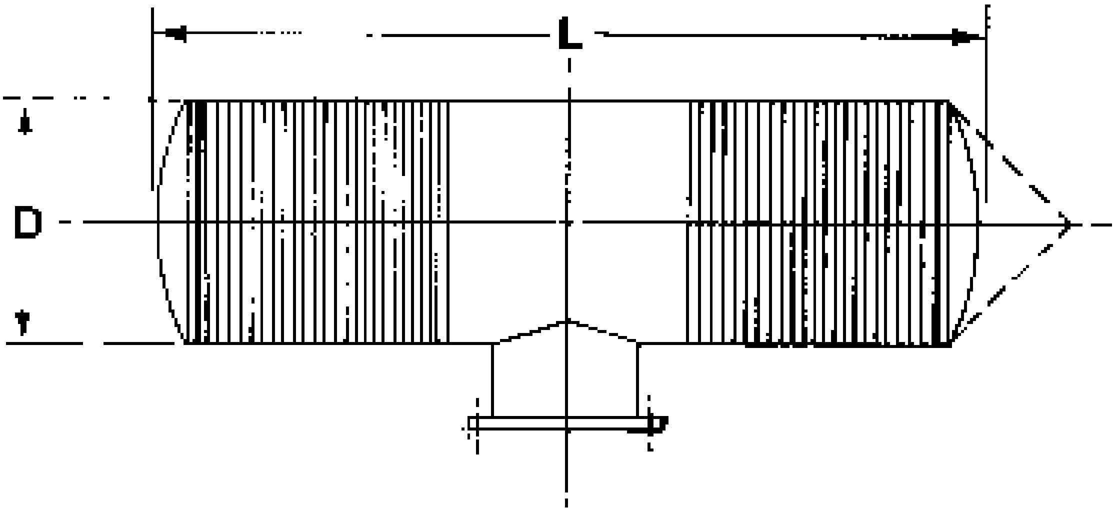

Figure 3.5 The basic form of the Passive Wedge-Wire Cylinder (PWWC) Tee-Screen (courtesy Johnson Screens)

The wedge-wire material is similar to that used in the Coanda screen (Figure 3.3). The profile of the wire that forms the screen surface is V-shaped. In manufacture, the longitudinal supporting bars are fixed about a mandrel, around which the vee-wire is wound in a spiral. The apex of the 'V' is welded onto the bars at each point of contact. The pitch of the spiral thus determines the slot-width of the screen. For some applications, the wedge-wire screening material is deployed in the form of flat panels, but it will first have been manufactured by this method and then flattened out.

The major benefits of using the V-profile wire in PWWC screens are that it offers low hydraulic resistance for a given open area (when compared with conventional screening materials), combined with low blocking risk: particles tend either to wash past the screen or to pass through the slots, as slot width increases towards the inside of the screen.

3.2.1.2 PWWC Screen Configurations

Manufacturers offer a range of PWWC configuration options, including single, bulkhead or pipe mounted units, tee-form screens and multiple groupings attached to a manifold. Figure 3.6 illustrates various typical arrangements. The arrangement used depends on the water depth, space available and other factors, but the options available make the configuration very flexible. Where, for example, water is shallow, a number of small-diameter units can be used rather than a single large one.

3.2.1.3 Air Backwash System

Although not fitted to all systems, PWWC screens are more often than not fitted with an air-blast backwash system, such as the Johnson Hydroburst™ system. In this, a perforated air discharge pipe is welded along the bottom, inside of the screen. This is fed by an air compressor and reservoir, from which explosive bursts of air (up to 10 bar pressure) are released at regular intervals (e.g. daily or more often, depending on debris levels), or else once a certain pressure differential has been measured across the inside and outside of the screen. This may be under manual or automatic control. The clearing action is caused by the displacement of water through the slots from inside the screen chamber, as the air volume expands following release. Any debris that has become pinned on the outer surface is thus lifted off and carried away by local water movement.

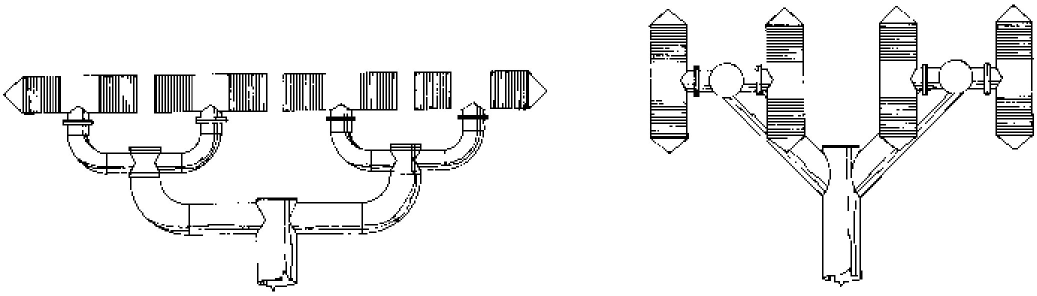

Figure 3.6 Examples of multiple PWWC screen arrangements. These usually involve connection to a manifold (courtesy Johnson Screens).

3.2.1.4 Construction Material and Biofouling

For freshwater use, screens are made from stainless steel, of a grade suited to water quality conditions. In marine and estuarine environments, stainless steel screens tend to biofoul rapidly and a copper-nickel alloy is preferred. Bamber and Turnpenny (1986) tested the efficacy of a small 70%:30% Cu:Ni test PWWC screen at Fawley Power Station on Southampton Water, Hampshire where the mean salinity is around 32‰. It showed little sign of biofouling after 15 months of operation without any cleaning other than the once-daily air backwash cycle. After this time the measured flow throughput was reduced by only 2% compared with the starting figure (nominal flow rate $10Ls^{-1}$). More recently, an alloy of 90%:10% Cu:Ni composition has been used for estuarine applications. A large cooling water make-up intake at Connah's Quay Power Station on the Dee Estuary (Cheshire) with PWWC screens constructed of this alloy has operated continuously since 1996 without any need for cleaning (W. Smith, PowerGen plc, personal communication).

3.2.1.5 Fish Protection Performance

PWWC screens have a number of features that make them suitable for prevention of fish entrainment. These include the low through-slot velocity, allowing fish to swim away, the relatively smooth external presentation of the screen, which reduces the risk of fish abrasion, and the narrow slot widths available, making it possible to prevent entrainment of fish even down to egg or larval sizes. The main reason for selecting PWWC screens in preference to lower cost alternatives is to improve the level of protection for the smallest individuals, i.e. egg or larval/postlarval stages ('pinhead fry'). This aspect has been investigated in North American studies (Heuer and Tomljanovich, 1979; Hanson, 1979).

Conclusions of the Heuer and Tomljanovich (1979) study were:

- For very small larvae (<6.0 mm total length), a slot width of 0.5 mm and through-slot velocity of ≤ 7.5 cm.s^{-1} would be required.
- For larvae of 7-10 mm total length, a slot size of 1.0 mm and through-slot velocity of 7.5 cm.s^{-1} was ideal, although a through-slot velocity of 15 cm.s^{-1} would be low enough for some species.

- For larvae of >10 mm total length, a slot width of ≥2.0 mm is satisfactory, with a through-slot velocity 7.5-15 $cm.s^{-1}$.

While close to 100% larval exclusion was achieved with the lower through-slot velocity and a slot size of ≤1.0 mm, significant entrainment of some species occurred at 15 $cm.s^{-1}$ through-slot velocity and 2.0 mm slot width, e.g. 18.1% for bluegill (*Lepomis machrochirus*) and 67.7% for channel catfish (*Ictalurus punctatus*).

Entrainment of fish eggs and larvae was also studied by Hanson (1979), in a laboratory flume with 1 and 2 mm slot-widths and a 15 cms^{-1} through-slot velocity. The particular significance of this study was that they measured the effect of the channel velocity (0.15, 0.3 and 0.6 $m.s^{-1}$) on fish entrainment rates, after releasing batches of fish eggs and larvae into the flume. The findings are summarised in Figure 3.7, which expresses the results as the percentage of fish exposed to the screen that became entrained. This indicates the importance of placing screens in a strong flow (>0.3ms^{-1}) if the best performance is to be achieved.

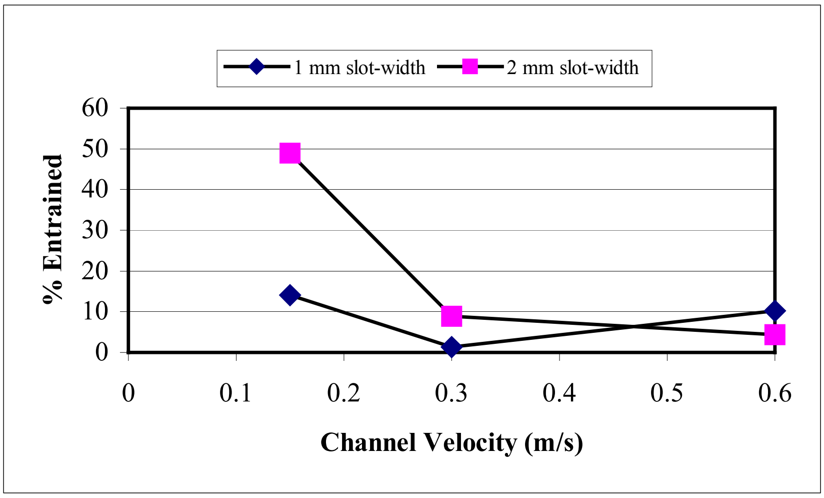

Figure 3.7 Entrainment rates of fish eggs through 1 mm and 2 mm slot-width screens at different channel velocities (after Hanson, 1979).

3.2.1.6 Design Best Practice

Manufacturers offer design guides that provide the information required for specifying the screening system. A detailed account is not therefore necessary here but the main points will be listed. The following information is taken largely from the Johnson Screens' guide.

3.2.1.7 Through-Slot Velocity.

The design velocity is commonly 15 $cm.s^{-1}$, a value that has been found to offer virtually maintenance-free performance of the screen. As screens seldom are operating in the fully clear state, a degree of occlusion is allowed for when sizing the screens. An allowance of 25% is normally made.

3.2.1.8 Slot Width.

Typical values used range from 0.5 mm to 9.5 mm. The very small slot widths may be used, e.g., where there is a risk of sand ingress. The most common size used in the UK for raw water screening is 3 mm, this being a reasonable compromise between open area and effective debris screening. Also, the smaller the slot width used, the larger the overall screening area required and the higher the capital cost and space occupied.

3.2.1.9 Screen Diameter and Spacing from Surfaces

The maximum screen diameter should be half the water depth at the lowest extreme of water level; preferably it should be no more than one-third. Where depth is shallow, the option of using tee-configurations or other multiple arrangements of small-diameter screens can be considered.

The recommended minimum submergence depth is half the screen diameter, with the screen being spaced an equivalent distance from the bed and any wall. Submergence to this depth avoids the risk of excessive entrainment of surface-carried debris into the abstraction flow. Spacings from the bed and wall are to avoid debris rolling along the bed becoming entrained, or larger items becoming jammed. Placing screens too close to the bed or wall may also compromise the uniformity of the hydraulic field around the screen.

3.2.1.10 Screen Sizing

The number, types and sizes of screen units required for a given abstraction are selected so as to satisfy the above requirements. Manufacturers' design guides provide tables and formulae from which requirements can readily be calculated.

3.2.1.11 Velocity of Flow Past Screen and Screen Siting

The successful clearance of debris following air backwashing is dependent on adequate ambient flow past the screen, otherwise, debris may accumulate. This may be through river or tidal flow, or through wind-driven circulation in lakes and reservoirs. It is also important that screens are not sited in backwaters where debris naturally accumulates as a result of eddy currents.

A steady current is required to ensure debris is carried away.

3.2.1.12 Applications

PWWC screens are suited to a wide range of flowing water applications in freshwater, estuarine and marine environments. They are best suited to smaller abstractions of a few m^3s^{-1} or less, as larger arrays may become cumbersome, unless space is unlimited. They are used, for example, for potable water abstractions, CCGT[8] power stations and fish farm supply, but are not suitable e.g. for low-head hydroelectric generation on account of the very large flows involved.

3.2.1.13 Fish Species/Lifestages

They are probably suitable for excluding all species and sizes of fish given suitable wire spacings. A particularly interesting case is the study carried out by the National Rivers Authority at Moor Monkton pumping station on the Yorkshire Ouse (Frear and Axford, 1991 and unpublished). Collections of impinged fish from the bandscreens were made before and after the fitting of PWWC screens to the intake. Between January 1990 and May 1991, 16,022 lampreys (brook- and river-) were collected from the band screens; most were recently metamorphosed pre-adults ("transformers"), along with some ammocoetes and adults. In 1995, the intakes were fitted with an array of eight Johnson PWWC screens (model T42 with 3 mm slot-width, total capacity 3.5 m^3s^{-1}). Subsequent surveys found virtually no lamprey or other fish impingement. The small numbers that were collected (around ten per week during the winter) may have passed through the screen but could also have been ones that remained resident in the abstraction lagoon,

[8] Combined-cycle gas turbine

between the intake and the band screens. Samples of lampreys retained in tanks following impingement indicated potentially high survival rates, suggesting that returning lampreys from the bandscreens to the river via a fish return system would be an option worth considering.

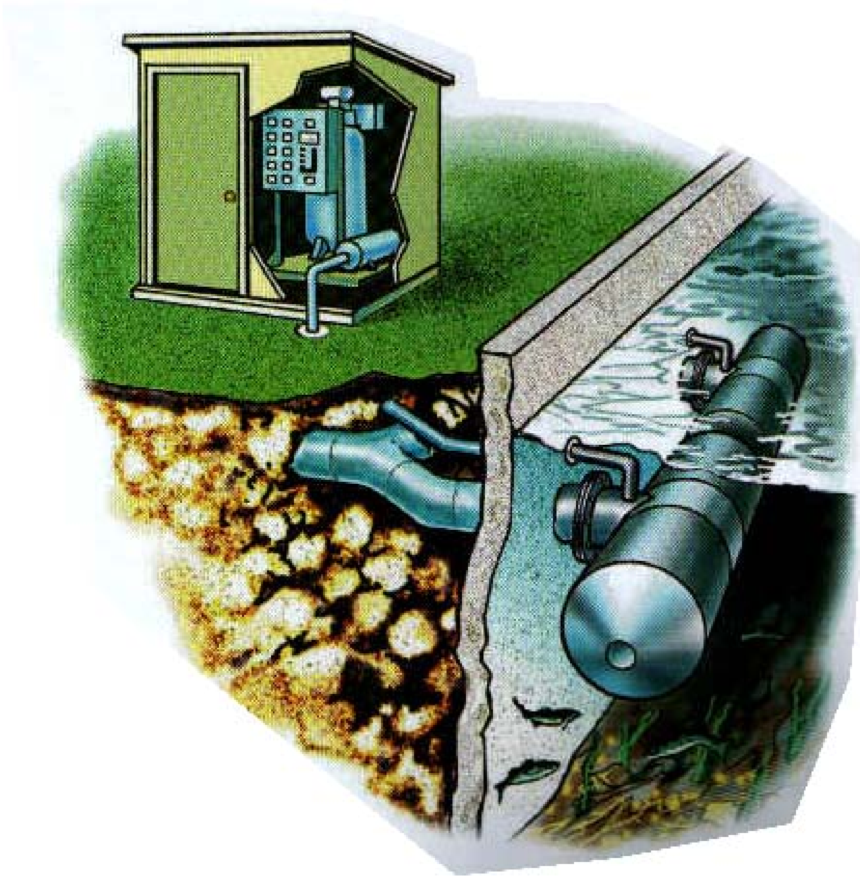

Figure 3.8 Illustration of bulkhead mounted PWWC screen array with manifold and air backwash system; the compressor is located in a bankside hut but could be located in any neighhbouring building. (courtesy Johnson Screens)

3.2.1.14 Ease of Retrofitting

PWWC screens do not lend themselves to retrofitting on existing intakes, except perhaps for end-of-pipe applications. Where the existing intake is constructed e.g. as an open channel or opening in the riverbank protected by a trashrack, it would be necessary to form a bulkhead onto which a screen manifold could be fixed (Figure 3.8). However, PWWC screens do have the advantage that they are available in a wide range of dimensions, so that many different configurations can be achieved.

3.2.2 Wedge-Wire Panel Screens

Wedge-wire can be used in flat panel screens (see section 3.1) as an alternative to mesh panels. This is found to be more practical for small fish exclusion, being less prone to clogging, than a mesh of equivalent spacings. An example of this type of screen was installed at a small hydroelectric plant in the Thames catchment at Huntsmoor on R. Colne (G. Armstrong, personal communication).

North American experience is that orienting the wires vertically rather than horizontally facilitates cleaning, as vertical raking machines can be adapted for this purpose (S. Rainey, US National Marine Fisheries Service, personal communication). However, use of the material in the PWWC screen format is to be greatly preferred, as the air-backwash system provides a very effective cleaning mechanism; air backwashing cannot be used in a vertical flat screen layout, as the air needs to rise through the gaps between the wires.

3.2.3 Sub-Gravel Intakes and Wells

Solomon (1992) discussed the applications of sub-gravel intakes and wells, since when there has been no real change in the approach. A brief summary of these technologies and examples is included here for completeness.

Sub-gravel intakes use the riverbed itself as a screen by abstracting the water from underneath the bed or from an aquifer. This system also has the advantage of natural filtration reducing treatment costs but has the drawback of there being an extremely limited number of suitable locations.

An example of this form of abstraction is found at Ibsley on the Hampshire Avon. An abstraction of 0.57 m^3s^{-1} is taken via 4 streams. A wedgewire screen with 8mm slot width is supported over a concrete chamber over which layers of gravel are placed up to the original bed level. A geomembrane sheet is placed between gravel layers and gravel cleanliness is maintained by backwashing.

Littlehampton abstraction uses a 4 m diameter collector well reaching down to bedrock at 10m below the riverbed. 12 lateral perforated pipes extend from the well at 2 depths. The abstraction licence granted to the well is for 0.28 m^3s^{-1} and is anticipated to benefit from both high fish protection and partial water treatment (Solomon, 1992).

3.2.3.1 Applications

This technique is only feasible for small abstractions in fast-flowing, eroding-substrate rivers and is suitable e.g. for potable water or fish-farm supply.

3.2.3.2 Fish Species/ Life Stages

The technique should prevent the entrainment of any fish present. It may be conjectured that the requirement to backflush periodically could affect the habitats of lithophilous fish/lifestages, e.g. bullheads, stone loaches or juvenile salmonids, but probably over an insignificant area.

3.2.3.3 Ease of Retrofitting

This is unlikely to be a method suitable for retrofitting in many circumstances.

3.2.4 Microfiltration Barriers

The Marine Life Exclusion System (MLES™), developed in the USA and patented by Gunderboom Inc.[9] is a new microfiltration barrier that is presently being tested widely in the USA for fish exclusion at power plant intakes. It is specifically intended to provide

[9] Gunderboom, Inc., 10 Hickman Dr., Sanford, Florida 32771 USA

protection for early life stages of fish. In the USA, the MLES is a contender for Best Technology Available status under the Clean Water Act, Section 316(b).

The following information is taken mainly from the company's website (www.gunderboom.com) and from correspondence with the manufacturer. The MLES was also reported and discussed in a number of papers presented at the US Environmental Protection Agency's Cooling Water Symposium held in Washington DC in May 2003: presentations may be viewed at the following URL: www.epa.gov/waterscience/316b/symposium. [10, 11, 12].

3.2.4.1 Description of the MLES Barrier

Gunderboom's MLES™ is a water-permeable barrier (Plate 3.9, Figure 3.9) that keeps fish eggs, larvae and other aquatic organisms away from the water intake. Comprised of a pocket formed by two layers of treated geotextile fabric, the curtain is arranged to full water depth across the front of the intake. It is made long enough to provide a very large surface filtration area, with typical velocities through the fabric of only 4-10 mm s^{-1}. The curtain is either suspended by flotation billets and anchored in place, or integrated into existing shoreline intake structures. The curtain fabric is porous, with pore sizes of <1 mm.

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[10] Development of Filter Fabric Technology to Reduce Aquatic Impacts at Water Intake Structures, Matthew J. Raffenberg, Lawler, Matusky and Skelly Engineers, LLP

[11] Vulnerability of Biofouling of Filter Curtain Materials Used for Entrainment Reduction, Peter Henderson, Pisces Conservation Ltd. & University of Oxford and Richard Seaby, Pisces Conservation, Ltd

[12] Effectiveness, Operation and Maintenance, and Costs of a Barrier Net System for Impingement Reduction at the Chalk Point Generating Station, David Bailey, Mirant Mid-Atlantic.

Plate 3.9 Gunderboom MLES barrier in place around an intake structure. The yellow support collar is visible and air backwashing is taking place along part of the barrier.

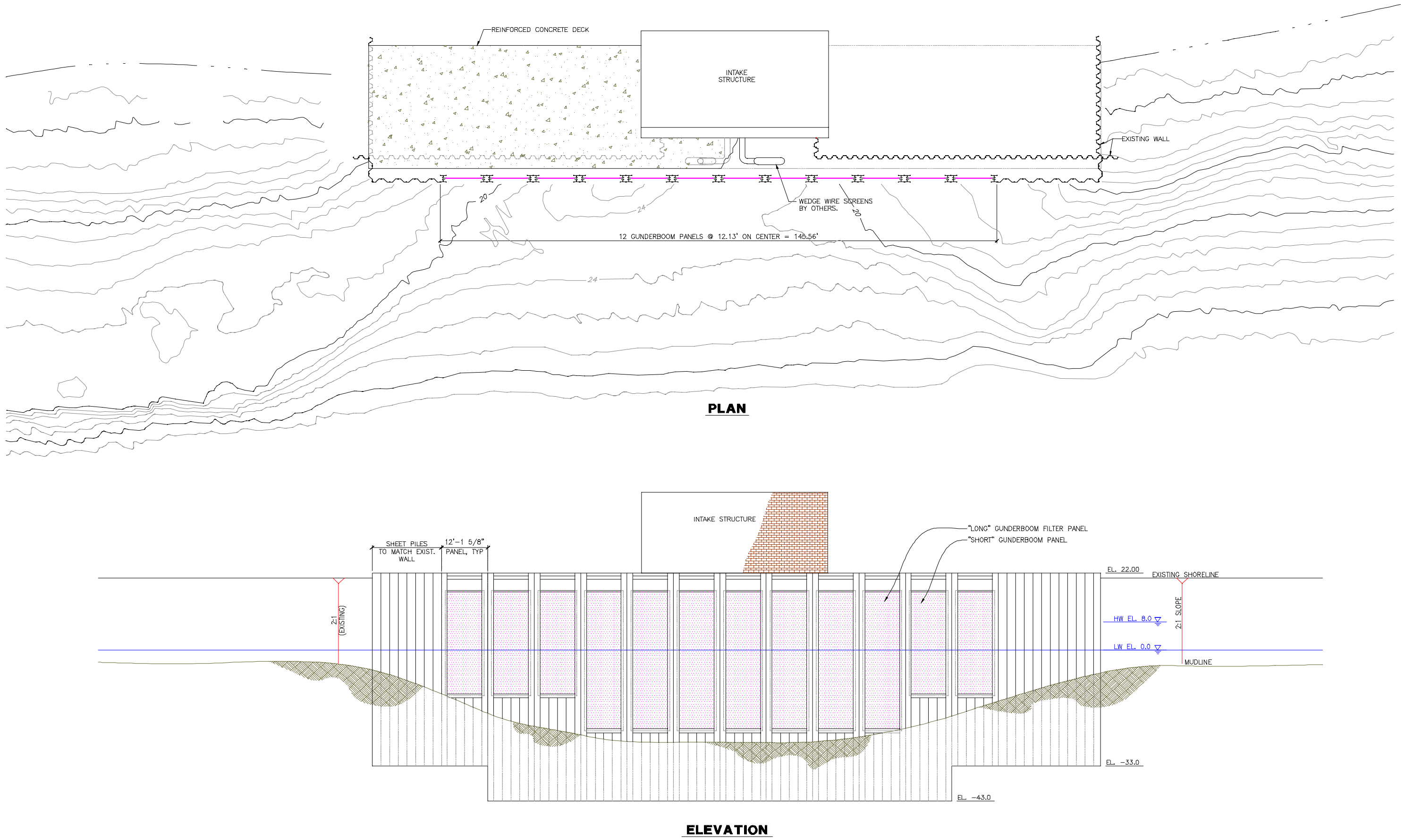

Figure 3.9 Example of a MLES layout (Gunderboom Inc.)

3.2.4.2 Self-Cleaning with AirBurst™ System

Similar to the PWWC screens, the MLES barrier uses an automatic AirBurst™ cleaning system. This is intended to remove sediment and organisms that are drawn onto the fabric when high-pressure air (8 bar) is released at the base of the curtain. Bursts of compressed air shake the fabric panel.

Presumably some tangential flow would be required to carry away debris but the manufacturers do not mention this.

3.2.4.3 Fish Exclusion Performance

As the pore size of the fabric is small, the MLES will *potentially* prevent the passage of all fish down to egg and larval size. Its effectiveness in practice will depend on the integrity of the curtain (freedom from tears, split seams, etc.), achievement of a good seal on the riverbed and banks or intake walls and the ability to resist overtopping by wave action. Raffenberg *et al*.[3] estimated an 80% reduction in larval fish entrainment at the Lovett generating station (USA) and while this might be bettered in some environments, it is unlikely that breaches by one of the above mechanisms can be entirely avoided.

A further concern is the development of a biofouling community. Despite manufacturer's claims that the MLES fabric is biofouling resistant, Henderson[4] monitored biofouling development over a 30 day period and showed that a diverse community can rapidly develop. His concern was not just over the potential for blinding of the pores with consequent lack of flow but also over the arrival of a number of known predators of larval fish, including ostracods, amphipods and crabs. He drew attention to the possibility that these organisms might crop some of the fish larvae, reducing the benefit of the MLES technology.

3.2.4.4 Design and Best Practice

Typically, the MLES technology is used for industrial and power plant applications where the through-fabric flow rates are in the range of 4-10 $Ls^{-1}m^{-2}$ (although the manufacturers suggest that through a combination of modification to the fabric and alterations to the perforation parameters, it is possible to reach higher sustainable flow rates). Barriers are designed to operate at a maximum of 50 mm head differential.

Using the AirBurst™ cleaning technology in conjunction with what the manufacturers claim to be a relatively non-biofouling fabric, the filtration-curtain design flow should be maintained. At present there is some skepticism in North American power plant circles about the generality of this claim and it would be unwise to invest heavily in MLES systems without undertaking pilot-scale site trials to prove the point. In the event of the curtain becoming temporarily blinded by debris, the system can be designed with relief mechanisms such that the operation can return to normal after the adjustment. This is accomplished by having the flotation sized to overtop at certain head differentials and by sizing the ballast on the bottom of the curtain to lift off the bottom given certain predetermined loading parameters. Large concrete anchors (e.g. 3m x 2.4m x 1.8m) are generally required.

At Chalk Point generating station, Bailey[5] reported the need to remove the barrier periodically for cleaning and repairs and allowed for 25% replacement of MLES fabric panels per year. This would need to be done at a time of the year when entrainment risk was low.

3.2.4.5 Applications

The uses of this technology are less obvious in a UK context than in North America, given the generally smaller sizes of water bodies, other than e.g. at estuarine and marine power plant sites. Biofouling, in any case, would almost certainly preclude the use of this approach in saline waters. At present, it cannot be recommended as an 'off-the-shelf' solution for UK waters. Nevertheless, it may be amenable for use at lake and reservoir offtakes, and perhaps in slow-moving lowland rivers and canals where space allowed without jeopardising navigation. Suitable trialling of the system would first be required.

3.2.4.6 Fish Species/Life Stages

Suitable for exclusion of all fish, down to egg and larval size.

3.2.4.7 Ease of Retrofitting

The MLES™ is intended as a retrofit 'fix' for existing abstraction plants and, because of its simplicity, is likely to be an easy retrofit, provided that space and environmental conditions (wave climate, boat traffic etc.) are suited.

3.3 Other Positive exclusion Fish Screens

A number of other positive exclusion fish screening methods are used or being trialled overseas, especially in North America, none of which have so far been introduced into the UK. In some cases this may simply be a matter of the larger scale of North American facilities and waterways but it is likely that we can learn from these techniques and adapt them for UK use. It would be premature to present them as "best practice" at this stage. Some of the material presented here has not been formally reported in publications. A number of the newer ideas were presented at a recent meeting on intake screening technologies organised by the Electric Power Research Institute (EPRI) at the Alden Laboratories in Massachusetts, USA (30 September 2004). Copies of the presentations are due to be released on the Internet by EPRI (epri.com).

3.3.1 Barrier Nets

Fish barrier nets have been used at a number of large US power stations to reduce fish impingement on cooling water screens. These are large nets that are arranged in an arc in front of the intake and can be several kilometers in length. They are therefore mainly suited to large water bodies. The size of the mesh needed is a function of the species present, typically varying from 4 mm to 32 mm. There is a risk of gilling fish if the meshes are too large. Diamond meshes are preferable to square meshes, as they do not deform so easily. Design approach velocities are kept to $\leq 7.5 cms^{-1}$.

The nets are supported on piles spaced 3-12m apart and may be deployed from shore-mounted drum winches, allowing retrieval for maintenance and cleaning. They may be arranged in two tiers, so that a clean net can be put in place before the soiled net is removed. Maintenance requirements depend on debris and biofouling levels, but would typically be every few weeks. Excessive fouling can cause the nets to lift from the bottom.

Barrier nets are most suitable for environments with low biofouling and debris levels, and where the fish risk is seasonal, so that they do not need to be in place all year round (as e.g. for many smolt screen installations in the UK).

3.3.2 Modular Inclined Screen

The Modular Inclined Screen (MIS: Figure 3.10) is a new type of fish screen from the USA, designed by the Electric Power Research Institute (EPRI)[13] to suit a variety of different water intakes, fish species and sizes (Amaral *et al.*, 1999).

The screen is formed from wedge-wire and is angled at 10-20° (relative to the horizontal) to the flow. The wires are spaced at approximately 1.9 mm to give 50% porosity. The screen is placed on a pivot to aid in rotation for cleaning via backflushing. A bypass system is provided for guiding fish to a diversion channel. A full-scale model of the screen will be approximately 9 m in length and 3 m in width. The system is completely enclosed and has a capacity of $2.8 m^3 s^{-1}$ at $3 m.s^{-1}$. It is designed to operate at a velocity of $0.6\text{-}3.0 m.s^{-1}$.

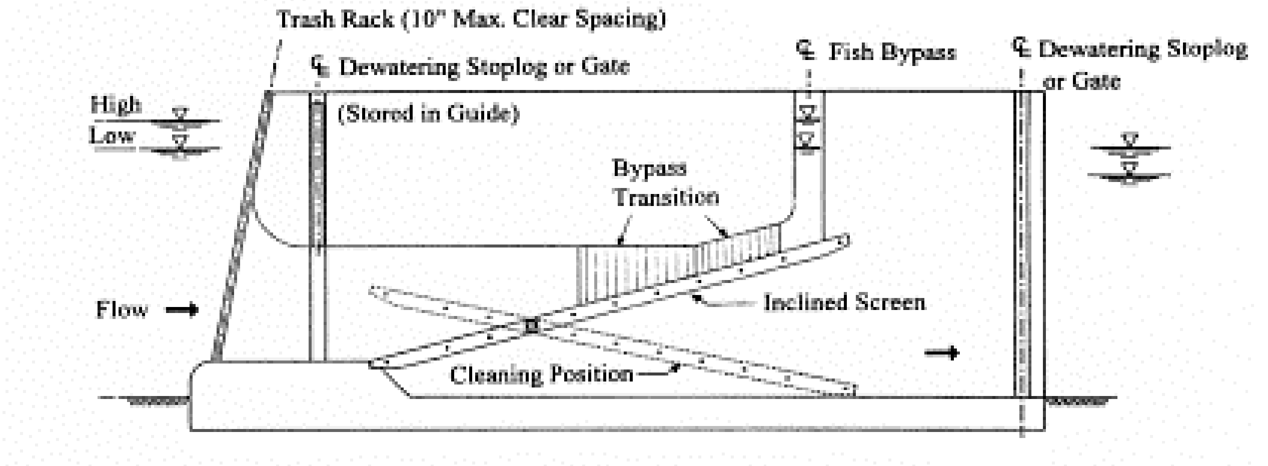

Figure 3.10 Diagram of a Modular Inclined Screen (www.aldenlab.com/scop-fisheries)[14]

Amaral *et al.* (1999) describe laboratory tests carried out in 1992 and 1993 to determine the efficiency of the system. The fish species evaluated included a variety of salmonid and clupeid species such as coho salmon (*Oncorhynchus kisutch*) and rainbow trout (*Oncorhynchus mykiss*). Diversion effectiveness was evaluated for a series of different approach velocities from 0.6 to $3.0 ms^{-1}$. The percentage of live fish that were diverted exceeded 96% for all velocities. In particular Atlantic salmon smolts were diverted with a 100% survival rate for all test velocities.

The success of this laboratory investigation led to a prototype being investigated in the field. The prototype was installed at the Green Island Hydroelectric Project, Hudson River, New York in 1995 and 1996. The facility had a trashrack at the entrance of the MIS and a transition wall guiding fish to a bywash entrance. Tests were conducted at velocities of 0.6 to $2.4 ms^{-1}$. The passage survival and live diversion rates exceeded 95% for many riverine species tested (Amaral *et al.*, 1999).

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[13] Electric Power Research Institute (EPRI), 3412 Hillview Avenue, Palo Alto, California, 94304, USA.

[14] Alden Research Laboratory, 30 Shrewsbury street, Holden, MA 01520-1845, USA.

In principle this would appear to offer a good solution to protecting juvenile fish such as elvers, lampreys and coarse fish at run-of-river hydroelectric projects but large size and high costs relative to flow may in practice limit application to higher head sites, where Coanda screens already have a track-record.

3.3.3 Self-Cleaning Belt Screens

This concept was presented at the EPRI meeting of 30/09/04 (Mr. Greg Gerow, FPI, personal communication) as a possible method for power plant cooling water screening. The screening system is similar to a band-screen, comprising a continuously moving conveyor belt of fine mesh (2.4mm) but whereas band screens are normally used within the plant, some way downstream of the intake, the is screen is fitted at the primary intake point on the river or water body. The screen described was operated inclined at an angle of 54^o to the horizontal, below the water at the lower end to screen the water intake; the upper part emerged through the water surface to deposit accumulated debris. The longest practical screen length is 15m. The screens can be deployed side-by-side to increase the filtration area.

The mesh is a 'fish-friendly', smooth stainless woven material. The screens have been used widely for screening irrigation intakes, with >700 systems installed. There has been no reported evidence of fish loss at existing installations although formal testing does not appear to have been carried out. A large surface area and low approach velocity (0.15ms^{-1}) are used with the aim of not impinging fish at all.

Plate 3.10 Example of a self-cleaning belt screen installation. The screens are sealed at the sides to prevent fish or debris entrainment; screened weed and other debris are dumped on the ground below the top of the screen (courtesy of FPI Water Screens, USA: www.fpi-co.com)

This type of screen appears suitable for a wide range of applications where self-cleaning, fine-meshed screens are required and may provide a more cost-effective alternative to PWWC screens in some cases. Being of stainless steel construction, it will not be proof against biofouling and therefore it is likely to be suitable only for freshwater applications. At exposed sites, trash racks may be required upstream to protect the fine meshes from flood damage. The design is well suited to intakes that lie flush with the bank and it may offer a retrofit option for many bankside intakes that are presently protected trashracks alone.

3.3.4 Labyrinth Screens

Labyrinth screens are a variation on the flat panel screen or bar rack described in section 3.1. In this case, vertical bar racks are arranged in chevron-formations (when seen in plan view: Figure 3.11), rather like an array of fyke-nets. The fish are guided into bywashes located at the downstream angle of the ‘V’. The bar spacing can be specified as usual, according to the sizes of fish to be excluded.

Meritec[15], source of the following information, recently reviewed the labyrinth screen for possible application at a large water intake on the River Waitiki, New Zealand. The river has the potential for six 90 MW capacity hydropower stations. A form of screen was needed in order to exclude ≥90% of the river’s twenty indigenous and four introduced species from flows of $>300 m^3 s^{-1}$, making this one of the largest fish screening projects in the world. The screen must exclude both adults and juveniles (25-1000 mm in length) of a range of species including salmonids and eels and be in place all year round. In order to avoid any impingement the maximum contact time has been specified at 60 seconds. The proposed screen gap size is 5 mm with bars orientated vertically.

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[15] Meritec Limited, 47 George Street, Newmarket, Po Box 4241, Auckland, New Zealand.

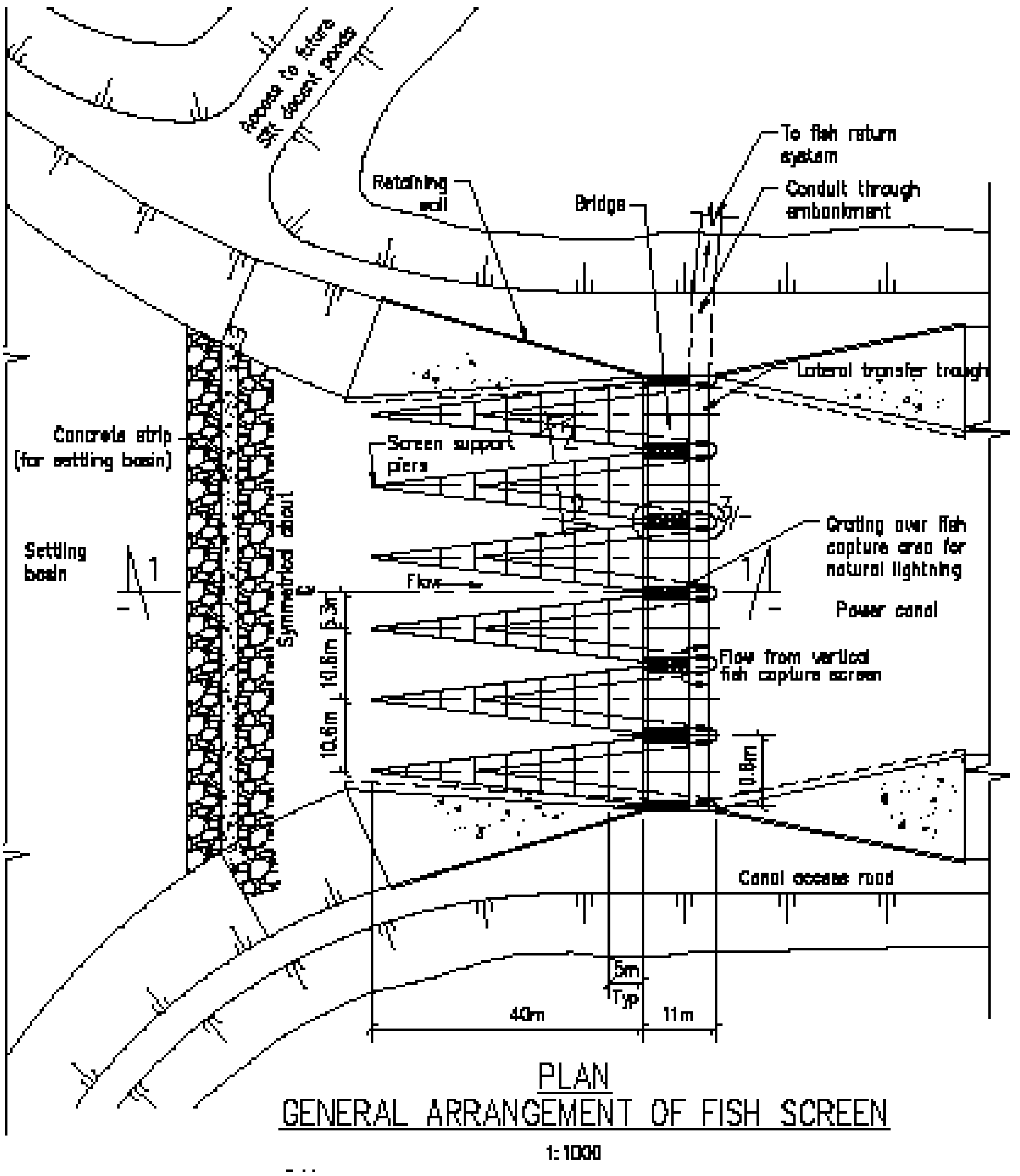

Figure 3.11 River Waitiki arrangement plan for the Labyrinth screen (www.ecan.govt.nz/consents/project-aqua)

The system is based on the 97-98% efficiency seen at the White River labyrinth screen in the USA. This screen is operated at a similar flow and angle as proposed for this installation and successfully excludes chinook salmon fry (*Oncorhynchus tshawytscha*) although using a slightly smaller screen gap of 3.1mm.

The proposed system would consist of wedge-wire screen panels, a collection system and a return system to transport collected fish back to the river. To obtain a low approach velocity the screen would be angled at 8½° to the flow. The labyrinth arrangement confines the screen to a relatively short length of canal making both operation and fish collection easier. A total of 7 labyrinth bays would require 40 m of canal whereas single line vertical screens would require 600 m. A full-height bywash opening and width of 600-900 mm allows fish collection over the full flow depth. Primary screens would consist of bars running perpendicular to the sweeping velocity in order to minimise head loss. An impermeable ramp on the bed angled at 45° ensures accelerating flow into the bywash.

The labyrinth screen concept could be of benefit in the UK at large intakes or where space is at a premium and a compact screening arrangement is required. Low-head hydro would be an obvious application.

3.4 Behavioural Barrier and Guidance Methods

3.4.1 Behavioural Deterrents Background

Deterrent methods are normally used where positive exclusion fish screening is impracticable, owing to the risk of fouling, either by attached biofouling or by waterborne organisms and debris. Fish deterrent systems are commonly known as 'behavioural barriers' or 'behavioural screens' and are a substitute for, or supplement to, more conventional positive exclusion fish screens. Whereas some positive exclusion screens, when operated and maintained correctly can achieve 100% fish exclusion, behavioural screens cannot.

Fish have a number of well developed senses, and are able to detect and react to light, sound and vibration, temperature, taste and odour, pressure change, touch, hydraulic shear, acceleration, electrical and possibly magnetic fields. The relative sensitivity and capacity to react to any of these stimuli varies with individual species and life stages, each being well adapted to cope with the conditions it is likely to encounter in its particular lifestyle. Environmental variables, such as flow, depth, turbidity, water temperature and others may also affect the success of behavioural methods.

Fish deterrent methods depend on the use of one or more of these stimuli to cause repulsion of fish from the immediate area of the water intake, and in some cases to guide them past the intake into a bywash or to a point downstream. To be effective, the stimulus must be strong enough to repel fish at a range where they are not at risk of being involuntarily drawn in by the strength of the water current. Equally, it must be weak enough to avoid the risk of injuring the fish or of clearing fish from too large an area, which might cause habitat loss and impact upon commercial fishing or block natural patterns of fish migration in rivers.

3.4.2 Louvre Screens

3.4.2.1 Description of Screen

Louvre screens have been used since the 1950s and can be an effective option for the diversion of salmonids and other species. They are in fact a semi-physical barrier which can provide high fish deflection efficiencies (>90%) under optimal conditions (Aitken *et al*, 1966, Solomon, 1992). In general the efficiency of louvre devices varies between 80-100%. In particular high efficiencies have been found for adult and juvenile salmonids as well as American shad (*Alosa sapidissima*), the efficiency is however, lower for alevins and individuals under 5 cm in length. Bottom dwelling fish are not as efficiently deflected, especially where only partial depth louvres are used (Therrien, 2000, Buerkett, 1994, Kynard and Buerkett, 1997).

The louvre screen is based on the reaction of fish to current vortices created by the action of water flow on the louvre slats (Figure 3.12). Approaching fish sense a shearing flow (i.e. different velocities across different points along its body) and as a result avoid the face of the screen. The fish are guided by the angle of the face of the screen into a bywash channel.

For best efficiency slats are positioned at a 90° angle to the incident flow. The individual slats of the screen are spaced at set intervals. The maximum gap used is about 30 cm, suitable for large fish such as adult Atlantic salmon, gaps down to 2.5cm being used for smaller species such as catfish and smelt (Therrien *et al.*, 2000). The angle of the screen to the axis of the flow can vary from 10° to 30° but the optimum is usually found to be between 10° to 15°; efficiency generally decreases as the angle increases. This optimum angle to the flow dictates the length of the screen, which is 3.86 to 5.76 times the channel width (Solomon, 1992). The majority of penetration by fish generally occurs close to the entrance of the bywash and the design is found to benefit from a reduction of slat gaps to around 5 cm close to the bywash entrance. This also reduces the required attraction velocity within the bypass channel. Provided that the slats run to full depth, water depth appears to have little effect on the efficiency of louvre screens and they have been successfully used within a channel depth of up to 4 m (Ducharme 1972).

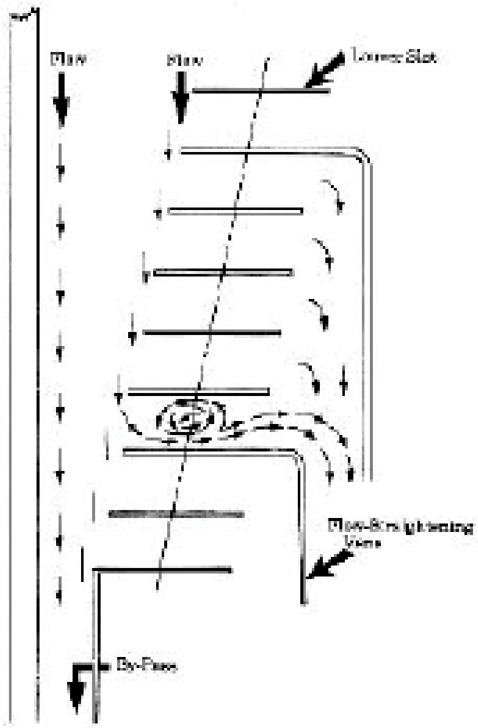

Figure 3.12 Schematic of louvre screen

Although this is a behavioural screen, there is a substantial physical structure involved and debris can become trapped within the channel. This will occur to a lesser extent than conventional mesh screens but regular maintenance will be required and there will be running costs. Cleaning is facilitated if the slats can be lifted away from the screen. Trashing can be reduced by the addition of a coarse trash rack upstream of the louvre screen, which would allow the unhindered passage of fish but prevent movement of debris items. For salmon smolt protection alone it may not be necessary to have the louvre screen in operation all year round and limiting use to the months e.g. of April-May will avoid periods of higher waterborne debris (Solomon, 1992); this, however, would require the negotiation of an exemption under SFFA s.14 unless a local byelaw already allowed this. In some rivers, screening may also be required during the autumn and winter months to protect pre-smolt migrations.

The range of suitable current velocities in the channel has been described in a number of papers and louvre screens have been shown to work from 0.3 – 1.2 ms^{-1} with no loss in efficiency, but they become ineffective as the approach velocity falls below this as shear flows are not generated. The water velocity perpendicular to the face of the louvre array (the 'escape velocity') must be less than the fishes' swimming ability. The velocity in the bywash entrance, however, must be greater than that of the channel in order to provide sufficient attraction. Of velocities tested within the range of 110-300% of the screen approach velocity, a figure of 140% is considered to be the ideal (Solomon, 1992). As the louvre screen itself restricts the water velocity in the main channel a bywash velocity of 1.4 times the main channel is generally easily achieved. At sites where headloss may be a problem the louvres can be fitted with deflectors or current rectifiers along the louvres line at regular intervals to improve hydraulic efficiency (Therrien, 2000).

3.4.2.2 Floating or partial-depth louvres

Floating louvres can be used when screening of just the surface layers is required. This may be the case when screening for fish that only travel in the upper layers of the water column such as salmon smolts, which migrate predominantly in the top 2 m of water. Shad, on the other hand, tend to migrate in the bottom layers. It is believed that with floating devices the current velocity should not exceed 1 ms^{-1} and that the optimum current for which designs are based on is 0.6 ms^{-1} (Therrien, 2000). Ruggles (1990) described a floating louvre screen array fitted at a hydroelectric scheme at Holyoke on the Connecticut River. Based on observations that salmon smolts tend to migrate only in the top metre or two of water, the screen extended over the upper 2.4 m of the 5.5 m water column. The louvre slats were constructed of polypropylene, suspended at 76.2 mm (3") centres along a 176 m array. This created a screen angle of 15^{o} across a 44m-wide channel, with a total flow of about 150 m^3s^{-1}. Tests with radio-tagged smolts indicated that 90% were successfully guided into the 4 m wide bypass channel.

Experience of one of the authors (AWHT) at a hydro station in southern Sweden suggests that the success of partial-depth louvres may be dependent on the flow characteristics of the channel. A smolt trap located at the Upper Hemsjo hydro station on the Morrumso River was intended to take advantage of the deflection of smolts swimming near the surface into the trap by an angled ice deflector. This was formed by a metal curtain suspended in the headrace from a floating boom, which was angled across the channel to deflect ice into a bywash chute. The curtain hung a metre or so below the water surface. When very few smolts were found to enter the trap, even though they were observed in the headrace, behavioural observations were made of smolts fitted with float tags (small polystyrene cubes attached to the dorsal fin by a monofilament line) released upstream. It was found that smolts followed the line of the ice boom along most of its length but at a point where it lay nearer to the turbine intake, the flow began to descend towards the submerged intake openings. The smolts were clearly able to detect this descending flow and immediately sounded down below the curtain and passed through the turbine. This observation suggests that partial-depth barrier of any kind are only likely to be effective when flow is uniformly horizontal in direction.

3.4.2.3 Installations in the UK

Very few louvre screens have been installed in the UK, despite extensive testing carried out by the hydroelectric industry in Scotland during the 1960s. There are however, at least two screens known to be installed in Scotland. One is situated at a small, privately owned 100 kVA hydroelectric scheme on the River Almond, a tributary of the River Tay, Perthshire. The screen was installed in the headrace canal to prevent the entrainment of salmon smolts in to the turbine. Such an arrangement benefits from the uniformity of the approach flow, which results in an even hydraulic pattern along the screen face. No testing has been carried out, so efficiency of the screen is unknown.

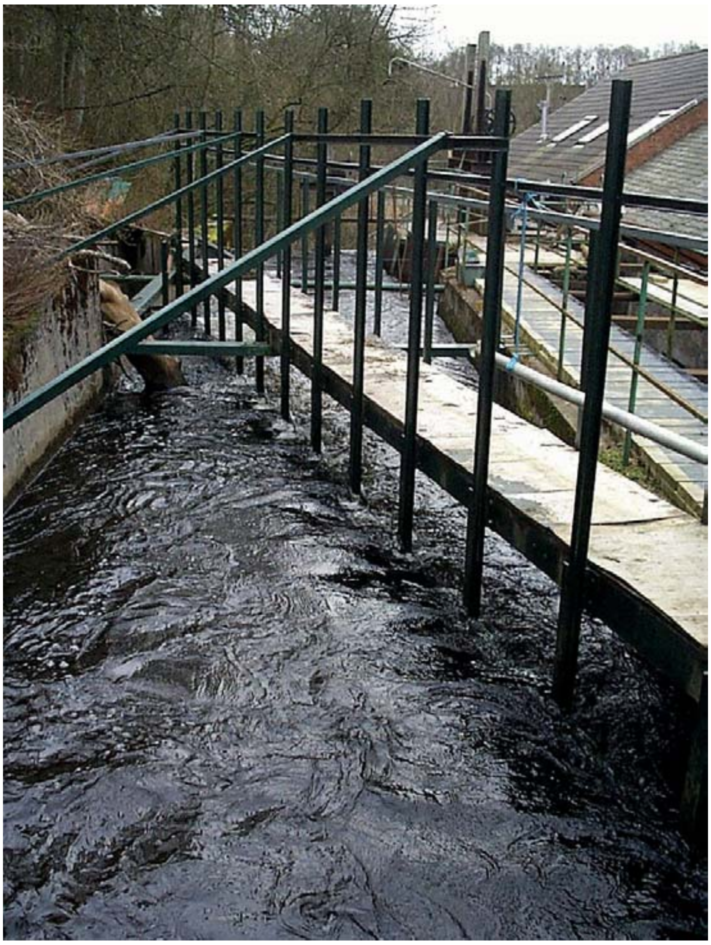

Plate 3.11 The louvre screen at Almond Bank Power Station. Only the superstructure is visible.

A second louvre screen was installed during the 1990s at the 500KVA Blantyre hydroelectric plant on the R. Clyde. This was a partial depth screen, which was not found to be effective, and which was subsequently removed. Unlike the Almond Bank example, it was located directly in the river, as the scheme has no headrace canal. Under these conditions, it is difficult to achieve a uniform velocity profile across the screen.

A form of louvre screen was employed in the 1980s by Thames Water Authority as a smolt trap at Walton water treatment works (Solomon, 1992). The aim of the trap was to provide a means of assessing the efficiency of any other screening device installed at the mouth of the channel. With a cod-end trap in place, bypass acceleration was between 130 and 136%, but when a finer-meshed cod end was installed, flow into the bywash decelerated. With this sub-optimal bywash velocity, it was estimated to be 67% efficient as a smolt trap at maximum discharge, falling to 40-45% at half-flow. Solomon concludes that very much higher efficiencies should have been attainable with increased bywash acceleration.

3.4.2.4 Design and Operational Best Practice

For best performance, louvre screens should be designed with the following characteristics:

- The screen array should be aligned at an angle of 10-15^{o} to the channel axis; the slats should be orientated at 90^{o} to the flow.
- The required slat spacing depends on the size of fish to be diverted, ranging from 30 cm for adult salmon or similarly sized fish, down to 5 cm for juveniles and smaller species. Where smaller slat spacings are needed, they can be arranged so that spacings gradually decrease to the required space along the length of the array, towards the bywash, taking advantage of the reluctance of fish to cross the shear. Flow straighteners should be used to achieve optimal performance.
- Approach velocities should be between 0.3-1.0 ms^{-1} *at all times*.
- Provision should be made for cleaning the louvres, e.g. by having upstream trash racks to catch most of the debris or by having removable slats. Safe access should be provided for this purpose, e.g. via an overhead walkway with safety handrails.
- The screen should run to the full river depth, unless it can be demonstrated that adequate efficiency can be maintained with a partial depth screen (e.g. for surface-swimming fish such as smolts). However, it should not be assumed that all smolts swim at the surface, as smolts tend to sound to the bottom on sensing danger.
- Louvre screens operate best when sited within a headrace canal, or other situations where uniform approach velocities can be achieved. Hydraulic modelling may be beneficial to assess the uniformity of approach flow.
- The bywash entrance design velocity should be around 140% of the screen approach velocity.
- For a more compact arrangement, louvre screens can be arranged in a V-shape (in plan), with the bywash located in the centre (see also Labyrinth screen arrangement (section 3.3).

Low or high velocities will impair screening efficiency, as will any accumulation of debris on the slats. It is important to recognise that they will not prevent fish entry when the water is very slow or static. This means that, for example, on a hydroelectric plant, fish may get past the screen when the turbines are shut down and subsequently be at risk of injury within the turbine(s).

3.4.2.5 Applications

Louvre screens are best suited to canalized waterways where a uniform approach flow can be achieved. They are advantageous over physical screens where large flows must be screened with minimal head loss (e.g. low-head hydroelectric plant). They may be unsuitable for locations subject to inundations of weed, e.g. on chalk streams where weed cutting is carried out.

3.4.2.6 Fish Species/Lifestages

Suitable for salmonid smolts and adults, adult shad, and probably most non-benthic species. Louvre screens are not suitable as fry screens, as the slat spacing would be impracticably small. For adult shad exclusion, the screen would need to be full depth.

3.4.2.7 Ease of retrofitting

Louvre screens are suitable for retrofitting into engineered channels, e.g. hydroelectric headraces or water supply aqueducts. A trash rack placed upstream will assist with debris clearance.

3.4.3 Bubble Curtains

Bubble screens are one of the most basic behavioural barrier types. This form of screen works on the principal of a curtain of bubbles being generated via a perforated tube laid along the riverbed through which compressed air is pumped. The wall of bubbles is usually laid at an angle to the flow, or in a loop around the intake entrance and is used to deflect approaching fish and guide them either into a bywash (*cf.* louvre screen arrangement) or to a point downstream of the intake. The exact nature of the deterrent effect is uncertain and may be due to a combination of visual, auditory or shear-current stimulus (Solomon, 1992).

Plate 3.12 Bubble curtain laid across a small stream

Turnpenny (1998) suggested that from personal experience that bubble curtains work at highest efficiency in flowing channels and when placed at a slight angle to the bank (~12°). This relies upon glancing contact with the fish in order to deflect them across the channel.

Aspects of the design that can effect the efficiency and performance of the screen include the size and spacing of bubbles, volumes of air discharged, air pressure, water velocity, screen layout and illumination (Solomon, 1992).

Several investigations have been carried out over the efficiency of these screens over the last 60 years. One of the first laboratory experiments was carried out in 1942 and found mixed success with different species (Bramsnaes *et al*., 1942). Whilst carp (*Cyprinus carpio*) and pike (*Esox lucius*) were deflected by the screen rainbow trout (*Onchorhynchus mykiss*) were not deterred and passed freely. Many investigations have shown inconclusive results although some have shown a high success rate. A deflection rate of up to 98% was recorded during British Columbian and Ontario Hydro experiments (Brett and MacKinnon, 1953, Patrick et al., 1985) although falling to 80-51% during darkness. This would suggest that a stimulus of reflected light is partially responsible for the screens deflection effects. These results of high deterrent abilities must be looked upon cautiously due to often mixed and inconclusive results from other investigations. Laboratory tests also generally do not allow for extended periods of continuous screen use in which time fish become habituated to the screen stimulus, although this effect is only likely to apply to resident populations rather than actively migrating fish. Field investigations, although few, have resulted in even more mixed opinions over efficiency and have in general resulted in lower efficiencies than laboratory investigations.

3.4.3.1 Installations in the UK

Solomon (1992) reports on bubble curtain trials carried out at the experimental installation at Walton water treatment works on the R. Thames. This comprised six 4m lengths of 50mm diameter galvanized pipe drilled with 2mm diameter holes at 25mm centres along the length. Air was supplied by a blower rated at $348m^3h^{-1}$ discharge @1 bar pressure. Water depth was around 2m. Fish entrainment was compared by monitoring catches in the louvre-screen trap (see above) with and without the bubble curtain operating. The bubble curtain was also operated in conjunction with an array of nine submerged strobe lights flashing at 440 flashes per minute. On four of six occasions when the bubble screen was operated alone, fish entrainment was less than predicted; when both the bubble screen and strobes were operated, entrainment was reduced by an estimated 62.5%. Overall, it was estimated to have reduced entrainment of smolts from 14.4% of the total run to 5.4%.

Experiments carried out on a 70 m-long bubble curtain placed across the entrance to the cooling water intake at Heysham Power Station (Lancashire) resulted in a reduction of fish entrapment by 37% which was significant at the $P<0.001$ level (Turnpenny, 1993). This was an improvement on the previous situation, probably saving some tonnes of juvenile fish each year. Catch rates on the cooling water drum screens were compared for alternating six-hour periods with bubble curtain on or off, and in daylight versus darkness. The bulk of the fish catch comprised sprat (*Sprattus sprattus*) and herring (*Clupea harengus*) but 42 fish species were recorded during the trials, which took place over a 24-day period during the month of February. The bubble curtain also reduced entrainment of brown shrimps (*Crangon crangon*) by 56%. An unexpected outcome of the trials was that the curtain was more effective at night. This was attributed to the nocturnal behaviours of clupeid fishes and shrimps, which tend to disperse vertically into the water column at night. Repulsion was considered by the author to be partly related to physical effects of the rising bubbles and induced currents.

In static and slow-moving conditions bubble curtains are less effective (Turnpenny, 1998). Use of bubble curtains was attempted by the Environment Agency at the intake of the Blackdyke Pumping Station in Lincolnshire. The water supply channel is virtually static and although results were initially positive the success rate reduced over the following weeks, presumably as fish habituated to the stimuli (Turnpenny, 1998). On the other hand fast, turbulent or deep waters can lead to break-up of the bubble sheet with loss of efficiency. This is important as performance may deteriorate at the most critical time for fish that migrate on floodwaters. The maximum reliable depth for a bubble curtain is about 3 m; above this, the bubbles tend to form cords, which split apart, leaving gaps. This could potentially be overcome by placing bubble pipes at height intervals of ≤3 m in the water column but this is not straightforward and puts the pipes at risk of damage by flood debris.

To achieve the most effective performance from a bubble curtain a strong flow of air must be used. The most economical way of generating the air supply depends on the flow rate, depth and application of the specific project. When used in less than 2m of water a simple, low pressure rotary blower gives economical and reliable mechanical performance, whereas for greater depths a multi-stage blower or air compressor may be needed to overcome the greater hydrostatic pressure (Turnpenny, 1998).

Before installing a bubble curtain certain behaviours of bubbles must be taken into account. Bubbles larger than 2mm in size will rise through the water at a rate of approximately $0.25ms^{-1}$; smaller bubble sizes are not recommended in moving water, as they rise too slowly. Before installation, the surfacing line of the bubbles should be calculated from the velocity of the water in order to determine the correct positioning of the barrier on the bed. Where a bywash is used, the width of the mouth must be able to accommodate any variation in surfacing position, otherwise fish may not find the entrance. It may be necessary to have more than one bubble pipe in order to accommodate any changes in flow conditions. The bubble curtain itself will also create a certain degree of turbulence and may therefore require some fine-tuning of airflow to achieve a uniform curtain of bubbles (Turnpenny, 1998).

A bubble curtain was recently installed at the entrance to the cooling water intake at Fawley Power Station (Hampshire). An acoustic fish deterrent (AFD) system was also installed. The application is unusual, since the curtain is not intended to deflect fish directly (although it may have some benefit in this respect) but to help prevent a build up of silt in the channel, which might increase the intake velocity and impair the propagation of sound from the AFD.

3.4.3.2 Bubble screens in combination with other behavioural stimuli

Combinations of bubble curtains with other types of behavioural screens generally achieve greater efficiencies than when used alone. The best combinations involve adding acoustic and or artificial light stimuli.

A combination of bubble curtains and strobe lights used at Walton-on-Thames has been described above. Another was tested by Sager *et al*. (1987). Very low efficiencies were found for bubble curtains alone with very little effect being seen in all species. On combining bubble screens with strobe lights at a flash rate of 300 min^{-1}, up to 100% efficiency was seen in spot (*Leiostomus xanthurus*), 68% for menhaden (*Brevoortia tyrannus*) and 36% for white perch (*Morone americana*).

The second option involves the combination of a sound generator with a bubble sheet creating a ‘wall of sound’ that can be used to guide fish into a bywash. The system is known as a ‘Bioacoustic Fish Fence’ (BAFF™) and is designed by Fish Guidance Systems (FGS). Further details of light and acoustic barriers are given below.

3.4.3.3 Design Best Practice

Key points in good bubble curtain design and operation are:

- ensure that a uniform bubble sheet, free of large gaps, is maintained under all flow conditions where fish exclusion is required; hole spacings in bubble curtain design are considered roughly analogous to bar separations in bar screens, so do not expect 15 cm hole spacings to exclude smolts! Small holes of 0.5-2 mm bore spaced at 1-3 cm are usually effective.
- allow for plenty of air flow: at least 1 ls^{-1} per metre of barrier length and up to 4 ls^{-1};
- estimate the velocity profile along the proposed screen line for the range of expected conditions and calculate the surfacing lines under various scenarios, making sure that the curtain leads into the bywash entrance (if applicable);
- select a position where the depth along the line is as uniform as possible to avoid loss of air flow in deeper areas; avoid areas where the bed is unstable;
- for best results, angle the curtain near-parallel to the flow and preferably at an angle of more than 15^{o} to the channel flow;
- check the bubble pipe regularly and keep it clear of bed materials and biofouling; blockage is more likely to occur if the curtain is not operated continuously; check for uniformity of the surface air plume.
- warning systems (e.g. via telemetry links or visual inspection) should be provided to inform plant operators of air supply failure.
- The equipment requires regular maintenance and service intervals should be displayed and logged in the plant control room.
- Back-up power or interlocks with pump controls may need to be provided to ensure that pumping does not occur when the system has lost power.

3.4.3.4 Applications

Bubble curtains may be used as a low-cost behavioural barrier in flowing water situations where high performance is not demanded. Fast-flowing or deep water may lead to an unacceptable breakup of the curtain's integrity, reducing effectiveness.

3.4.3.5 Fish Species and Lifestages

Many fish species, including UK salmonids, clupeids and cyprinids can be deflected by a bubble barrier but habituation is rapid. Consequently they are best suited to deflection of migrating fish in rivers, or of fish moving with the tide in tidal systems. In these situations contact time is likely to be short. Bubble curtains alone are probably ineffective for eels and lampreys, but the addition of artificial lights or strobe lights enhances their efficiency for eel deflection (see below). There is a risk, however, that illumination may attract some species, for example 3-spined stickleback (*Gasterosteus aculeatus*) (Hadderingh, 1982).

3.4.3.6 Ease of retrofitting

Bubble curtains can easily be retrofitted to almost any existing application.

3.4.4 Electric Barriers

Electric intake screens were first developed in the 1950s by MAFF Fisheries Laboratory. After their development several were installed across the UK but most were later removed over fears of their safety. The effectiveness of such screens is uncertain and has historically been thrown into doubt. As well as uncertainty over the efficiency there are also concerns about safety and the risks that they may pose to both animals and humans, although that is not to say that all electric screens are inherently unsafe.

A critical issue with electric screens is that the potential difference experienced by a fish is dependent upon the source voltage and the size of the fish. Larger fish are exposed to a proportionately greater voltage than smaller fish. The electric field must be strong enough to repel small fish but at the same time may be too strong for larger fish, stunning them and causing them to be drawn into the intake (Turnpenny, 1998).

The MAFF electric screen was an array of vertical electrodes set approximately 15-30cm apart and of alternating polarity. They were arranged across the intake entrance throughout the depth of the water column. Upon energising, a local electric field is created designed to repel fish.

More recently a USA company[16] has developed a newer version of the electric fish screen called a Graduated Field Fish Barrier (GFFB™), which claims to be both safer and more effective than traditional designs. The GFFB™ uses direct current (DC) which is less stressful to fish than an alternating current (AC). Short pulses energise a parallel array of electrodes. To produce the most effective electric field for fish deterrence it is desirable for the electric lines to run from head to tail along the fish. As fish instinctively swim with their head into the flow the most efficient design is to therefore have electric field lines running parallel to the water flow. When the fish is crosswise to the field it will receive no shock.

The most important feature of the GFFB™ is the graduated field itself. An increasing voltage field is produced along the array. This results in larger fish being affected by the electric field at an early stage of the array and gradually smaller and smaller fish are affected as they penetrate further into the array. Large fish turn and are carried out or swim away from the intake before they are stunned and smaller fish are deterred at a later stage.

The GFFB™ is supplied in versions for upstream or downstream guidance (see also section 3.4). For downstream guidance the system differs in that it has an abrupt leading field edge designed to invoke a startle reaction in the fish causing them to dart away from the array. The fish are guided into a bywash system by angling the array in relation to flow (Figure 3.13).

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[16] Smith root Inc., 14014 NE Salmon Creek Avenue, Vancouver, WA 98686, USA.

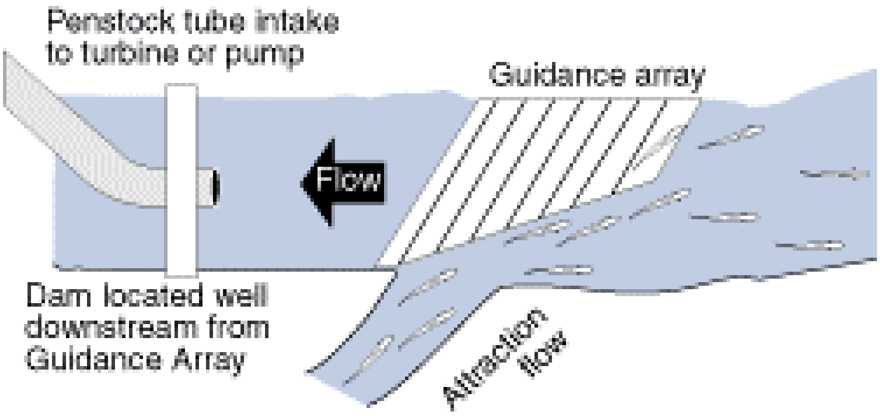

Figure 3.13 Diagram of the GFFB™ in use as a downstream guidance system (www.smith-root.com). Note that fish often turn to face the flow when confronted with a barrier.

Safety to humans is obviously a concern as an electric field is still present in this design. The manufacturers claim that the short electrical pulses used by this system are much less hazardous to humans. Safety can, however, be further improved by limiting public access, a course of action which is recommended.

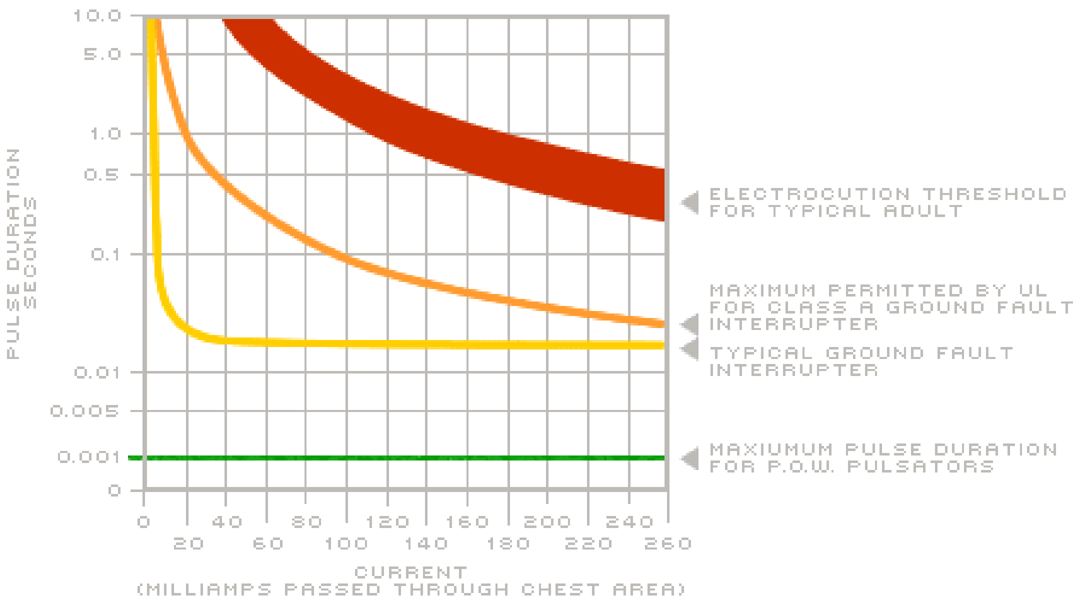

Figure 3.14 Electrical pulse duration and current data for the GFFB™ pulse generator in relation to human risk criteria (www.smith-root.com).

Hilgert (1992) carried out investigations on both the effectiveness of the system and long and short-term physiological impacts on adult salmonids and their gametes. A test on the potential injury to pre-spawning adults resulted in no injuries or mortality to adult coho salmon (*Oncorhynchus kisutch*) after exposure to an electric field of 0.2 to 0.9 Vcm^{-1} for 10 seconds. It was also concluded that there was no effect on gamete viability or early development after exposure of up to 0.9 $V.cm^{-1}$ for 10 seconds. The effectiveness of the system as a barrier was monitored at the Quilcene National Hatchery and although the system was generally successful fish did pass during high water conditions. The problem has since been overcome by the addition of an automatic pulse-width control, which regulates the electrical output in relation to flow conditions.

Barwick and Miller (1994) attempted to simulate the downstream migration conditions in a hydroelectric headrace canal. A variety of North American fish (salmonids and clupeids) were introduced to the canal whilst the GFFB™ was operated at 10 pulses per second. The percentage of fish not passing the barrier while water was flowing was 83% with an electric field strength of 1.5 $V.cm^{-1}$; this rose to 97% when the water was static. These results are encouraging but it should be noted that the size of the canal was comparatively small, being 2 m wide x 1 m deep.

Results of the Graduated Field Fish Barrier seem to be more promising than the early MAFF-designed electric barrier although further testing is still necessary.

A German company, Geiger International GmbH (website: http://www.geiger-international.de) also markets an electric fish screen, known as the Fipro-Fimat Fish Repelling Device. It uses a randomized electrical pulse generator, with the stated purpose of reducing habituation to the electrical signal. The system is intended to be detected by fish some 5-10m upstream of the electrode array. No information is given on the website about the effectiveness of the system as a fish barrier, nor concerning health and safety aspects, nor of any existing installations of the system.

3.4.4.1 Installations in the UK

Other than perhaps the odd MAFF-type screen remaining in place, no electric intake barrier installations are known of in the UK. Installations at outfalls are discussed below (section 3.6).

3.4.4.2 Design Best Practice

Electric screens in general are not recommended for intake screening. The GFFB™ may be more suitable, owing to its use of a graduated field, which should, in theory, lessen the risk of larger fish becoming stunned while smaller fish remain insensitive to the field. There has been no scientific testing of the GFFB™ for intake screening and therefore its performance is unknown and it is premature to discuss 'best practice'. Where testing is contemplated, the manufacturer's recommendations should be followed. Warning systems (e.g. via telemetry links) should be provided to inform plant operators of failure. In general for electric screens (for intake and outfall applications), the following points should be noted:

- The equipment should be regularly maintained and service records should be displayed in the plant control room.
- Visible indicators of the operational status of the electric screen should be displayed at or close to the intake to inform operational and enforcement personnel.
- Back-up power or interlocks with pump controls may need to be provided to ensure that pumping does not occur when the system has lost power.

3.4.4.3 Applications

Electric barriers are affected by water conductivity and are unsuitable for marine or brackish water environments.

3.4.4.4 Fish Species and Lifestages

Electric barriers are best suited to the deflection of large fish, as relatively low, safe voltages can be used; conversely, it is unlikely that small fry could be protected without using excessively high voltage. The GFFB™ would appear to lend itself to diversion of eels and lampreys, being elongate species that swim close to the riverbed. This merits further testing in the UK.

3.4.4.5 Ease of Retrofitting

The traditional MAFF-type electrode array was a very simple retrofit to almost any kind of intake. The GFFB™ is less straightforward to retrofit, as the electrodes must be attached to a flat bed/walls of insulating material. Nevertheless, this is not usually an insuperable civil engineering task.

3.4.5 Acoustic Guidance

The hearing range of most fish falls within the audible range to humans, maximum sensitivity lying in the sub-3 kHz band down to infrasound frequencies (Hawkins, 1981; Sand and Karlsen, 1986). Acoustic fish deterrent (AFD) systems mostly exploit hearing sensitivity in the 20 to 500 Hz range, although infrasound (<20 Hz) and ultrasound (usually >100 kHz) systems have been used with some success (Knudsen *et al*., 1992, 1994, 1997; Carslon, 1995; Turnpenny *et al.*, 1998; Sand *et al.*, 2001). The usefulness of ultrasound in this context appears to be limited to guidance of clupeid species, which have auditory sensitivity at these frequencies, possibly an evolutionary adaptation to evade cetacean predators (Mann *et al.*, 1997).

Early work in this field was by American researchers Loeffelman *et al.* (1991a,b) and Klinect *et al.*(1992), who discovered that underwater machinery noise emitted by bulb turbines at Racine hydroelectric plant (Columbia River, USA) caused fish to avoid areas close to the turbine intakes. Bulb turbines differ from most designs in that the generating machinery is submerged. These researchers investigated acoustic repulsion further and developed and patented a method of signal development, based on recording and analysing fish communication sounds. The process involves the spectral analysis of fish sounds, followed by the synthesis of a signal containing key elements of the spectrum. The synthesised sound signals were then amplified electronically and generated underwater using military sound projectors. Field trials showed that significant fish avoidance could be achieved using this technology, sparking interest in the method for applications in the UK. The Energy Technology Support Unit (ETSU), Harwell, funded work initially to establish whether and how the technique could be applied to fish protection at tidal power schemes. The resulting collaborative study with the American team (Turnpenny *et al*., 1993) demonstrated that repellent signals could be developed for European fish species, although it was shown that a more empirical method of signal development than that proposed by Loeffelman was more cost-effective. The species studied included Atlantic salmon, trout (*Salmo trutta*) and various estuarine species. Subsequent experiments have found signals that are effective against other fish, including Twaite shad, most cyprinid and percid species and a wide range of marine and estuarine fishes. In recent years there have been considerable advances in the field of acoustic fish guidance and sound-based systems are now widely used and validated. Nevertheless, the apparent failure of acoustic methods in various scientific trials (see e.g. Turnpenny *et al*., 1994; Goetz *et al*., 2001) highlights the fact that this is not an easy or universally suitable technology.

Plate 3.13 Acoustic sound projectors being prepared for installation at Amer Power Station (The Netherlands) (courtesy Fish Guidance Systems Ltd)

3.4.5.1 Sound Signal Characteristics

AFD sound signals need to have maximum effect for minimum energy input. Low frequency (LF) sound (10 Hz – 3kHz) is used for all species other than clupeids; for clupeids either low frequency or ultrasound can be used for good results.

Two main methods of generating a LF acoustic barrier are presently in use in Europe. One, known as the SPA™[17] (Sound Projector Array), uses arrays of underwater transducers or "sound projectors" to produce a diffuse field of sound that will block fish movement. The other, known as the BAFF™ (Bio-Acoustic Fish Fence) employs sound sources coupled to a bubble curtain (see also discussion of bubble barriers above) to produce a discreet "wall of sound" that can be used for more precise guidance of fish, e.g. into a bywash channel. The BAFF™ system is used primarily for diversion of fish into bywash channels rather than for blockage.

Benefits of using LF sound signals are:

- Low-frequency sound (unlike ultrasound or light) penetrates even the most turbid waters.
- Detection of sound and vibration is one of the primary sensory modalities in fish, especially in waters of low transparency; most fish are sensitive to LF sound.

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[17] Fish Guidance Systems Ltd, Belmore Hill Court, Owslebury, Winchester, Hants SO21 1 JW. Website: www.fish-guide.com

Lambert *et al.* (1997) identified the following key signal characteristics for a LF SPA system:

1. The sound signal should be within the frequency spectrum 10 Hz – 3 kHz.
2. The nature of the signal should be repellent to fish. Pure tones do not deter fish, except at very low frequencies that are difficult to generate (e.g. 10 Hz) or at very high sound pressure levels, which are expensive to generate. The most cost-effective deterrent signals use either a blend of different frequencies applied as a pulse or crescendo, or a 'chirp' comprising sweep across a frequency band.
3. The sound level received by the fish at the required point of deflection should be sufficiently above ambient noise level (typically at least ten times, or >20dB), although this depends on the species of fish and the type of signal).

More recent investigation helps to clarify the last of these points. Nedwell *et al.* (in press) have proposed that the degree of reaction to sound in fish cannot be predicted from just the received sound level and the background noise level without knowledge of the hearing sensitivity of the fish, as expressed by an audiogram (plot of hearing sensitivity on a decibel or dB scale versus sound frequency). Based on field trials, they propose the following approximate levels in relation to fish behaviour; the levels shown are the peak sound pressure levels calculated when the audiogram values are subtracted from the received noise spectrum and are known as $dB(ht)_{species}$ levels[18]:

Sound Level ($dB(ht)_{species}$)	Fish Behaviour
+30 dB	Threshold of visible reaction in more sensitive individuals
+50dB	Most fish swim away from the sound
+70dB	Strong aversive reaction.

While this advice is an advance, it is not complete, as the shape of the sound signal also influences the degree of fish reaction (Turnpenny *et al*., 1983).

3.4.5.2 SPA System Hardware

A SPA acoustic deflection system comprises the following components, arranged as shown in Figure 3.16:

- an electronic signal generator,
- one or more power amplifiers,
- an array of underwater sound projectors,
- inter-connecting cables.

[18] 'ht' stands for 'hearing threshold'; the subscript 'species' represents the particular species; thus, $dBht_{salmon}$ measures the peak level of a sound emission as heard by a salmon.

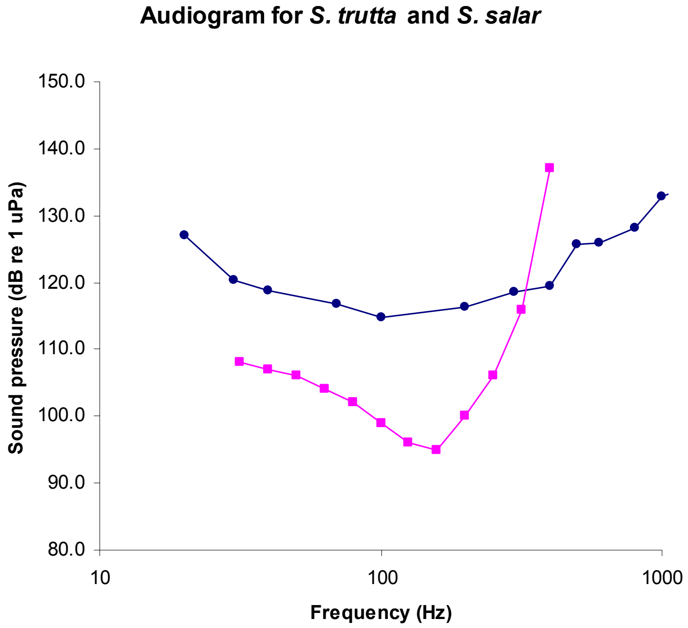

Figure 3.15 Audiograms of Atlantic salmon (*Salmo salar*) (■) and trout (*S. trutta*) (●) (Nedwell *et al*., 2003).

The system is analogous to a public address or domestic hi-fi system. The signal is usually recorded onto an EPROM-chip and the signal generator may contain a number of these, which can be manually selected or played at random or in rotation. One or more high-power audio amplifiers that are matched and filtered to suit the sound projectors amplify the signal. The sound projectors are underwater transducers, analogous to loudspeakers. These are electromagnetic devices, with a piston-type arrangement connected to a rubber diaphragm.

As there is an air cavity behind the diaphragm, sound projectors are susceptible to pressure change, increasing pressure tending to force the diaphragm inwards. This limits the throw of the diaphragm and must be compensated by a balancing pressure from behind. Sound projectors are therefore either pre-pressurised to cope with the expected operating depth, or else have some form of pressure compensation device. The latter type is best suited to use at fixed positions in tidal waters.

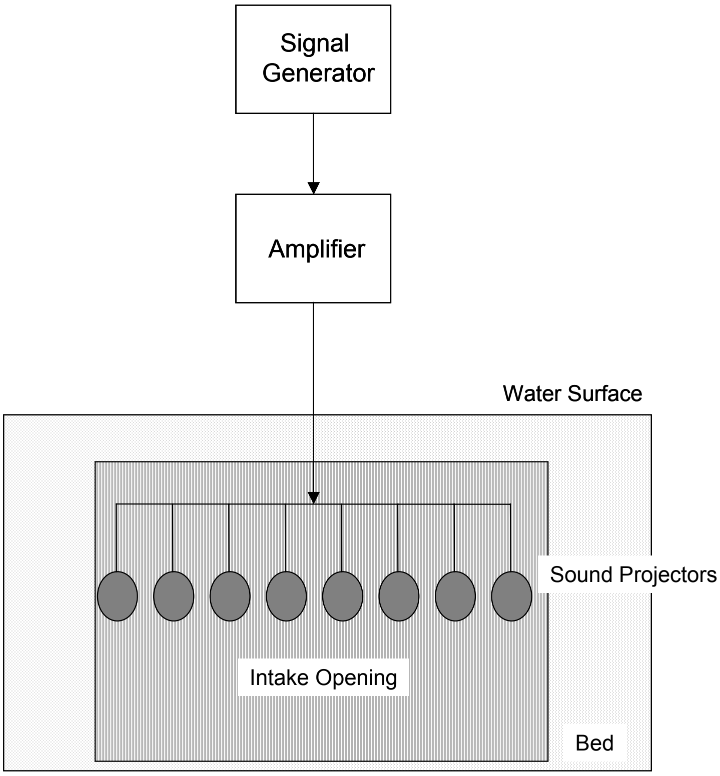

Figure 3.16 Schematic layout of SPA AFD system (intake elevation)

3.4.5.3 Acoustic Field Design

For best results, the sound projectors are located close to the intake opening, so as to yield high signal particle velocities in the paths of incoming fish. The optimum number and positioning of sound projectors can be determined using an acoustic model such as PrISM™[19] to predict the resulting sound pressure and particle-movement field (see example in Figure 3.17). The PrISM model also accommodates information on the geometry and bathymetry of the intake area and adjacent structures, and ensures that surface and bed reflections are taken into account in the final system design.

The ideal sound field should form a steep acoustic gradient approaching the entrance, free from acoustic nulls caused by destructive interference within the sound field. The presence of such nulls could cause fish to be guided into, rather than away from the intake (Lambert *et al.*, 1998). After commissioning, measurements can be taken to confirm the field characteristics and to ensure that there is no risk of deterring fish over too large an area.

[19]Subacoustech Ltd, Chase Mill, Bishops Waltham, Hants, SO32 1AH

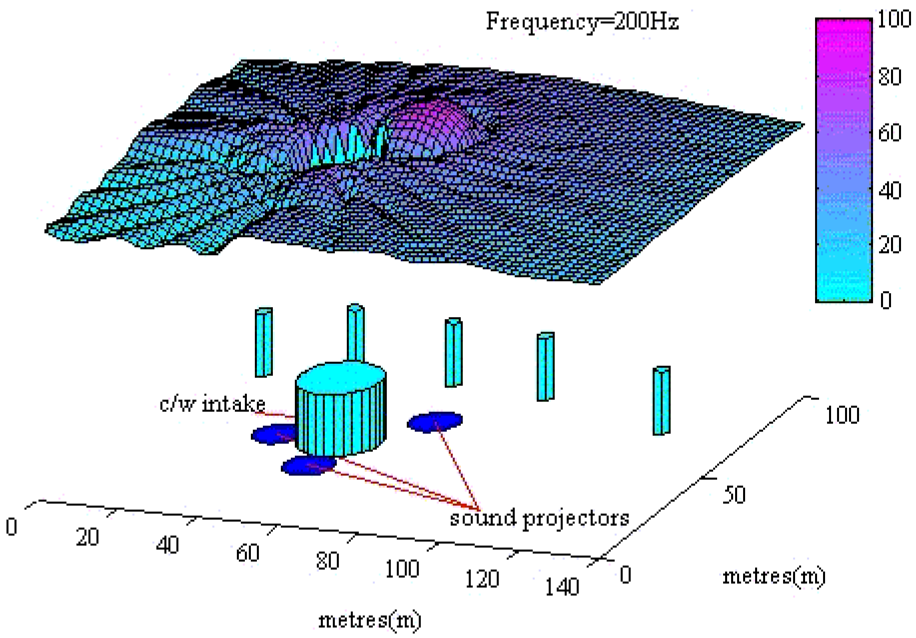

Figure 3.17 PrISM acoustic model of the acoustic deterrent field at Doel nuclear power station, Belgium (Subacoustech Ltd).

The lower part of the diagram shows the positions of the sound projector clusters around the intake caisson. The five pale blue columns are dolphins that protect the offshore side of the intake from damage by shipping. The upper part of the plot shows the acoustic field at 200 Hz, represented in units of dB re 1μPa. In practice, the model is run for a variety of tidal heights and over the full range of signal frequencies to be used.

3.4.5.4 Effectiveness of SPA Acoustic Deterrents

Turnpenny *et al*. (1998) showed that well designed LF SPA acoustic deterrent systems offer amongst the highest deflection efficiencies available from any type of behavioural barrier. Values of up to around 80% can be attained for many teleost species possessing a developed swimbladder, with recorded values of between 90% and 100% for the most sensitive species such as herring. Table 3.2 shows test results from various installations that have been studied.

The longest-running trials of a SPA system have been conducted at Doel Nuclear Power Station on the Zeeschelde Estuary (Belgium). Since the installation of an FGS SPA system in 1997, regular monitoring has been carried out by Leuven University (Maes *et al*, 2004). As in most trials of this kind, comparisons have been made of the fish impingement rates on alternate days with the sound system turned on or off. Although the species captured have been primarily of estuarine or marine origin, quantities of freshwater fishes have been caught.

As with other behavioural systems, habituation to the stimuli must be considered. Habituation, again, is not a problem with migratory or highly mobile fish, which are rarely in contact with the sound for a long period. Nevertheless, it is an aspect relevant to resident fish populations, where fish may be in contact with the sound for extended periods. Acoustic deterrent signals are developed specifically to minimise the risk of habituation over a period of a few days at least (Turnpenny *et al.*, 1993), but for more extended exposure the deterrent signal may need to be altered at intervals (e.g. once per day). Signal generators with multi-signal capability may be used for this purpose.

Table 3.2 Results from Acoustic Barrier Trials

Location	Fish Species	Diversion Efficiency, Significance Level	Reference
R. Foss flood relief pumping station, York (32 $m^3.s^{-1}$) [Freshwater- river]	Chub (*Leuciscus cephalus*) Roach (*Rutilus rutilus*) Bleak (*Alburnus alburnus*) Bream (*Abramis brama*) Perch (*Perca fluviatilis*) All species	87% P<0.02 68% P<0.001 72% P<0.05 74% P<0.05 56% P<0.05 80% P<0.001	Wood *et al*., 1994
Hartlepool nuclear power station (34 $m^3.s^{-1}$) [marine]	Herring (*Clupea harengus*) Sprat (*Sprattus sprattus*) Whiting (*Merlangius merlangus*) Other swimbladder fish Non-swimbladder fish	79% P<0.01 60% P<0.05 54% P<0.05 55% P<0.05 16% P>0.05	Turnpenny *et al*., 1995; Turnpenny & Nedwell, in press.
Blantyre Hydro-electric plant (20 $m^3.s^{-1}$) [Freshwater - river]	Salmon (*Salmo salar*) Mixed cyprinid species	74% P<0.02 92% P<0.02	Anon., 1996
Farmoor Water Supply Intake [Freshwater - river]	Coarse fish, mainly perch (*Perca fluviatilis*)	87% P<0.02	Turnpenny *et al*., 1998
Doel 3 & 4 Nuclear Power Station [Estuarine]	Herring Sprat Smelt (*Osmerus eperlanus*) Bass (*Dicentrarchus labrax*) Flounder (*Platichthys flesus*) Gobies (*Pomatoschistus spp.*) Crustaceans	95% P<0.001 88% P<0.001 64% P=0.004 76% P<0.001 38% P<0.05 46% P=0.028 50% P>0.05	Maes *et al*., 2004

3.4.5.5 SPA Maintenance and Monitoring Requirements

Sound projectors are electro-mechanical devices and regular maintenance of them is required to maintain optimum performance. This involves removing the underwater units to replace perished seals and to check moving components. Also, it is desirable to raise and clean the units occasionally to remove any build-up of silt or fouling. It is essential that some mechanism be provided to bring sound projectors to the surface for maintenance, without the need to use divers.

As it is difficult to check the performance of submerged equipment, diagnostic units can be attached to the shore-based electronics to monitor performance of the sound projectors and associated electronics. These can be linked by telemetry systems to control centres in the case of remote sites. Performance of the systems can then be electronically logged and made available to regulatory enforcement staff.

3.4.5.6 Potential Public Noise Nuisance

Although emitting frequencies that are within the human audible range, the location of the sound projectors below water generally prevents any audible acoustic propagation into the air above. SPA systems are occasionally just audible from at the intake position under exceptionally quiet conditions, particularly if they have been mounted on any metallic structures that project out from the water. A SPA system operated by the Environment Agency at the River Foss flood relief pumping station in York is located <50m from a city-centre hotel and has operated during pumping since 1995 without complaint.

3.4.5.7 Installations in the UK

SPA AFD systems are widely used in the UK, with examples at locations shown in Table 3.2. Also shown is other information about the specifications of the systems, the operating environment and the types of fish to be protected.

Table 3.3 Examples of Sound Projector Array AFD Systems Installed in the UK (source: Fish Guidance Systems Ltd)

Application	Location & Max. Intake Flow	Main System Components	Main Fish to be Protected
Estuarine Power Stations	Great Yarmouth, Norfolk 9.3m^3s^{-1}	Signal generator, 8 x large sound projectors, 8 x 450W amplifiers	Estuarine & marine fish, mixed
	Fawley, Hampshire 31m^3s^{-1}	Signal generator, 8 x large sound projectors, 8 x 450W amplifiers	Estuarine & marine fish, mixed, salmon & sea trout
	Shoreham, West Sussex 5.6m^3s^{-1}	Signal generator, 6 x large sound projectors, 6 x 450W amplifiers	Estuarine & marine fish, mixed & sea trout
Potable Water Intakes	Surbiton, R. Thames 2.7m^3s^{-1}	Signal generator, 8 x small sound projectors, 1 x 450W amplifiers	Salmonids and mixed coarse fish
	Laleham, R. Thames 12m^3s^{-1}	Signal generator, 8 x small sound projectors, 1 x 450W amplifiers	Salmonids and mixed coarse fish
	Hythe End, R. Thames 3.2m^3s^{-1}	Signal generator, 8 x small sound projectors, 1 x 450W amplifiers	Salmonids and mixed coarse fish
	Datchet, R. Thames 24m^3s^{-1}	Signal generator, 8 x small sound projectors, 1 x 450W amplifiers	Salmonids and mixed coarse fish
	Walton, R. Thames 14m^3s^{-1}	Signal generator, 8 x small sound projectors, 1 x 450W amplifiers	Salmonids and mixed coarse fish
	Hampton, R. Thames 5.8m^3s^{-1}	Signal generator, 8 x small sound projectors, 1 x 450W amplifiers	Salmonids and mixed coarse fish
	Farmoor, R. Thames 2.7m^3s^{-1}	Signal generator, 8 x small sound projectors, 1 x 450W amplifiers	Mixed coarse fish
	Canaston, W. Cleddau 0.70 m^3s^{-1}	Signal generator, 8 x small sound projectors, 1 x 450W amplifiers	Salmonids
	Kilgram Bridge, R. Nidd 0.54 m^3s^{-1}	Signal generator, 4 x large sound projectors, 4 x 450W amplifiers	Salmonids and mixed coarse fish
	Barcombe, R. Sussex Ouse, 0.845 m^3s^{-1}	Signal generator, 4 x small sound projectors, 1 x 450W amplifiers	Salmonids and mixed coarse fish

3.4.5.8 Evanescent Sound: The BioAcoustic Fish Fence (BAFF™)

An evanescent (non-propagating) sound field is one that decays rapidly with distance from its source. The Bio-Acoustic Fish Fence (BAFF™) is a proprietary product of Fish Guidance Systems Ltd (FGS) of Southampton, England that uses a combination of a sound source and a bubble curtain to create a field that is largely contained within the bubble sheet (Nedwell and Turnpenny, 1997). Physically, it comprises an electromagnetic or pneumatic sound transducer coupled to a bubble-sheet generator, causing sound waves to propagate within the rising curtain of bubbles. The sound is contained within the bubble curtain as a result of refraction, since the velocity of sound in a bubble-water mixture differs from that in either water or air alone. The sound level inside the bubble curtain may be as high as 170 dB re 1μPa, typically decaying to 5% of this value within 0.5-1 m from the bubble sheet (Figure 3.18). It can be deployed in much the same way as a standard bubble curtain, but its effectiveness as a fish barrier is greatly enhanced by the addition of a repellent sound signal. The characteristics of the sound signals are similar to those used in SPA systems, i.e. within the 20-500 Hz frequency range and using frequency or amplitude sweeps. Typically, the BAFF™ is used to divert fish from a major flow, e.g. entering a turbine, into the minor flow of a bywash channel. Recently, the Illinois Natural History Survey have conducted trials of the BAFF™ in a concrete raceway to assess its effectiveness as a barrier to the migration of invasive Asian carp species *Hypophthalmichthys nobilis* (Taylor *et al.*, in press). Initial trials using a 20-500Hz signal yielded only moderate performance, with 56% of approaches being successfully repelled. The signal was subsequently replaced by a 20-2000Hz signal, which increased deflection efficiency to 95%. This was comparable to results obtained with the GFFB electrical barrier in parallel tests.

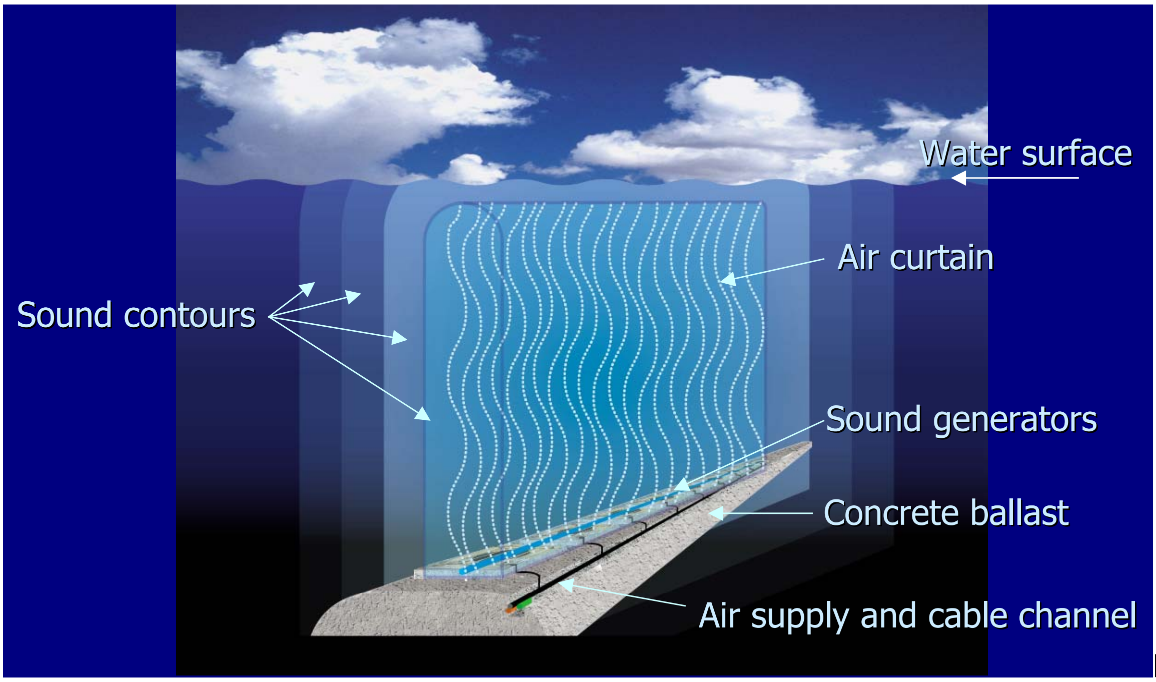

Figure 3.18 Schematic of BAFF™ acoustic bubble curtain (Fish Guidance Systems Ltd)

3.4.5.9 Installations in the UK

Investigations of a BAFF™ angled at 15^{o} system across a small (~5m width) mill stream of the River Frome (Dorset) yielded deflection rate of 20.3-43.8% in daylight and 72.9-73.8% in darkness with Atlantic salmon smolts (Welton *et al.*, 2002). The sound is generated pneumatically, with frequencies in the 50-600Hz band. A larger (24 m-long) BAFF placed at an angle across the main river to divert descending smolts into the mill stream for census purposes has regularly achieved efficiencies of 95-98% (S. Welton, personal communication). The river depth along the BAFF line is about 1.2m. The trials were conducted as part of an Environment Agency research programme. The better performance of the larger BAFF may have been due to the larger 'bywash' created by the entrance to the millstream. Observations at the BAFF located in the millstream demonstrated that many of the fish were effectively diverted by the BAFF but then turned back at the bywash entrance, owing perhaps to inadequate attraction flow. Such fish would often make several attempts, circling in the area upstream of the BAFF and finally 'rushing' the bubble curtain and passing through. A more detailed analysis of fish behaviour in front of a BAFF is provided by Turnpenny *et al*. (2002, in press), based on observations of fish fitted with float-tags.

A pneumatic BAFF is installed at a small hydropower scheme at Backbarrow on the R. Leven (Cumbria). It was installed in the headrace canal, principally to divert salmonid smolts into a bywash, which uses between 2 and 5% of the turbine flow as attraction flow. It also operates with frequencies in the 50-600Hz band. Performance trials have been carried out by the Environment Agency, by placing a rotary-screw smolt trap in the flow behind the BAFF to sample fish passing through the air curtain and simultaneously counting fish entering the bywash (Spiby, 2004). Bywash monitoring was carried out using a submerged video camera in the bywash entrance with infra-red illumination, connected to a video recorder. Observations were made over 44 days during the spring of 2003, during which time 109 fish were recorded. These were distributed as follows:

- 56.9% entered the bywash (video)
- 30.3% swam back into the headrace (video)
- 5.5% uncertain- either entered bywash or swam back into headrace (video)
- 7.3% passed through BAFF (rotary screw trap).

Spiby proposed a best estimate of 92.7% of fish being prevented from entering the turbine, although as only 56.9% were seen to enter the bywash, the true deflection efficiency may have been between 56.9% and 92.7%. Only 2.7% of the 7.3% of fish estimated to pass through the turbine were smolts. The author drew attention to a number of limitations of the study, particularly with regard to the quality of video monitoring and the performance of the trap under low flow or heavy weed conditions and recommended that further proving trials should be conducted.

3.4.5.10 Infrasound

Whereas the acoustic techniques described above may contain frequencies extending down into the infrasound (<20Hz) region, true infrasound devices are designed to emit primarily in this waveband. A review is given by Sand *et al.* (2001). Normally, the sound is generated by a mechanical, motor-driven device, driving pistons to generate high particle velocities in the region of the source. For Atlantic salmon smolts, sound intensities above $10^{-1}ms^{-2}$ at 10Hz are an effective deterrent and have been used successfully to block channels. Sand *et al*. mention mechanical reliability and metal fatigue problems with the source devices that have limited their practicability in the past but these may be reduced eliminated with further development. A particular interest with infrasound lies in the finding that adult silver eels (*Anguilla anguilla*) migrations were successfully influenced by an infrasound source in river trials. Audiogram measurements have shown that eels are most sensitive to sound pressure at frequencies centering on 90Hz but to vibrations of around 40Hz (Jerkø *et al*, 1989). Given the relatively limited range of screening methods suitable for eels, particularly in the hydropower and thermal power context, infrasound or low frequency sound merits further investigation.

3.4.5.11 Ultrasound Transducer Arrays

Ultrasound systems have so far been used mainly in north America, where arrays of ultrasound transmitters have been fitted around intake structures to repel shad and herring species (Carlson, 1995). Ultrasound may be worth considering for some UK applications, for example where shad are present, although shad also show a good sensitivity to LF systems, to which clupeids are more sensitive than ultrasound (Mann *et al*., 1997). The latter have the advantage of also repelling non-clupeid species.

3.4.5.12 Acoustic Attraction

While most studies have reported the use of acoustic stimuli as a fish deterrent, Patrick *et al.* (2001) demonstrated in tank experiments that eels (*Anguilla rostrata*) were attracted towards a transducer emitting a “complex signal” containing frequencies of <1000Hz. The signal characteristics were not described beyond this and the levels involved are not stated, although the source level was < 190µPa @1m. The authors suggest that sound may have some potential for attracting eels towards bywashes.

3.4.5.13 Design and Operational Best Practice

AFD systems should be installed according to manufacturers’ specifications. Important considerations are:

- Background noise levels should be measured prior to AFD specification to ensure that the signal is not going to be masked by noise from pumps, turbines, etc..
- For SPA systems, acoustic modelling (e.g. using PrISM™) is essential for all but the smallest applications. This should also be used to ensure that the spread of the sound field is not excessive, which might interfere with movements of migratory fish or cause local loss of habitat. Levels should also be measured at commissioning to validate predicted values.
- Diagnostic/monitoring systems should be fitted so that the performance of the underwater equipment can be monitored e.g. from a plant control room. Some form of indicator should be fitted at the abstraction point to show the operational status to operational and enforcement staff.
- Provision should be made for retrieving the underwater equipment for servicing.
- Some redundancy (i.e. using more sound sources than are strictly needed) is desirable to allow for sound projector failures.
- The equipment requires regular maintenance and service intervals should be displayed and logged in the plant control room.
- Back-up power or interlocks with pump controls may need to be provided to ensure that pumping does not occur when the system has lost power.

- In the case of the BAFF™, the recommendations made regarding bubble curtains (see above) also apply, as do physical limitations regarding water depth and flow.

3.4.5.14 Applications

Acoustic fish deterrents are particularly suited to high flow rate intakes where positive exclusion screens are impractical owing to the hydraulic head loss or the risk of screen blockage and where <100% exclusion is acceptable. Electrical power is required, which makes them unsuitable for unpowered, remote sites. There are more than sixty installations in Britain, Europe and North America, with applications including potable water intakes, flood relief pumping stations, thermal and hydroelectric power plant and a fish census station. SPA and BAFF™ are also being tested in the USA for possible use as invasive species barriers against the spread of Asian carp species, with excellent results to date (Taylor *et al*., in press).

Since estuarine and coastal power stations tend to draw in large quantities of hearing-sensitive pelagic species, such as sprat, herring and smelt, AFDs have been found to yield large reductions in catch of these species. Systems have recently been installed in the UK at new CCGT power stations at Shoreham (W. Sussex) and Great Yarmouth (Norfolk) and retrofitted to Fawley Power Station (Hampshire). These stations also operate fish return techniques that put back to the wild any hearing-insensitive animals that get past the AFD system. These are mainly eels, flatfishes and other benthic species, as well as shrimps and crabs. Post-commissioning surveys conducted at Shoreham in the three years since its completion suggest that it has the lowest fish catch of any major British coastal power station.

3.4.5.15 Species and Lifestages

AFD systems are best suited to fishes with moderate to high hearing sensitivity. Best results are obtained with hearing specialists, e.g. clupeids (herrings and shads), cyprinids, other sensitive species including smelt (*Osmerus eperlanus*) and bass (*Dicentrarchus labrax*). Non-specialist species with a fully developed swim bladder are also amenable to AFD guidance, e.g. salmonids and gadoids. Species with a poorly developed or no swim bladder, e.g. most benthic species, such as flatfish, can be deterred using high sound levels but this may not be cost-effective. In particular, eels and lampreys show very little reaction to AFD signals, although the use of infrasound merits further research.

3.4.5.16 Ease of Retrofitting

AFD systems lend themselves to retrofitting, requiring very little engineering work to install. As well as being used to upgrade fish protection on older intakes, for example by Thames Water Utilities Ltd on R. Thames intakes, Yorkshire Water plc have used them for fish diversion at temporary water abstractions.

3.4.6 Light-based Systems

Light is used in two ways to reduce entrapment. The first is to illuminate physical or behavioural screens to make them more visible so that fish can orientate themselves in relation to the flow (using the optomotor response); the second is to use the stimulus of light in its own right to either attract or repel.

The fish deterrent effects of light were first studied in the 1950s when Brett and MacKinnon (1953) used light to restrict the movement of animals in a canal. Although these early tests were not extensive there were two important findings: firstly, that different reactions were displayed by different species and secondly that flashing lights were more effective at eliciting a response than continuous light (OTA, 1995).

It is commonly found when using physical screens, greatest impingement occurs during hours of darkness. Up to 97% of young fish will be entrained at night (Pavlov, 1989). During hours of darkness in particular, artificial lighting will allow improved orientation of fish and therefore reduced entrainment. This effect may be further enhanced by careful positioning of light sources behind structural elements to provide maximum visual contrast by throwing the structure into silhouette (Turnpenny, 1998). With the addition of lights to an intake structure Pavlov achieved a reduction of entrainment of young cyprinids and percids of up to 91%. The effectiveness of this behavioural system, however, varies with species with up to 100% deterrence being seen for perch (*Perca fluviatilis*) and ruffe (*Gymnocephalus cernua*) whereas entrapment was increased with illumination in the case of three-spined-sticklebacks (*Gasterosteus aculeatus*) (Hadderingh, 1982). Light can therefore act as either a repellent or an attractant to different species.

To minimise light pollution and to achieve the highest possible effectiveness it is necessary to submerge the light source. This results in a significant increase in the capital and maintenance cost due to necessary frequent cleaning of lamps requiring a mechanical recovery system. The most common positioning of lamps is in an arc on the bed around the intake entrance ensuring water velocities at this point are low enough to allow fish to escape (Turnpenny, 1998). The angle of positioning of the lamps is also important with an upwards tilt of 40-45° having been found to be most effective (Johnson *et al*., 2001).

3.4.6.1 Constant Illumination

Continuous illumination is not the optimum method for most species but is useful in the case of eels. This approach has been tested extensively in the Netherlands (Hadderingh and Smythe, 1997). Eels show strong phototaxis and positive rheotaxis (orientation into currents). Light can therefore be used to discourage the tendency of eels to follow water flow. The lights can be incandescent lights, mercury vapour lights or fluorescent lights. Trials have mainly used the latter (specified as 36W, PL-L Philips, spectrum with peaks at 440, 550 and 610nm). Deflection rates of up to 74% have been observed at some thermal and hydroelectric power stations.

3.4.6.2 Strobe lights

Strobe lights generally give better results than continuous illumination. Most experiments have again centred on the eel. Patrick *et al.* (1982, 2001) conducted experiments on eels. The first study was to determine if strobe lights could be used to deter eels from entering a turbine unit during its shutdown period. The second involved initial laboratory tests followed by field trials at a fish ladder. Both investigations showed a reduction of eel movement of between 65% and 92%. The laboratory tests in the second study used flash frequencies from 66 to 1090 flashes per minute (FPM) and showed that all were effecting in repelling eels. The fish ladder trials used a flash rate of >800 FPM. The threshold light level for eel repulsion was found to be $\geq 0.1 \mu Em^{-2}s^{-1}$ ($\geq$5 lux).

Work has also been carried out on other species, including white perch (*Morone americana*), spot (*Leiostomus xanthurus*) and Atlantic menhaden (*Brevoortia tyrannus*) although the level of effectiveness and the necessary flash rate varied with species (Sager *et al*., 1987). Other species investigated by Patrick *et al.*(1982) included Atlantic salmon, which were also repelled by strobe lights. Flash rates of 300 FPM appeared to be most effective. Johnson *et al* (2001) also found 300 FPM to be effective in achieving vertical displacement of steelhead trout (*Oncorhynchus mykiss*); their concept was to shift the fish upwards in the water column away from an intake to reduce entrainment. Tests with kokanee (*O. nerka*) found flash rates of 300, 360 and 450 FPM all to be an effective repellent, even when light levels were <0.00016 lux above ambient light levels; the repellent effect continued throughout the longest test duration of 5h 50min (Maiolie *et al*, 2001).

The success of using strobe lights as a deterrent has been found to be site specific, indicating that hydraulic and environmental conditions have an effect (OTA, 1995).

Strobe lights may prove to be more effective when used in conjunction with other forms of behavioural and physical screening systems. In particular bubble screens /strobe light combinations work well for some species, e.g. alewife (*Alosa pseudoharengus*), smelt (*Osmerus mordax*) and gizzard shad (*Dorosoma cepedianum*) (Patrick *et al*., 1985). This combination was also tested in the UK at Walton-on-Thames raw water intake, where a reduction of 62.5% entrainment of salmon smolts was observed (Solomon, 1992).

In earlier systems a problem with the short lifespan of the xenon discharge tube made operation difficult. Modern tubes however, will last for a year or more when correctly driven. New models of strobe lights are now available with greater flexibility in flash rate, light intensity and sequencing via a laptop computer. This will allow for easier adjustment of the lights without the need for removal, therefore reducing costs (Johnson *et al*., 2001).

3.4.6.3 Design and Operational Best Practice

There has been very little use of this approach in the UK to date and therefore ‘best practice’ is unclear. Important issues are:

- Water clarity must be high.
- A lamp retrieval mechanism must be installed.
- Adequate testing is required to optimize the flash rate when strobes are used; there is a risk of attracting rather than repelling fish at some flash rates. Flash rates of ≥300 FPM appear to work best with a range of species.
- Some redundancy (i.e. using more lights than are strictly needed) is desirable to allow for lamp failures.
- Warning systems (e.g. via telemetry links) should be provided to inform plant operators of failure.
- The equipment requires regular maintenance and service intervals should be displayed and logged in the plant control room.
- Visible indicators of the operational status (e.g. number lamps operating versus failures) should be displayed at or close to the intake to inform operational and enforcement personnel.
- Back-up power or interlocks with pump controls may need to be provided to ensure that pumping does not occur when the system has lost power.

The use of ‘high-tech’ computer control systems appears to enhance flexibility and control of the systems and looks promising.

3.4.6.4 Applications

Light-based techniques are appropriate in similar situations to acoustic methods, i.e. where large flows are to be screened with zero headloss (e.g. hydroelectric and thermal power plant intakes). However, unlike acoustic methods they are not suitable for turbid waters.

Strobe light systems appear to work well in combination with bubble curtains from the limited research available. A BAFF™/strobe combination in particular merits investigation. Recent improvements in strobe lamp technology, which now offer greatly extended operating life, make the technology potentially more useful.

3.4.6.5 Fish Species/Lifestages

Light-based methods show promise for eel guidance in particular, although a number of other species can be deterred using strobe lights. Combinations of AFDs and strobe lights are worth considering where eels need to be deterred along with acoustically sensitive species.

3.4.6.6 Ease of Retrofitting

Light-based systems of any kind are relatively easy to install and provide an attractive retrofit option.

3.4.7 Velocity Caps and Other Flow Control Measures for Offshore Intakes

The velocity cap represents a simple modification to unscreened intakes in open sea or lake situations which can significantly reduce entrainment. Many coastal power stations constructed before the 1970s used vertically opening offshore “bath-plug” intakes which are prone to draw fish down (Schuler and Larson, 1975; Hocutt and Edinger, 1980). This occurs because fish are adapted to respond to horizontal rather than vertical currents. The velocity cap, usually made of concrete or steel, forms a flat, horizontal lid to the intake that therefore draws water in horizontally. Schuler and Larson (1975) proposed that the cap and lip of the intake riser should extend out 1.5 times the height of the intake opening (Figure 3.19). This straightens the flow and allows the fish some distance over which to react. These authors reported substantial reductions in pelagic fish entrainment when a velocity cap was fitted to a Californian power plant intake. Velocity capping of some form has now become standard practice in offshore cooling water intake design, as it also offers the advantage of selective withdrawal of water from the cooler, deeper layers (Turnpenny, 1988).

Turnpenny (1988) identified a further fish entrainment issue associated with offshore intakes drawing from tidal streams. Whereas in still water, velocities will be radially symmetrical around a circular intake, in flowing water the water is abstracted primarily from the upstream side, giving rise to higher intake velocities on this side. At Sizewell ‘A’ nuclear power station (Suffolk), it was shown that fish impingement on the drum screens peaked on the mid-ebb and mid-flood tides when this effect became maximal. Physical and numerical hydraulic modelling studies (Turnpenny 1988 and unpublished) have shown that blanking off the upstream and downstream sides of an intake, as well as velocity capping it, can provide an intake velocity regime that remains consistently favourable for fish throughout the tidal cycle. A suitable design which has emerged from the model tests uses two circular caissons placed in line with the intake, with a velocity cap extending across the whole structure; water is abstracted from a central seabed port (Figure 3.20). At present, this design has not been built at full-scale.

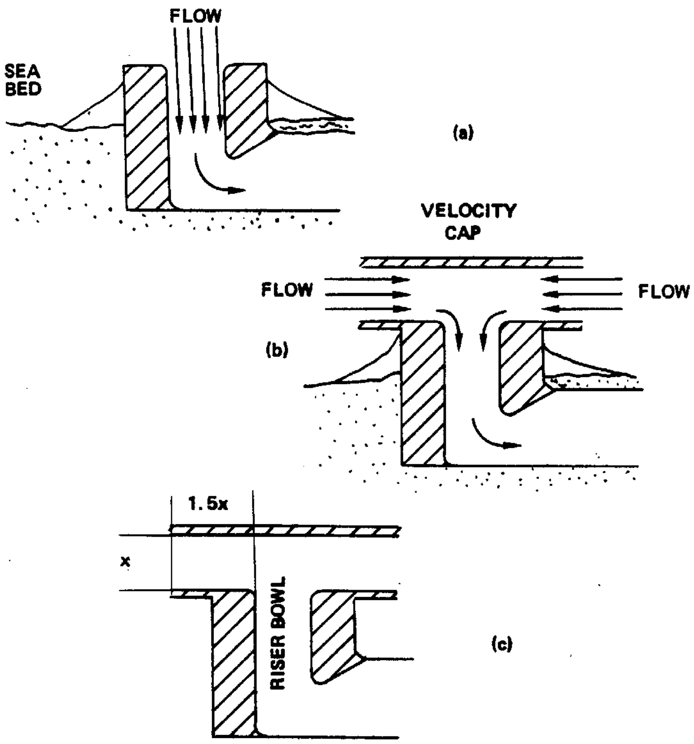

Figure 3.19 The velocity cap: (a) section of uncapped intake showing vertical draw-down pattern, (b) section of capped intake showing horizontal flow pattern, (c) as (b) but showing critical relationship between vertical opening [x] and length of horizontal entrance [1.5x] for fish reactions (after Schuler and Larson, 1975).

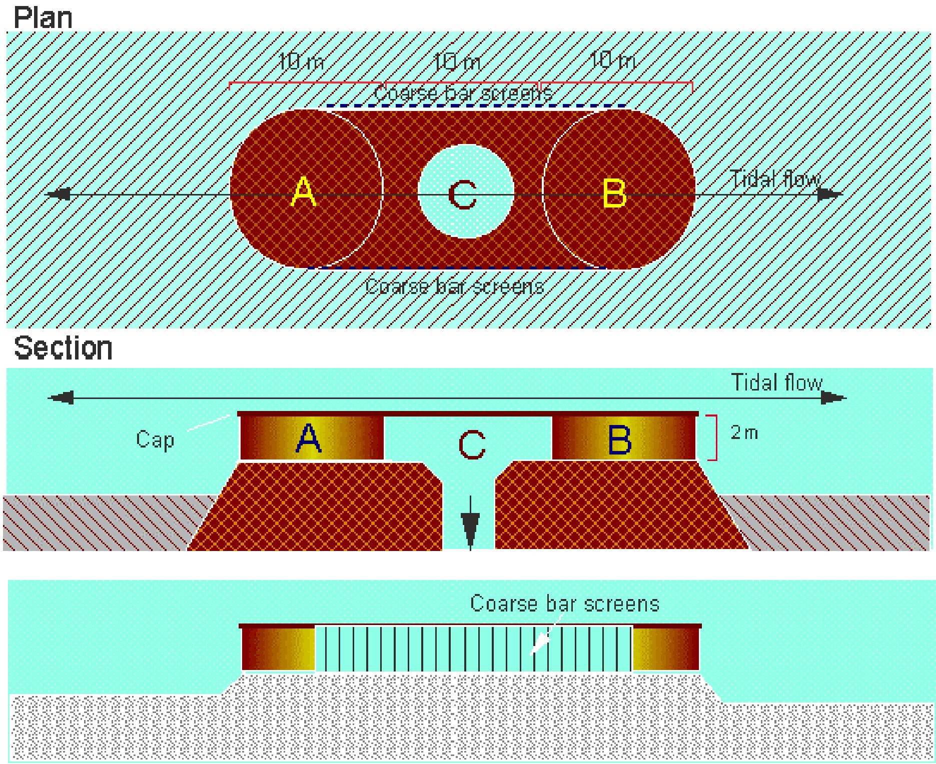

Figure 3.20 Concept design for a low-velocity, side-entry offshore intake structure with velocity cap, based on physical and hydraulic model tests carried out at Fawley Aquatic Research laboratories (Turnpenny, 1988 and unpublished). A and B are the cylindrical caissons. Water enters C.

3.4.7.1 Design and Operational Best Practice

- Where it is not feasible to use more effective fish screening methods such as PWWC screens, offshore intakes should be designed to ensure that flows are kept horizontal and that intake velocities are not unduly influenced by tidal movement or river flow. These conditions are best achieved by fitting a velocity cap and lateral intake ports.
- Offshore intakes are usually costly structures and it is strongly recommended that physical or numerical hydraulic modelling studies are undertaken to demonstrate that the above intake flow conditions are attained.
- Experience at UK sites where velocity caps are present has shown that fish entrainment remains a problem and velocity caps are therefore not in themselves a solution. Other measures, including use of side-entry, of behavioural deterrents and onshore fish return systems need to be considered.

3.4.7.2 Applications

The measures described should be applied to all offshore intakes and mid-river intakes where fish are not protected by more stringent screening measures such as PWWC screens.

3.4.7.3 Fish Species/Lifestages

Velocity caps are most important for the protection of pelagic species or lifestages that are found in the upper water column. At most power plant intakes, pelagic fish are usually overwhelmingly the major entrained component. Side-entry devices are appropriate to all species and lifestages.

3.4.7.4 Installations in the UK

Many UK offshore intakes have capped intake structures but few can be described as true velocity caps as described by Schuler and Larson (1975). Dungeness 'B' (Kent) and Sizewell 'B' (Suffolk) nuclear power stations both have velocity caps, as does Stallingborough power station (Humber estuary). None are known to have any device deliberately to control the radial distribution of intake flow for the purpose of reducing entrainment.

3.4.7.5 Ease of Retrofitting

Some attempts to reduce vertical draw have been made on offshore intakes. At Dungeness 'A' power station, the top bars of the original caged structure were blanked off with concrete to reduce vertical flow, although this does not form a true velocity cap. A badly designed intake (from the fish protection point of view) cannot easily be remedied without major civil works. Acoustic fish deterrents and fish return systems have so far proved the best remediation option for such cases.

3.5 Other Behavioural Guidance Techniques

There are examples of other interesting techniques that have been investigated in North America and which may have some potential for use in Britain.

3.5.1 Turbulent Attraction Flow

The *turbulent attraction flow* concept attempts to mimic natural river turbulence cues that downstream migrating fish use to follow currents (Coutant, 2001). Any stream or river has turbulences along its watercourse due to interactions with the topographic features of the riverbed. These turbulences alter the velocity, direction and pressure of the water flow. One main form of turbulence found in a river is a 'turbulent burst', which is a high-speed ejection of water and suspended solids as water passes an obstruction. Rows of vortices are another common feature created in the wake behind solid objects. It is believed that migrating juvenile salmon use the enhanced water velocities found within these turbulences to assist in their downstream migration. While high turbulence intensities and small vortex diameters can be damaging to fish, low intensities create an attractive stimulus.

It follows from this that low turbulence intensities can be created to attract fish to a bywash entrance. A trail of turbulence can be engineered either actively or passively. Passive devices are structures such as concrete cylinders that are placed on the riverbed. When placed at intervals, a chain of vortices and increasing velocity can be generated, leading into the bywash. Where there is insufficient momentum in the water, active devices may be necessary. Turbulence can be actively created using devices such as a pumped water jet, propeller or paddle wheel suspended midway in the water column (Coutant, 2001).

A prototype 'current inducer' was tested by Truebe *et al*. (1997, 1998). A mechanically generated current was created to direct Atlantic salmon to a surface bywash system.

Prior to installation of the device, natural flow was minimal within the area and fish were drawn towards the turbine intake. The current was generated by two 2-hp, low-speed electrically driven propellers. The system resulted in a bypass efficiency of up to 93% (Coutant, 2001).

Turbulence induction may be most useful as an adjunct to other behavioural and positive exclusion screening technologies. This area deserves further research to establish design criteria and its effectiveness with different fish species and lifestages.

3.5.2 Surface Collectors

This fish diversion technique, used at large dams, is based upon the natural tendency of salmonid smolts to migrate in the surface layers of the water column, allowing fish to be skimmed off by surface bypasses or 'collectors'. The surface collectors are located on the dam and fish can be either bypassed around the dam or transported downstream in trucks or barges.

Until very recently, surface collectors have been implemented in the field only as prototypes. Prototype trials have been carried out by the US Army Corps of Engineers in the Pacific Northwest region of the USA and are the source for the following information (Dankel, 1999; Lemon, 2000).

One of the largest of these prototypes was installed at the Bonneville Dam on the Columbia River, Oregon in 1996. The main structure of the dam houses ten Kaplan turbine. The surface collector has 12 modules spanning four of the ten turbine bays. The modules are 21 m high, 8.4 m wide and 7 m deep. An attraction flow is provided by means of current inducers located within each unit. The system then diverts fish towards an existing fish screen, which channels them around the dam. The surface collector system is expected to divert 50-60% of approaching fish whereas the combination of the surface collector and the existing screen system should achieve 90% diversion.

In 2001 a seven-year prototype trial surface collector screen was removed from the Rocky Reach hydroelectric project on the Columbia River (Plates 3.14, 3.15). It has been replaced with one of the first permanent systems, which began full operation in April 2003 (www.chelanpud.org)[20]. The system is made up of two parts. First is the collector system itself which uses 29 pumps to create a strong current in the upper 60 feet of the flow to attract fish away from the turbine flow into the bypass system. The bypass system consists of a 7.7 m diameter tube which passes through the dam and extends some 1,380 m around the back of the powerhouse and 0.5 km down the east bank of the river. The total trip for fish passing through the system is 6 to 8 minutes long. The system cost $112 million to construct; this is expected to be recovered by the $400 million saving within 15 years due to a reduction in spill loss. The system is expected to achieve a 98% fish survival rate.

[20] Chelan County Public Utilities District – Rocky Reach Hydro Project

Plate 3.14 Rocky Reach dam with the powerhouse on the left and the bypass pipe in the bottom right (Chelan County PUD).

Plate 3.15 The bypass pipe traversing the dam (Chelan County PUD).

The system is still being monitored in the field and needs further investigation both in the field and the laboratory before widespread installation.

3.5.3 Eel Bypasses

One further technique of interest is the eel bypass channel. An example is found at Backbarrow hydropower scheme on the R. Leven in Cumbria (Spiby, 2004), which is claimed to be based on a traditional eel fishing method. The bypass comprises a trough set in the floor of the headrace at an angle of 60^{o} to the flow, with a 20 cm high wall on the downstream side (Plate 3.15) and a 20 cm bywash pipe at its downstream end. The effectiveness of this bypass is not known. Similar arrangements are reported in Richkus (2001), who cites French and German examples of this method used for European eel (*Anguilla anguilla*) diversion (Travade, unpublished and Rathke, 1993, unreferenced). The French example refers to the Halsou hydroelectric project in the Pyrenees, where a deep trough is set into the floor of the headrace upstream of the trash racks. This connects to a bywash, which draws 3-5% of the turbine flow. From radio-tracking studies, it was estimated that between 50% and 80% of eels used the deep bypass. In Germany, in one case the eel bypass was formed by a steel half-pipe set into the floor of a turbine spiral chamber. When fully opened, the pipe carried 1000 Ls^{-1} (proportion of total turbine flow unspecified). Using farmed (presumably yellow) eels, 41% of eels released used the bypass. No further information is given. Another German example from the same author used a bypass depression of 50 cm wide and 15 cm deep across the width of the intake channel, leading into a 25 cm bywash pipe. From studies carried out during silver eel migrations, this was reported to be used by “a high percentage” of eels at low and intermediate river discharge, but a smaller percentage at higher flows. Richkus (2001) provides a comprehensive review of downstream eel migration and deflection technologies, from which the evidence is that concerted silver eel migrations tend to occur on high river discharges. This would suggest that this technique is not enough by itself to protect eels. Nonetheless, given the relatively poor performance of virtually every other technique against eels, it is clearly a potentially valuable option.

Richkus (2001) concludes that to date there has been no rigorous research to either optimize or evaluate the eel bypass technique. Available information suggests that eel bypasses should have entrance velocities the same as those occurring at the intake trash racks and that bypass flows should be 3-5 % or more of total river discharge. Presumably in the case of a hydropower scheme or other lade-type offtake, the bypass flow should be 5% of the channel flow, not the whole river discharge; this would accord with the upper end of the range 2-5% of turbine flow commonly recommended for fish bypasses at hydropower sites (Turnpenny *et al*, 1998).

Plate 3.15 Eel bypass trough at Backbarrow hydropower scheme, R. Leven, Cumbria (Spiby, 2004).

3.6 Outfall Screening

3.6.1 Introduction

The screening of outfalls is for one or both of two purposes:

1. to prevent upstream swimming fishes that may be attracted to a discharge flow from entering the discharge or being distracted from the natural flow;
2. to avoid losses of fish stock from a fish farm, reservoir or pond outlet into a natural watercourse.

Outfall screens are limited to two types that have been shown to be effective: mechanical mesh or bar screens and electric screens or ‘hecks’. Acoustic methods, and possibly other behavioural methods, have been attempted to block upstream movements, but largely unsuccessfully. The lack of reliably good results appears to be because of the strong motivation of fish as they migrate towards their spawning grounds: stimuli that might under other circumstances deter them become ineffective.

Screening against up-migrating elvers has not traditionally been practiced but must now be considered, in the light of the current declining status of eel stocks. This is probably not an issue at hydropower sites or other large, high velocity outfalls that elvers would find difficult to ascend, but may be at low velocity outfalls. Swimming speed measurements for elvers of *A. anguilla* made as part of the Environment Agency National R & D Project No. W2-049 “Swimming Speeds in Fish” indicate that upstream-migrating elvers can attain an average burst speed of 0.5 ms^{-1}, suggesting that the discharge velocity would need to be at least 0.7-0.8 ms^{-1} to ensure that elvers could not ascend. However, this in itself could attract larger migratory fish and therefore these would need to be screened out. There are options other than screening; for example, since eels cannot leap, raising the discharge point above flood water level would be effective.

3.6.2 Positive exclusion Screens

From the fish protection point of view, there are a number of criteria for effective outfall screening:

3.6.2.1 Mesh or Bar Spacing

The screen should have mesh or bar spacings suited to the sizes of fish to be excluded. Standard sizes are e.g. 40 mm horizontal spacings (free gap) for adult Atlantic salmon or 30 mm for adult sea trout (Anon., 1995). Smaller spacings may be required for other species (see section 3.1). Square or rectangular bar is preferable to round bar for fish screens.

Fish farm outfalls represent a special case, where screening needs to be provided to keep farm fish inside the farm without allowing escapes to the watercourse. In this case, the screening should reflect the sizes of fish held on the farm. Normally, however, this function is provided by fish screens located at strategic points around the farm, and not necessarily at the final outfall position. An outfall screen suited to the river fish will then need to be provided at the point of outfall.

3.6.2.2 Screen Location

Outfall screens should be located at the most downstream point of the discharge; failure to do this can create blind alleys where fish become trapped and possibly vulnerable to poachers. The position and alignment of the screen can be arranged to guide fish upstream towards the preferred route, e.g. the main river channel or the entrance to a fish pass. This is particularly important where screens are placed across hydroelectric tailraces.

3.6.2.3 Working Depth

Where screens are not e.g. fitted to cover the end of a pipe or tunnel but are placed across an open channel, the height and the extent of the screen should take account of the local topography and foreseeable flood levels; otherwise fish may circumvent the screens during floods and become trapped when the level falls. The same proviso applies to screens used to retain fish on fish farms.

3.6.3 *Electric Barriers*

Electric barriers or hecks have been used for many years to prevent the ascent of fish into hydroelectric tailraces and they are generally considered to work well for the purpose. This method is sometimes preferred to positive exclusion screening at low-head hydro sites, where the additional loss of head caused by the screens may be significant. Most of the MAFF-type electric screens (see section 3.3) have now, however, been removed owing to safety concerns.

The GFFB system described in section 3.3 is also used for outfall screening but is considered to be a safer option, for reasons discussed in section 3.3. The GFFB can be fitted as an electrode array running across the bed (Figure 3.21) or as an annular array fixed within the confines of a tunnel. It is found to work best with a minimum water velocity of 0.6-0.9 m.s^{-1}, which causes fish to be pushed away as they cross the electric field, and with a maximum operating depth of about 5 m.

In an investigation carried out at the Pere Marquette River (Rozich, 1989) the GFFB system was found to be effective in preventing upstream sea lamprey migration whilst still allowing downstream penetration of steelhead adults and smolts and chinook smolts with no injury.

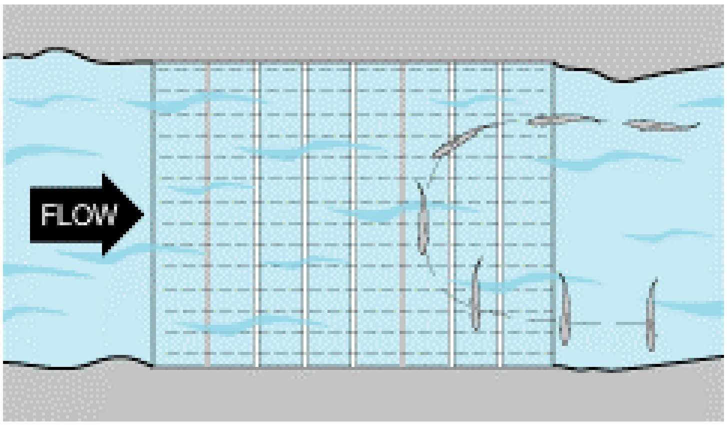

Figure 3.21 Diagram showing fish movement in response to the GFFB electric fish barrier. In the diagram, the energisation voltage of the electrode strips increases from right to left of the diagram. The fish turn away at a point depending on their length and hence the voltage received along the body (www.smith-root.com).

Two GFFB™ barriers have recently been installed in Britain for deflecting upstream migrants. One, fitted into the draft tubes of a small hydroelectric plant at Beeston Weir (R. Trent, Notts.), has been in operation for about five years. It is intended to prevent the ascent of salmon and adult coarse fish into the turbines rather than the adjacent vertical-slot fish pass. While no formal efficiency testing has been undertaken, it appears to have worked well when operated correctly (see comment in section 2.2).

3.6.3.1 Design and Operational Best Practice

Key points are:

- All fish farm outfalls should be screened to prevent accidental loss of fish from the site at the 10-year return period flood level.
- Other outfalls should be screened or raised above flood level to prevent the risk of fish ascending the discharge.
- In the case of physical screens, mesh sizes or bar-spacings should be selected based on data given in section 5.7.
- For electric screens, the electric field strength should be set as per the manufacturer's recommendations for the fish species, sizes and site conditions. Manufacturer's health and safety guidance should also be followed. For public safety, it is desirable to limit access to electrified areas, and to display adequate warning notices. Other relevant data are given in section 3.4.4.
- Screens on tailraces and other types of outfall channel should be located at the confluence with the natural channel and not at the upstream end of a blind channel.
- Outfall screens on fish farms should be constructed sufficiently sturdily to withstand flood conditions.

4 PERFORMANCE CRITERIA

4.1 How Effective Should a Fish Screen Be?

There is a common misconception that all positive exclusion fish screens, provided that they are designed with the optimum mesh size and velocity conditions are 100% effective. In practice, this success rate is seldom achieved. Inspection surveys frequently reveal faults in the operation or maintenance of even the best designed screening systems. Common faults with mesh panel screens for example include:

- Damaged mesh panels;
- Damaged screen seals;
- Screens not fully seated;
- Screens removed to avoid clogging problems;
- Screens heavily clogged, leading velocity hot-spots where fish are at risk of becoming impinged on the screens.

These, of course, can all be overcome with appropriate monitoring, maintenance and enforcement.

Certain types of positive exclusion screen are much less prone to maintenance failures like these, for example PWWC screens or rotary disc screens are inherently proof against fish entry, unless they become seriously damaged by flood debris. Coanda screens also offer a high degree of protection, provided that they are operated with sufficient surplus flow to allow fish to pass. Where the sensitive status of the fishery demands near-100% efficiency, these methods should be used, if feasible.

Physical and cost constraints of particular sites, environments or applications dictate that these methods are not always viable, which is why a variety of methods has grown up to provide alternative solutions. Behavioural methods have been developed primarily to deal with issues of high waterborne detritus loads, and risks of screen clogging and consequent hydraulic losses. These issues are particularly critical to hydroelectric generation, where flow and operating head equate directly to revenue, but also to e.g. thermal power generation and other industries where loss of the water supply might be critical to operation or safety. For large coastal power stations, no solution has been found to date that will yield near to 100% fish exclusion. The problems include: very high biofouling rates of submerged screens, inundation by weed, jellyfish, shrimps, crabs and even sprat shoals and very high rates of water abstraction (60 m^3s^{-1} for a 2000 MWe fossil fuel plant: Turnpenny and Coughlan, 2003).

Meeting the conflicting demands of an industrial society and the need for ecological conservation means that it is therefore essential to establish what the performance criteria for screening system should be before selecting the screening method.

4.2 Risk Assessment for Fish Screening

4.2.1 In General

The risk assessment approach requires that the effectiveness of the screening measures should reflect the level of risk to the fish stock or fish community and the importance attached to the stock, community or associated habitat. It is strongly recommended that the principles of risk analysis are applied to any intake screening proposal. However, the requirements of the relevant legislation must be taken fully into account.

Risk assessment in the fish screening context was addressed by Turnpenny *et al.*, (1998, 2000), who identified a number of factors that may be used in a risk assessment of an abstraction scheme (hydroelectric schemes in their examples, but equally applicable to other types):

- the value of the fish stock in economic or conservation terms;
- the percentage of the fish stock that must pass the scheme;
- the percentage of those fish that pass successfully;
- the additional loss due to other schemes (i.e. cumulative impacts);
- the significance of given percentage levels of loss in economic and conservation terms.

These authors present simple mathematical approaches that could be extended to different applications. For example, they demonstrated that a behavioural barrier having a 90% efficiency might achieve a successful scheme bypass rate of 98% when all factors (proportion of flow screened, etc.) are taken into account.

4.2.2 For Hydropower Sites

Specific consideration should be given to the following additional aspects at hydropower sites:

- the risk of fish injuries or mortalities in the turbines (via both intakes and outfalls);
- possible delays in fish migration and increased predation risk when water is diverted through long head- and tailrace systems;
- possible losses at bywash outfalls where the increased concentration of diverted fish may attract predators, especially if fish are disorientated.

Issues associated with fish passage through turbines have been investigated in some detail in studies funded by the Department of Trade and Industry (Turnpenny, 1998; Turnpenny *et al.*, 1998, 2000). These authors conducted a series of laboratory and field experiments, culminating in a computer model ('STRIKER') which predicts the probable injury rates of fish of different sizes during passage through a hydroelectric turbine of the Francis or Kaplan/propeller types. The model was validated on operating turbine sites. It takes account of injuries due to the following effects:

1. Runner strike- i.e. contact with the turbine blade;
2. Contact with fixed elements (guide vanes etc.);
3. Hydraulic shear stress (caused by hydraulic anomalies near the moving blades);
4. Rapid pressure change (as the fish passes from the high-pressure to low-pressure side of the blade).

Turnpenny *et al.* (1998, 2000) describe how the model can be applied in fish risk assessment for a hydropower scheme.

Methods of examining some of these factors on operating sites are discussed in section 7.

4.2.3 For Water Transfer Schemes

Risk assessment for procedures for screening at water transfer schemes, whether local (e.g. canal lock recharge pumping) or long-distance, should take account not only of impacts on fish communities in the source water body but also in the receiving water. This should include consideration of possible transfer of non-indigenous species as eggs, fry or other stages, spread of disease and interference with genetic integrity.

4.2.4 Under SFFA s.14

Another approach is exemplified by the Environment Agency's SFFA *s*. 14 risk assessment procedure. The Environment Agency is keen to demonstrate an effective but transparent implementation of the SFFA *s*.14. The key elements of the Environment Agency's *s*.14 policy are:

1. A standard risk assessment checklist procedure is used, the results of which are made available to the responsible person/ owner and open to appeal.
2. Full recognition is given to the precautionary approach ("where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation"). This is complementary to the approach adopted in the Habitats Regulations.
3. The Agency will ensure that adequate screening provisions are implemented but it is recognised that the *costs to industry should be in proportion to the magnitude of the perceived risk*. At all times the principle of 'best available technology not entailing excessive cost' (BATNEEC[21]) should be employed in options for screening.
4. Site inspections may only be carried out by enforcement staff who have received formal training in the new SFFA *s*.14 procedure. Such staff are required not to offer advice on the design and construction of the suitable screening arrangements, which are the responsibility of the responsible person or owner.
5. Figure 4.1 shows an example of the Agency's SFFA *s*.14 checklist used as a basis for the risk assessment.

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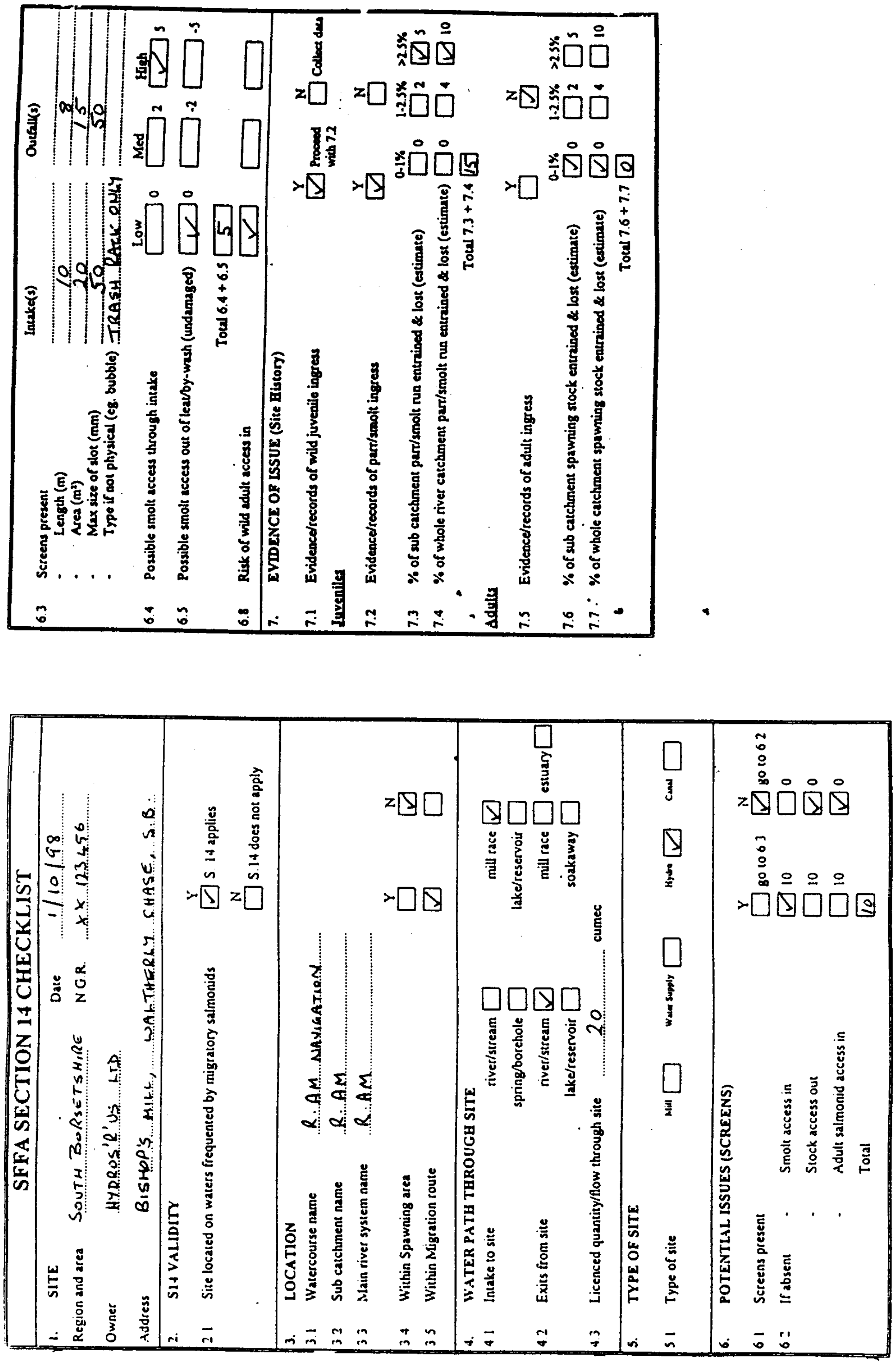
[21] Note that there is no formal definition of Best Available Technology (*sensu* Environment Act 1995) for fish screening at present



SFFA SECTION 14 CHECKLIST

1. SITE — Date 1/10/98
Region and area SOUTH BORSETSHIRE — NGR XX 123456
Owner HYDROS 'R' US LTD
Address BISHOP'S MILL, WALTHERLY CHASE, S.B.

2. S14 VALIDITY
2.1 Site located on waters frequented by migratory salmonids — Y ☑ S.14 applies; N ☐ S.14 does not apply

3. LOCATION
3.1 Watercourse name R. AM NAVIGATION
3.2 Sub catchment name R. AM
3.3 Main river system name R. AM
3.4 Within Spawning area — Y ☐ N ☑
3.5 Within Migration route — Y ☑ N ☐

4. WATER PATH THROUGH SITE
4.1 Intake to site — river/stream ☐ spring/borehole ☐ mill race ☑ lake/reservoir ☐
4.2 Exits from site — river/stream ☑ lake/reservoir ☐ mill race ☐ soakaway ☐ estuary ☐
4.3 Licenced quantity/flow through site 20 cumec

5. TYPE OF SITE
5.1 Type of site — Mill ☐ Water Supply ☐ Hydro ☑ Canal ☐

6. POTENTIAL ISSUES (SCREENS)
6.1 Screens present — Y ☐ go to 6.3; N ☑ go to 6.2
6.2 If absent — Smolt access in: Y ☑ 10, N ☐ 0; Stock access out: Y ☐ 10, N ☑ 0; Adult salmonid access in: Y ☐ 10, N ☑ 0; Total 10

6.3 Screens present — Intake(s) / Outfall(s)
Length (m) 10 / 8
Area (m²) 20 / 15
Max size of slot (mm) 50 / 50
Type if not physical (eg. bubble) TRASH RACK ONLY
6.4 Possible smolt access through intake — Low ☐ 0, Med ☐ 2, High ☑ 5
6.5 Possible smolt access out of leat/by-wash (undamaged) — ☑ 0, ☐ -2, ☐ -5
Total 6.4 + 6.5 5
6.8 Risk of wild adult access in ☑ ☐ ☐

7. EVIDENCE OF ISSUE (Site History)
7.1 Evidence/records of wild juvenile ingress — Y ☑ Proceed with 7.2; N ☐ Collect data
Juveniles
7.2 Evidence/records of parr/smolt ingress — Y ☑ N ☐
7.3 % of sub catchment parr/smolt run entrained & lost (estimate) — 0-1% ☐ 0, 1-2.5% ☐ 2, >2.5% ☑ 5
7.4 % of whole river catchment parr/smolt run entrained & lost (estimate) — ☐ 0, ☐ 4, ☑ 10
Total 7.3 + 7.4 15
Adults
7.5 Evidence/records of adult ingress — Y ☐ N ☑
7.6 % of sub catchment spawning stock entrained & lost (estimate) — 0-1% ☑ 0, 1-2.5% ☐ 2, >2.5% ☐ 5
7.7 % of whole catchment spawning stock entrained & lost (estimate) — ☑ 0, ☐ 4, ☐ 10
Total 7.6 + 7.7 0

Figure 4.1 Environment Agency checklist for a hypothetical SFFAs.14 site (Turnpenny *et al*, 1998).

4.2.5 Under the Habitats Regulations

Projects within or connected with a designated SAC and therefore regulated under the Habitats Regulations demand more stringent risk assessment criteria. The critical test is whether the *appropriate assessment* can demonstrate no adverse effect on integrity of the European site. In this context, the BATNEEC criteria are replaced by BAT (Best Available Technology), without consideration to cost. The project may not proceed if adverse effect on site integrity cannot be avoided. The appropriate assessment therefore is the form of risk assessment procedure used in such cases.

The Agency's policy is summed in the following extracts from the website (www.environment-agency.gov.uk); note that the powers can apply to new and existing plans or projects that may be impacting upon SACs:

"The Agency will ensure that all applications for new permissions will be screened for potential impacts on European Sites. This applies to all proposals that require Agency approval and is a consolidation of existing statutory obligations to protect SSSIs under the Wildlife and Countryside Act (1981), as amended by the Countryside and Rights of Way Act (2000).

Where a significant effect on a European site is likely, an appropriate assessment will be carried out by the Agency in consultation with EN[22] and CCW[23].

In all cases the determination will be made by the Agency on best available information and taking full account of advice from EN/CCW as agreed in this joint guidance.

The Agency has obligations to review existing consents, licences, permissions and activities that are likely to be having a significant effect on a European Site. This assessment of likely significant effect is in relation to the permission alone or in combination with other permissions or plans or projects. Where a likely significant effect is established, the Agency will carry out an appropriate assessment to determine whether to affirm, modify or revoke the permission.

Under the Review of Consents process, an appropriate assessment will be undertaken for those European sites protected in the UK by means of Regulation 10 (1) of the Conservation (Natural Habitats, & c.) Regulations 1994 as amended by the Conservation (Natural Habitats, & c) (Amendment) (England) Regulations 2000.

The process will affect only those permissions that have been identified as 'relevant' using guidance agreed with EN and CCW, and by those with the legal powers to do so".

The process is well illustrated by the case of Fawley Power Station in Hampshire, an oil-fired plant that has been in operation since the late 1960s. Following the designation of candidate SACs on the Solent (marine habitat) and R. Itchen (salmon river), lying to the south and north respectively of the plant, a new abstraction licence was issued in the year 2002. As a result of an assessment under the Habitat Regulations, to remove the risk of an adverse effect on site integrity, various conditions were attached to the licence, including:

- the installation and operation of an acoustic fish deterrent system at the cooling water intake;

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[22] English Nature

[23] Countryside Council for Wales

- implementation of a fish rescue and return facility at the cooling water drum screens;
- operation of a weekly/monthly fish catch monitoring programme on the cooling water drum screens to estimate total annual fish catch for an indefinite period;
- quarterly sampling of fish by several capture methods at designated reference sites in Southampton water and the Solent, against which to judge any change in fish catch at the plant;
- annual reporting of the findings to the Agency.

5 DESIGNING FOR PERFORMANCE

Most of the information given here is drawn from the various screening guidance documents listed in section 1.

5.1 Timing of Fish Movements

Effective screening must first of all be targeted to the species and lifestages of fish that are to be protected. This will determine the method best suited, the critical times of the year and the specific design details for the fish screen (mesh size, etc.).

Table 5.1 Downstream migrations of some fish species found in UK waters and times of the years when vulnerable to entrainment (Lucas *et al*, 1998)

Fish Species	Migratory Habit	Vulnerable Life Stage	Time of Year
Atlantic salmon (*Salmo salar*)	Anadromous	parr* (8-10cm) smolt (12-15cm) kelt (>60cm)	autumn* spring, autumn* winter
Sea trout (*Salmo trutta*)	Anadromous	parr* (8-10cm) smolt (15-22cm) kelt (>40cm)	autumn* spring, autumn* winter
Twaite shad (*Alosa fallax*), allis shad (*A.. alosa*)	**Anadromous**	descending fry & juveniles spent adults	late summer/early autumn early summer
Smelt (*Osmerus eperlanus*)	Anadromous	fry	early summer
River lamprey (*Lampetra fluviatilis*)	Anadromous	descending juveniles (9-13cm)	winter/spring
Sea lamprey (*Petromyzon marinus*)	Anadromous	descending juveniles (9-13cm)	winter/spring
Brook lamprey (*Lampetra planeri*)	Potomadromous	descending juveniles	autumn
Eel (*Anguilla anguilla*)	Catadromous	descending adults	all year but mainly autumn
Cyprinids	Potomadromous	pinhead fry 0 & 1 gp	spring (post-hatch) summer/early autumn

Seasonal events may allow more focus in the design. It is common practice with smolt screening, for example, to install the screens only during the spring period of the smolt run; at other times of the year they are replaced by coarser screens or bar racks to ease operational problems. It may also restrict the range of water temperatures that need be considered when looking at fish swimming speeds. Most important of all, knowledge of the timing of fish runs will allow options of modulating or temporarily ceasing abstraction to be considered. In some operations, it is found to be more cost-effective to cease or reduce abstraction during critical periods than to install screens.

Temporal modulation may be seasonal (e.g. during the period of a smolt run), daily (e.g. shut-down on days when fish movements have been reported) or diurnal (e.g. cessation at night to avoid nocturnal migrations) (Solomon, 1992). Table 5.1 provides a summary of the seasonality and vulnerable life–stages of UK migratory species.

5.2 Intake Velocities and Fish Swimming Performance

Swimming performance is strongly influenced by the species and the length of the fish and to a lesser extent by water temperature. The required criterion is that the fish approaching an intake should be able to swim fast enough and for long enough to ensure their escape via the bywash or any other route provided to return them to the main river flow. Whether this is achieved by using sustained (aerobic) or burst (anaerobic) swimming will depend on conditions: burst swimming will usually require high motivation by the fish, e.g. a startle response that might be caused by a strong stimulus (e.g. electric shock, sound pulse or strobe light flash).

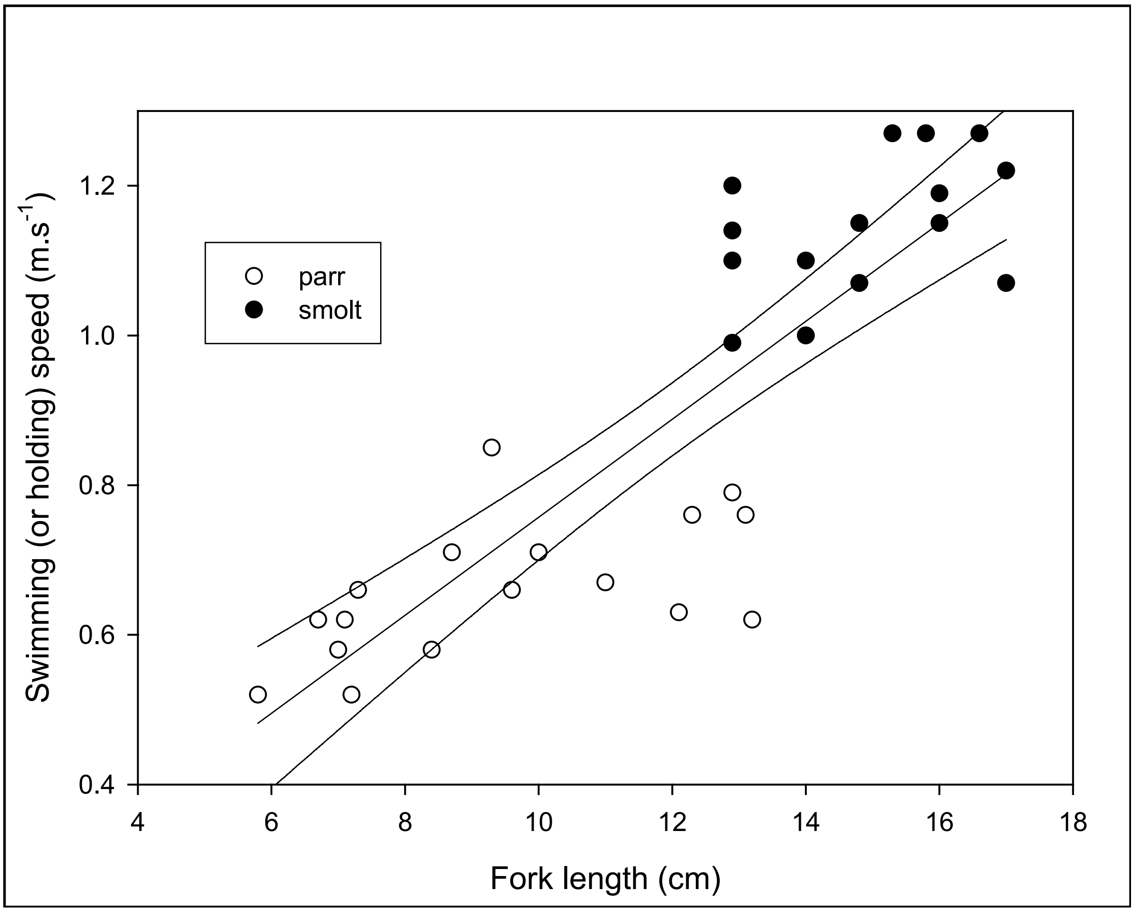

Figure 5.1 The relationship between fork length and swimming speed maintainable for at least 200 min for Atlantic salmon parr and smolts. Dotted lines are 95% confidence intervals (after Peake & McKinley, 1998).

5.2.1 Salmonid Smolts

For salmonid smolts, a swimming speed equivalent to 2 body-lengths per second (bl s^{-1}) has for a long time been taken as the 'design' value for water intakes (Solomon, 1992). While the 2 bl.s^{-1} criterion has been widely used, it is based at least in part upon the notion that the process of smoltification causes some physiological impairment of swimming ability. Solomon (1992) refers to data from Thorpe & Morgan (1978) which indicated that a 12 cm parr could maintain station in current speeds of up to 7 bl.s^{-1}, whereas hatchery-reared smolts were unable to maintain station at >2 bl.s^{-1}. In fact, their paper refers to position-holding in non-swimming smolt, not smolts in the water column. More recent studies with actively migrating wild Atlantic salmon smolts showed that smolts performed at least as well as parr (Peake & McKinley, 1998; see Figure 5.1) and better than some other salmonids (Peake *et al.*, 1997). Data from Peake & McKinley (1998) indicate that e.g. an average 12 cm smolt could sustain a swimming speed of 7.1 bl.s^{-1} (85 cms^{-1}) indefinitely. Following the Agency's recommendations from the fish swimming speed R & D[24] that the 90^{th}%ile value should be used (i.e. the swimming speed attainable by 90% of the population), when using swimming speeds in fisheries engineering designs, it would be safer to work with a lower-than-average value, e.g. 75 cms^{-1} (equating to the average for a 10 cm parr or smolt); this value is equivalent to the 90%ile value for parr or smolts in the size range 10-15cm. The Peake & McKinley tests were carried out at temperatures of between 12-20^{o}C; while water temperature potentially may influence fish swimming performance, the effect of temperature across this range was not statistically discernible within their dataset. At very low temperatures (i.e. below 5^{o}C) it might be expected that swimming would be cold-impaired but smolt migrations do not commonly occur at such low temperatures. Swimming trials of brown tout conducted under R & D Project W2-026[25] concluded that performance was generally better at temperatures between 5-12^{o}C than at higher temperatures, and the same may be true for salmon and sea trout, both of which are cold-water species. Therefore the 75 cms^{-1} value can be considered a speed that would be sustainable by smolts of either species at sizes and temperatures commonly found in British waters.

5.2.2 Salmonid Kelt

Measurements by Booth *et al.* (in Turnpenny *et al*., 1998) show maximum sustainable swimming speed of 2 bl.s^{-1} for Atlantic salmon kelt at a water temperature of 7^{o}C.

5.2.3 Other Freshwater Fish Species

R & D Project No. W2-049 "Swimming Speeds in Fish" investigated the swimming speeds of various freshwater fish species, including: brown trout, barbel (*Barbus barbus*), grayling (*Thymallus thymallus*), eel, bream, roach, chub (*Leuciscus cephalus*), dace (*Leuciscus leuciscus*) smelt, and adult shad. Data are available for a range of fish sizes (but not fry, at present) and water temperatures. A computer program "SWIMIT (v2.1)" allows swimming speeds to be calculated for each of these species according to body length and temperature. Table 5.1 presents data extracted from SWIMIT (v2.1) for a range of fish sizes and water temperatures. It is recommended that 90^{th} percentile values for *endurance* (not burst) speed should be used to determine design values for intake escape velocity. It is prudent when doing so to allow for the smallest size group of fish likely to be present and the lowest water temperature band. Note that shad have not

[24] Environment Agency National R & D Project W2-026, "Swimming Speed in Fish"

been included in Table 5.1, as it is principally 0-group fish that would be at risk of entrainment and these have yet to be tested.

For a mixed cyprinid population, for instance, from Table 5.1, a maximum escape velocity of 22 cms^{-1} would protect most species at all times of the year and for sizes down to 5 cm length, although a lower value would be required where juvenile bream were at risk. However, the essence of the approach is to be flexible and make use of the detailed information available. The same principle can be applied to the other species shown.

In the case of down-migrating juvenile lampreys, the nearest relevant data is that given by North American workers (Moursund *et al.,* 2003) on Pacific lamprey (*Lampetra tridentata*). In view of current UK interest in lamprey conservation, it is worth taking a brief look at their findings.

Laboratory investigations were carried out into Pacific lamprey impingement on fixed wedge-wire (3 mm spaces) bar screens. At a velocity of zero, individuals were able to swim freely within the test chamber. When this velocity was increased to 45 cms^{-1}, 70% and 97% of fish were impinged after exposures of 1 minute and 12 hours respectively. The tendency of juvenile lamprey to use their tails for locomotion resulted in many individuals becoming wedged between the bar spaces. At velocities <45 cms^{-1}, juvenile lampreys were able to free themselves from the screen surface (Moursund *et al.*, 2003). Figure 5.2 illustrates critical velocities in relation to a 3 mm wedge-wire screen.

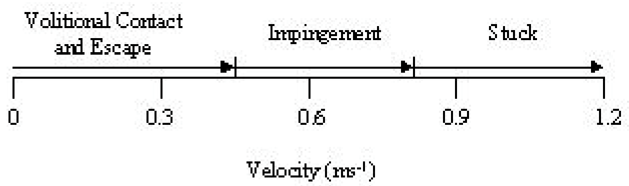

Figure 5.2 Pacific lamprey impingement velocities for a 3 mm wedge-wire screen (after Moursund *et al.*, 2003).

Moursand *et al.* (2003) reported swimming speed tests on 13-cm-long Pacific lamprey juveniles, which gave burst speeds of 70 cms^{-1} (5.2 body lengths per second: $bl.s^{-1}$) and prolonged swimming speeds of 23 cms^{-1} over 5 min and 15 cms^{-1} over 15 min. Water temperature was not stated. They also conducted tests to investigate the performance of different screen materials. After starting with a 3 mm wedge-wire bar screen, they tested one with a 1.75 mm spacing, which gave much improved results, even at velocities of up to 1.2 ms^{-1} (Figure 5.3), since the lampreys were less susceptible to becoming trapped between the bars. Also, they found that lampreys were far more likely to become wedged between horizontally aligned bars than vertical ones. However, the 3 mm bar spacing appeared to be suitable when used with a velocity <45 cms^{-1}.

Species	Test Type	<10 ºC band						10-15 ºC band						>15 ºC band					
		5cm		10cm		20cm		5cm		10cm		20cm		5cm		10cm		20cm	
		Mean	90th	Mean	90th	Mean	90th	Mean	90th	Mean	90th	Mean	90th	Mean	90th	Mean	90th	Mean	90th
Chub	**Sustained**	51	33	81	49	78	29	53	37	85	58	86	48	55	42	89	67	95	66
	Burst	92	50	112	67	133	84	104	58	125	75	145	92	112	64	133	81	153	98
Roach	**Sustained**	25	22	48	37	92	42	25	24	48	40	93	48	25	25	49	44	94	55
	Burst	70	13	103	41	137	70	79	19	113	47	147	76	86	23	120	51	153	79
Bream	**Sustained**	11	9	21	19	42	37	14	12	28	25	55	49	17	15	34	31	68	61
	Burst	121	90	138	107	155	124	100	69	117	86	135	104	87	56	104	73	121	90
Dace	**Sustained**	38	31	45	46	64	29	49	33	52	50	71	36	61	35	58	53	77	43
	Burst	83	44	114	71	144	98	91	49	121	76	151	103	96	53	126	79	156	106
Barbel	**Sustained**	43	26	49	32	60	43	53	32	59	38	70	50	63	39	69	45	80	56
	Burst	141	79	182	120	223	161	161	99	202	140	244	182	175	113	216	154	257	195
Grayling	**Sustained**	28	17	34	21	47	28	35	18	41	21	53	29	41	18	48	22	60	30
	Burst	103	48	136	81	170	115	99	44	132	77	166	111	96	41	130	75	163	108
Brown trout	**Sustained**	45	37	86	66	150	100	42	31	79	55	137	78	39	26	73	44	124	56
	Burst	63	0	11	0	158	30	57	0	104	0	152	21	53	0	100	0	148	15
Eel	**Sustained**			<0.33	<5	10	<5			<0.33	<5	14	<5			8	<5	18	7
	Burst			97	76	111	90			101	80	115	94			103	82	117	96
Smelt	**Sustained**	30	25	36	29	47	36	38	35	44	38	55	45	45	44	51	48	62	55
	Burst	87	80	119	102	18	0	85	78	116	97	11	0	84	75	112	93	4	0

Table 5.1 Burst and sustained speeds of freshwater fish in relation to fish size and temperature, with mean and 90th percentile values (from SWIMIT v2.1)

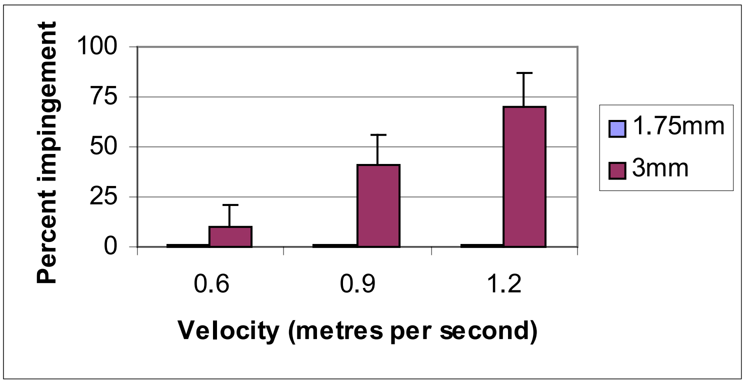

Figure 5.3 Impingement of Pacific lamprey juveniles on a wedge-wire screens with different spacings over a range of approach velocities (after Moursund *et al.*, 2003).

5.2.4 Marine & Estuarine Fish

Turnpenny (1988) provided data to estimate the sustained swimming speeds of a variety of marine and estuarine fish species (Table 5.2) The coefficients shown in Table 5.1 are used in a standard model of the form:

Sustained swimming speed = $(a + b.T)L^{0.6}$ ... (2),

Where: T is the water temperature, *a* and *b* are species-specific temperature coefficients.

Table 5. 2 Swimming speed coefficients for coastal species (Turnpenny, 1988a).

Species		Coefficients a	b	n
Sprat Herring	}	9.3	0.58	285
Cod Whiting Pout Poor Cod	}	3.8	0.56	170
Plaice Flounder Dab Sole	}	3.8	0.56	170
Bass		6.2	0.82	56
Grey Mullets		6.2	0.82	67
Sand Smelt		5.0	0.55	166
Salmon		8.0	0.32	35

n = number of experimental observations.

These can be used when considering coastal waters, but allowance should be made for the fact that these are mean and not 90th%ile values. It is suggested that the calculated values should be multiplied by 0.66 to obtain a design value approximating to the

90^{th}%ile: this is typically the difference found between mean and 90^{th} percentile values in R & D Project No. W2-049 (Table 5.1)

5.2.5 Channel Velocities and Approach/Escape Velocities

There is some confusion over the terminology used by different authors and the following definitions are proposed (see Figure 5.5):

1. the *channel velocity* is the velocity in front of the screen measured axial to the flow channel;
2. the *escape velocity* is the velocity in front of the screen measured perpendicular to the screen face, irrespective of the screen angle to flow - i.e. it is the minimum velocity at which a fish would need to swim in order to escape. This is also known by some authors as the 'approach velocity'; by convention, this is measured a short distance (e.g. 10 cm) in front of the screen, where a fish might swim, rather than for example between the bars of the screen (Nordland, 1996; Turnpenny *et al.*, 1998).

The screen should be designed to give a maximum escape velocity that is within the swimming performance capabilities of the fish that are to be excluded by the screen (see above). In selecting an appropriate value, allowance should be made for:

- partial clogging of the screen (depending on the level of debris present and the expected efficiency of any screen cleaning mechanism);
- any silt build-up in front of the screen that is likely to occur between routine de-silting operations.

It is recommended that screens should be designed with at least 20% over-capacity to allow for partial blockage or blinding.

5.2.6 Advisory Escape Velocities for Fish Screens

No statutory limits on escape velocities exist at present within the UK and the onus on the operator is to provide a system that avoids injury to fish (Turnpenny *et al*., 1998). The Salmon Advisory Committee (1995) recommended an escape velocity of 25 cms^{-1}, while The Scottish Office (Anon., 1995) suggest 2 body-lengths per second (bl s^{-1}), which might equate to 25 cms^{-1} for a typical Scottish smolt size of 12.5 cm, or 30 cms^{-1} for a 15 cm smolt that might be found further south. Solomon (1992), suggested an escape velocity of 30 cms^{-1} would be appropriate for smolt, while a lower velocity of 15 cms^{-1} would be required where coarse fish were present.

In the light of the published scientific data presented in section 5.2, these values appear too restrictive for many situations and would potentially impose unnecessary construction and maintenance costs on developers and operators of intakes. Where good experimental data exist to develop more informed design criteria, their use is recommended. For most cases it will be appropriate to use the 90^{th} percentile maximum sustainable swimming speed (MSSS), based on the smallest size of fish and the lowest water temperature that the species is likely to encounter at the facility. This value implies that 90% of the fish approaching the screening system would be capable of maintaining that speed for up to 200 min. In a well-designed screening system, which offers adequate guidance cues to steer fish towards the bywash entrance, this period should be more than adequate for fish to pass the screen.

For most purposes, the swimming speed R & D (W2-026) (see Table 5.1) indicates that the following criteria would be suitable (Table 5.3):

Table 5.3 Maximum recommended escape velocities for intake where salmonids or cyprinids are present

Fish Present	Maximum Escape Velocity Perpendicular to the Screen
Salmonids ≥10cm in length, including kelt	75 cms^{-1}
Cyprinids (except bream) ≥ 5cm in length	22 cms^{-1}

Aitken *et al.* (1966) refer to design limits of 0.75-0.90 ms^{-1} for kelt. Based on the swimming speed information given above, which indicates a sustainable speed of 2 bls^{-1} for kelt, the 75 cms^{-1} value for smolts would be a suitable design limit for all Atlantic salmon applications, although smaller sea trout kelt would require a proportionately lower limit.

For fish of different sizes or other species, these values would need to be revised according to available experimental data.

Experimental data are not yet available for juvenile shad, nor for European lamprey species. Where 3 mm wedge-wire screening material is used, the 45 cms^{-1} 'volitional escape' value given by Moursand *et al*. (2002) for Pacific lampreys may be appropriate, but it is recommended that a more conservative design value of 30 cms^{-1} should be adopted until robust experimental data for European species become available. For juvenile shad, sprat/herring data from Table 5.2 should provide a reasonable approximation.

5.2.7 Uniformity of Flow Conditions

In calculating escape velocities, the most common approach used by engineers is to take the average velocity (U), as given by the flow (Q) divided by the total screen area (A):

$$U = \left[\frac{Q}{A}\right] \qquad (1).$$

This provides an initial indication but does not take account of bed and wall friction, which will tend to reduce velocities near to surfaces, leading to higher values in the mid- and upper-channel, nor does it allow for any flow asymmetry caused by inertial effects on bends or angles. Hydraulic modelling can provide useful insights into these aspects and allow an intake design to be developed or modified to achieve the desired flows at the screen surface.

Should the velocity at the screen face always be uniform? Generally it should. The chief purpose in hydraulic design is to avoid high velocity 'hot-spots' that might cause fish to be impinged onto the screen, resulting in possible death or injury (see below).

Attention is also drawn to asymmetrical changes to the flow distribution that can be caused by sedimentation. Ideally, this possibility would be anticipated through the application of hydraulic studies to predict the sedimentation regime.

5.3 Fish Behaviour in Front of Screens

A screen or trash rack represents an obstacle in the flow-path and fish approaching the screen generally turn to face upstream upon meeting it. However, their behaviour in front of the screen depends on the velocity conditions. This effect has been described by various authors (Rainey, 1985; Pavlov, 1989; Turnpenny *et al*., 1998).

- At **low escape velocities** relative to their swimming capacity (e.g. @<2 bls^{-1}), a school of fish approaching a screen are often seen to circle around upstream of it, searching for an escape route. The leading fish may then locate the bywash entrance and enter it, head first, some or all of the other fish in the school then following it. If the hydraulic or other conditions in the bywash are unsuitable, and the channel velocity is low, the fish may elect to swim back upstream to find another route. The author (AWHT) has observed smolts migrating back up a lade over a distance of 500 m to re-enter the main river when the bywash was unsuitable.
- At **intermediate escape velocities**, close to their maximum sustainable speed, fish will face upstream into the flow and pass tail-first into the bywash (see Figure 5.4, lower diagram).
- At **high escape velocities**, above their maximum sustainable speed, fish will orientate perpendicular to the screen face and pass tail-first into the bywash. This orientation allows the fish to avoid impingement on the screen using the lowest possible swimming speed and is therefore the limiting case for screen design.

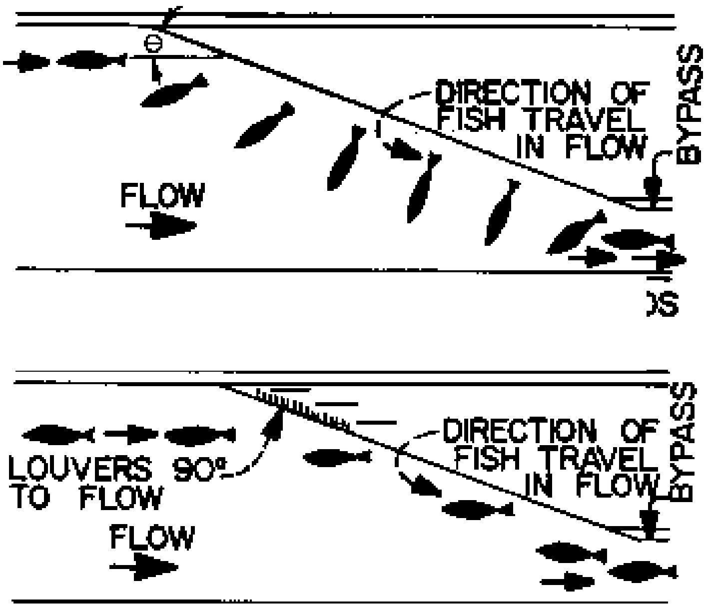

Figure 5.4 Fish movement in front of angled screens and louvres. Lower diagram applies when the channel velocity is below or near the maximum sustainable swimming speed of the fish, upper diagram when channel velocity exceeds the swimming speed of the fish (Rainey, 1985).

5.4 Effect of Screen Angle to Flow

By placing the screen or trash rack at a diagonal angle to the flow (as seen in plan view), fish can be guided to the lower end of the diagonal where a bywash is provided to permit their safe transit downstream. Figure 5.4 again illustrates this principle. Furthermore, the angle of the screen can be set to ensure that the escape velocity is kept below required design value. A screen or trash rack set at a diagonal angle to the flow to bias the fish towards the bywash is always better than one set at right-angles to the flow; in a perpendicular arrangement, no guidance is offered to the fish and this extends the time taken for them to locate the bywash. With large screen arrays, they may become exhausted by the water flow before they can escape.

Figure 5.5 shows the relevant velocity components for an angled fish barrier. The main channel velocity is denoted U_a. The velocity perpendicular to the screen face is the fish's escape velocity, U_e. For a barrier angle ϕ, this is calculated as:

$$U_e = U_a \sin \phi \qquad (2).$$

The sweeping velocity, ***Us***, is the component parallel to the screen face. This is used to calculate the time taken for the fish to traverse the screen from any given point, when swimming at velocity U_e. It is calculated as:

$$U_s = U_a \cos \phi \qquad (3).$$

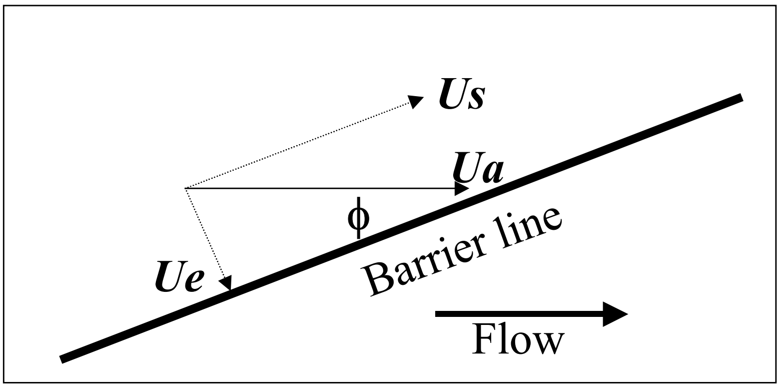

Figure 5.5 Flow velocity components in front of an angled fish barrier. U_a is the channel velocity, *Ue* is the fish escape velocity and *Us* is the sweeping velocity component along the face of the screen (after Turnpenny *et al*., 1998).

For design purposes, the worst case is taken, i.e. the travel time ***T*** (s) for a fish at the extreme upstream end of the screen to reach the bywash. For a screen of length ***L*** m, this is calculated:

$$T = L / U_s \qquad (4).$$

The United States National Marine Fisheries Service recommends that the number of bywashes provided should ensure that the maximum time *T* taken by a fish once it has reached the screen to enter the bywash should be 60s as calculated by this method (Nordland, 1996).

5.5 Selection of Mesh Aperture

The mesh aperture required depends on the size of the fish to be excluded. Turnpenny (1981) gave a formula for computing the rectangular mesh size needed to exclude fish of a given shape and size:

$$M = L/(0.0209L + 0.656 + 1.2F) \qquad (5).$$

Where: M is the square mesh size in mm, L is the fish length in mm (*standard length* - measured from the tip of the snout to the caudal peduncle) and F is the fineness ratio (defined here as the length divided by the maximum depth of the fish). This formula ensures that the calculated aperture size is small enough to exclude a fish by the bony part of the head, i.e. it is not the size at which a fish would just penetrate the mesh.

Values for F in different species are shown in Table 5.1 and Figure 5.6, shows the F values with examples of mesh size *vs*. length of fish excluded. A mesh size commonly used for smolt exclusion is 12.5 mm square; from Figure 3.1 it is seen that this would exclude smolts down to a length of around 12 cm. In Scotland, a rectangular mesh size of 12.5 mm (vertical) x 25 mm (horizontal) is commonplace (Anon, 1995) and is also found widely in England and Wales. Recently, there has been a tendency for regulators to specify smaller mesh (e.g. 10 mm square or 102 x 20 mm rectangular) sizes to protect autumn-run salmonid parr and smaller individuals of other species. As the 12.5 mm (vertical) x 25 mm are found by operators already to be onerous, owing to the hydraulic head loss, the risk of blocking and the frequent cleaning requirement, the requirement for smaller meshes is understandably unpopular and sometimes totally impracticable. This has led to the search for alternative screening methods using self-cleaning technologies or behavioural guidance methods.

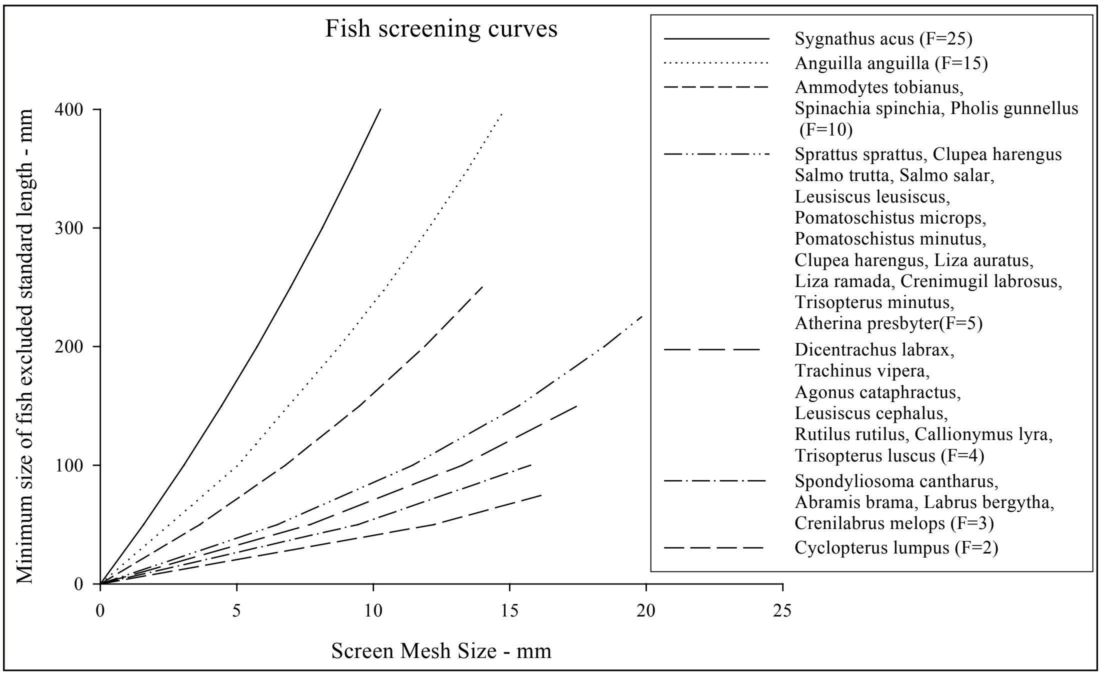

Figure 5.6 Mesh size curves for screening fish of different body shape, plotted from equation 1 (after Turnpenny, 1981, with additional coarse fish data from Table 5.1).

Table 5.1 Observed fineness ratios for 24 marine and freshwater fish species (Turnpenny, 1981, with additional data for cyprinids)

Species	Scientific Name	Fineness Ratio (F)
Bass	*Dicentrachus labrax*	3.67
Bream	*Abramis brama*	2.99
Butterfish	*Pholis gunnellus*	7.73
Chub	*Leusiscus cephalus*	4.39
Dace	*Leusiscus leusiscus*	4.83
Dragonet	*Callionymus lyra*	4.28
Eel	*Anguilla anguilla*	16
Goby (Common)	*Pomatoschistus microps*	5.7
Goby (Sand)	*Pomatoschistus minutus*	5.7
Herring	*Clupea harengus*	4.75
Hooknose	*Agonus cataphractus*	3.87
Lumpsucker	*Cyclopterus lumpus*	2.07
Mullet (Golden)	*Liza auratus*	4.67
Mullet (Thick Lip)	*Crenimugil labrosus*	4.67
Mullet (Thin Lip)	*Liza ramada*	4.67
Pipefish (Greater)	*Sygnathus acus*	25.2
Poor Cod	*Trispoterus minutus*	4.58
Pout	*Trispoterus luscus*	3.92
Roach	*Rutilus rutilus*	3.51
Salmon	*Salmo salar*	4.65
Sand eel	*Ammodytes tobianus*	10.2
Sand smelt	*Atherina presbyter*	5.29
Sea Bream (Black)	*Spondyliosoma cantharus*	2.88
Sprat	*Sprattus sprattus*	4.75
Stickleback (15 spine)	*Spinachia spinachia*	10.9
Trout	*Salmo trutta*	4.37
Weever (Lesser)	*Trachinus vipera*	3.68
Wrasse (Ballan)	*Labrus bergylta*	3.06
Wrasse (Corkwing)	*Crenilabrus melops*	3.06

5.6 Screening for Epibenthic Species

For species that normally live close to the bed, the simple precaution of raising the invert or threshold of any horizontal intake opening may help in reducing entrainment. In a recent survey carried out to determine the optimum opening level for an intake in an estuarine location, different trawling gears were used to compare catch rates just below the water surface and at bed level (A.W.H.Turnpenny, Babtie Aquatic, unpublished data). This was intended to simulate abstraction from a floating pontoon-mounted intake versus a fixed bed-level intake. Predicted fish entrainment levels were reduced by 50% for the floating intake compared with the bed-mounted option. The composition of the catch shifted from one dominated by flatfish and gobies to principally pelagic species.

This concept is also valid for freshwater intakes to reduce the risk to species such as bullheads and loaches. Heuer and Tomljanovich (1979), investigating factors affecting impingement of fish on vertical screens found that provision of a bottom refuge made by blanking off the lower 9 cm of the screen significantly reduced the risk to species living near to the bed.

5.7 Bywash Design Criteria

The placement of a screen flush at the entrance to a channel avoids the need for a bywash, but a sweeping flow is then required to carry fish downstream. Spillway screens (Coanda-effect, Smoltsafe™) require no dedicated bywash structure as such, but do require a surplus flow to convey fish downstream. The bywash must be regarded as integral part of the screening system. A good bywash requires thoughtful design and verification of performance.

5.7.1 Bywash Location

Location of the bywash entrance is important. The entrance to a bywash should be positioned so as to maximise the chances of fish locating it. For an angled screen arrangement, it should be located at the downstream end, in the cleft formed by the screen and the bank or channel wall (see Figure 5.4). The opening should be no more than a metre or two upstream of the screen face. For very large screen arrays, there is a risk that fish may become exhausted or disorientated before fully traversing the screen, in which case, additional bywash entrances would need to be provided at intervals along the screen face. It is unlikely that this would be necessary for screen arrays less than a hundred metres in length, provided that the escape velocity was kept within the sustainable swimming speed limits of the fish, and that there were no structures such as piers getting in the way. At hydropower plants, the bywash entrance should avoid areas of turbulence and plunging water flows near to the turbine inlets, which may make the entrance difficult for fish to detect, and high levels of underwater noise close to the turbines.

5.7.2 Entrance Design

The hydraulic conditions at a bywash entrance are critical to fish diversion efficiency. Rapid changes of velocity and turbulence may cause fish to avoid entering the bywash (Ruggles and Ryan, 1964; Rainey, 1985; Travade and Larinier, 1992). Transitions should be hydraulically efficient, using e.g. a bellmouth entrance design. Haro *et al*. (1998) compared a bellmouth entrance with a simple sharp crested weir design. The water in the bellmouth was accelerated smoothly to a maximum value of 3 ms^{-1} at a rate of 1 ms^{-1} per metre length. Within the first 30 min after release, significantly more Atlantic salmon smolts passed through the bellmouth design than the sharp-crested version. Rapid passage of the bywash is important in reducing the risk of fish entrainment with behavioural barriers or of impingement with mechanical screens. The use of a high entrance velocity reduces the risk of fish turning around and swimming back out. The passage rate of juvenile American shad (*Alosa sapidissima*) was also tested, but found not to be different for the two designs, which would suggest that this species is less influenced by flow conditions. In both species, use of the bellmouth design reduced the tendency of shoals of fish to break up before passing, which suggests that behaviour is less disturbed.

The success of a bywash is strongly influenced by the amount of flow used. The larger the flow, the more likely the fish are to enter it. The US Fish and Wildlife Service call for a minimum bywash attraction flow equating to 2% of the turbine capacity where the screen is oblique to the flow, rising to 5% where the screen is perpendicular to the flow (Odeh and Orvis, 1998). Although there is inevitably a limit on the amount of water that can be allocated to this purpose within any abstraction scheme, it can be economic in hydropower schemes to pump back attraction water after it has fallen by only a small fraction of the nett scheme head (Odeh and Orvis, 1998).

The relative velocities at the bywash entrance and in the main channel are critical. For louvre screen designs, the ratio should be 1.2 -1.4 (Bates and Visonhaler*,* 1957), while Rainey (1985) recommended a value of 1.0 for general use. He proposed that dam-board slots should be provided at the bywash entrance to allow control of the entrance velocity for different flows. When this is done it is preferable to use inserts having an efficient hydraulic lip profile, so that turbulence is kept to a minimum.

Rainey (1985) reported finding bywash arrangements with entrance sizes starting as small as 50 to 150 mm. Openings this small were not attractive to fish and too easily became blocked by debris. His recommendation was to provide a slot to the full depth of the channel, with an entrance width of 300-600 mm. Flow can be regulated by a telescopic weir gate, set back from the entrance, or, in low-cost installations, by dam-boards located in slots across the channel.

Given the sensitivity of bywash effectiveness to good entrance hydraulics, it is recommended that bywash entrances should be 'soft'-engineered from materials such as timber or stone-filled gabions, such that the entrance profile can be readily modified and fine-tuned to give optimum bywash performance. This requires detailed visual monitoring of fish behaviour at the entrance, e.g. by closed-circuit television monitoring.

5.7.3 Light and Visual Attributes

Smolts are reluctant to enter darkened culverts during downstream migration (Rainey, 1985). The same appears to be true of non-salmonid species (percids and clupeids) that have been investigated in Australia (Mallen-Cooper, 1997). Fish tend to resist entry into any form of bywash, such as an orifice or pipe that does not admit light. Open-topped bypass channels are therefore the preferred solution.

The visual appearance of a bypass, as seen from the fish's eye view, is important. Any apparent discontinuity of surroundings may cause fish to turn back, reducing or delaying passage. Fish moving from open water and meeting a visible structure will generally turn around and face upstream, as a result of the optomotor reflex (Harden-Jones, 1967; Arnold, 1974). In experiments, Haro *et al*. (1998) showed that smolts and shad mostly displayed this behaviour when entering a bypass, up to the point when they became exhausted and passed downstream. This was the case even at very low light levels (<0.1 lux), indicating the persistence of visual cues, or detection of the flow field or detection of displacement by another sensory system. Reduction of visible discontinuities from the fish's aspect may therefore improve bypass efficiency, for example blending the colour of the bypass entrance into its surroundings. Flat grey colour is often used for this purpose on any painted surfaces, although biofouling will soon naturalise most surfaces. Inspection using an underwater television camera or diver may be helpful.

Artificial lighting has been used to enhance bypass attractiveness. In an early study, Fields *et al.* (1958) found that juvenile salmonids were repelled by bright light but attracted by dim light. On the other hand, Larinier and Boyer-Bernard (1991) found that passage rates of Atlantic salmon smolts through a bypass at night increased when adjacent lights were turned off, presumably owing to the loss of visual cues. Illumination has been observed to enhance bypass efficiency for juvenile American shad (Anon., 1994). As no clear message emerges from these studies, no specific recommendation can be made. Given the ease and low cost of trying out lights, some experimentation may be worthwhile.

5.7.4 Bywash Conduits and Outfalls

Fish handling within the bywash and at the return point should be as gentle as possible, avoiding sharp bends (3 m minimum radius), sudden drops, and rough surfaces and irregularities that might cause abrasion. This is particularly important for smolts, which have loose scales and become vulnerable to osmotic disorders upon scale loss. The maximum scale loss tolerated by smolts is of the order of 20-30% (Kostecki *et al*., 1987). Open, half-round channels are preferred.

Even steep chutes have proved successful, provided that there is adequate water depth at the receiving end. The smolt return chute at Dunalastair Dam (Scottish HydroElectric plc), which is in the form of an open channel some 15 m long and angled at 45^o to the vertical, functions well, with no evident harm to smolts. It is important that the fish are not dazed or disorientated at the point of return, which would make them more vulnerable to predators. The risk of predation of returned fish is a weak point in any diversion scheme and has received little investigation. Odeh and Orvis (1998) give the following criteria for the plunge pool from a return chute:

- plunge pool volume: 10 m^3 per cumec of bywash flow;
- plunge pool depth: ¼ of the differential head but no less than 0.9 m for head differences of <3.6 m;
- at tailraces, the chute elevation should be 1.8-2.4 m above the free surface level to avoid adult fish jumping into the chute.

6 SELECTING THE BEST SCREENING SOLUTION

6.1 The Selection Process

Given the wide variety of screening applications and environments and the need to consider the protection of a much-enlarged list of fish species than perhaps in the past, the developer or operator is faced with a potentially bewildering array of options. From the foregoing sections, it should be evident that the following questions must be addressed:

- What is the motivation for fish screening (e.g. statutory/planning requirement, desire to improve environmental performance, 'good-neighbour' policy, etc.)?
- What species and lifestages are to be protected and at what times of the year?
- What level of protection is required under BAT/BATNEEC[25] principles (establish via risk assessment/consultation)?
- What screening techniques will achieve the above cost-efficiently and within the environmental and engineering constraints of the site and with due regard to public safety?
- How will the screening system be maintained, taking account of health and safety issues for the operator?
- What provisions should be made to demonstrate that the screens are working effectively and are being operated and maintained in a way that consistently achieves the required level of performance?

The overall process is shown by the flowchart given in Figure 6.1. This sets out the main steps in developing a fish protection solution for a water intake. Consultation with the various bodies shown is the most important aspect of the whole process. Discussing the issues with the relevant parties at an early stage avoids misunderstandings and can save much time, trouble and cost.

Table 6.1 provides a summary of techniques that, from current knowledge, are likely to provide suitable screening solutions for different applications/environments for the various categories of fish of concern. Various techniques may be shown for each case; the options that are most likely to be suitable are shown in emboldened typeface. In selecting a technique, the issues of required performance, engineering and environmental suitability, public and operator safety and cost-benefit listed above must be taken into account. This will be highly site-specific and a matter of skilled professional judgement. The Environment Agency, as regulator, will not be able to advise on the selection of techniques and it is the responsibility of the operator to consult fully and take any necessary professional advice in this matter. Table 6.1 is not comprehensive and there inevitably remain at this time gaps in our knowledge and uncertainties in the performance of certain techniques with particular fish species and applications/environments. There are also circumstances where there is no established reliable solution at the present and where further research and evaluation will be required.

[25] Best Available Technology/ Best Available Technology Not Entailing Excessive Cost

Figure 6.1 Flow Chart for Planning a Fish Screen

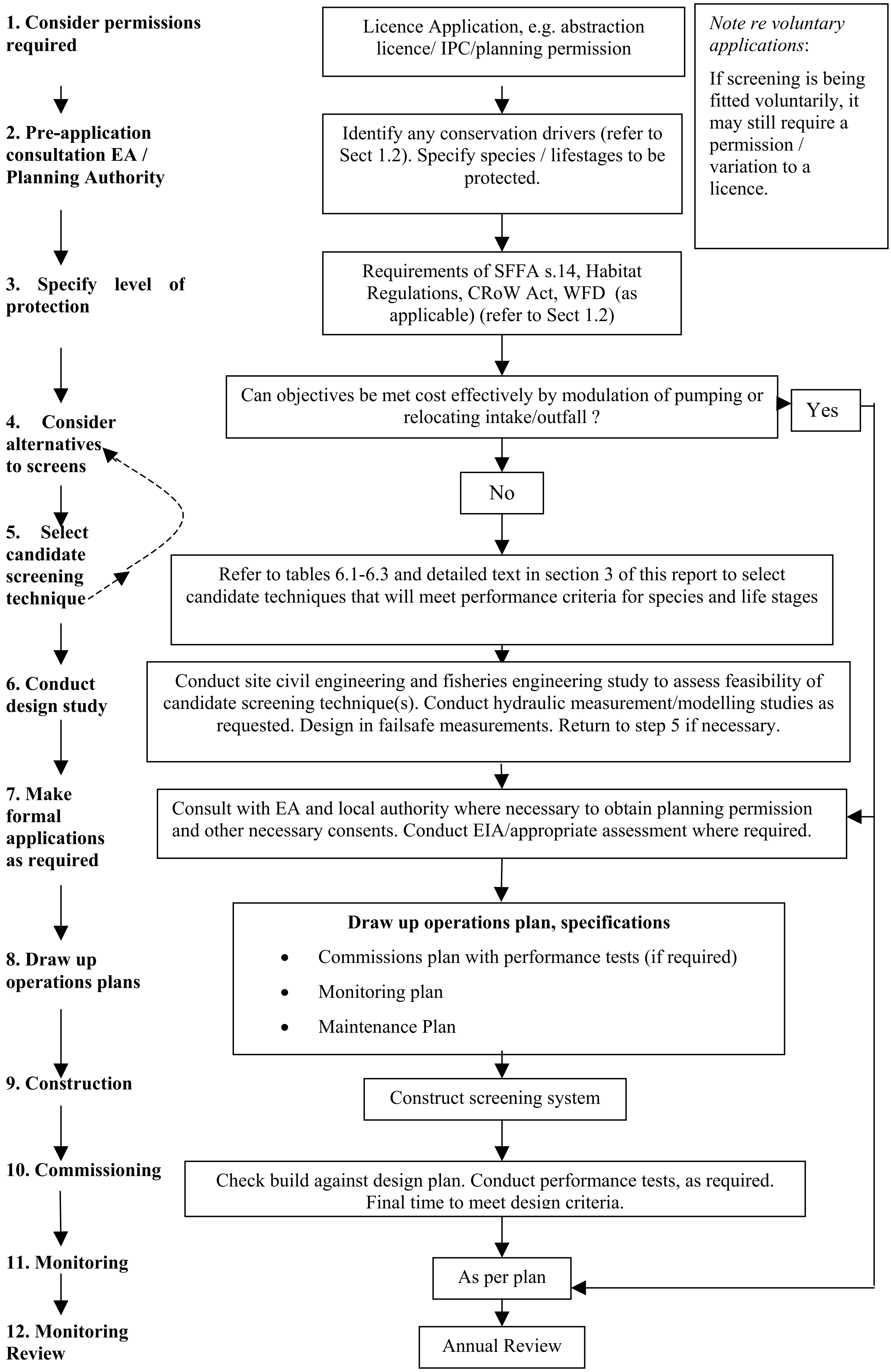

Table 6.1 Screening Techniques Suitable for Freshwater Sites

Freshwater						
Fish species	**Life stage**	**Canal / Industrial / Potable supplies & Fish farms**	**Thermal Power Plant**	**Hydro Electric Power Plant: Low Head**	**Hydro Electric Power Plant: High Head**	**Outfalls**
Salmonids and Coregonids	Juvenile	**Passive Mesh, PWWC, Sub-**gravel intakes, MLES, Acoustic, Light, Bubble	**Passive Mesh, PWWC, Coanda,** Acoustic, Light, Bubble	Acoustic, Light, Bubble	**Passive Mesh, Coanda,** Acoustic, Light, Bubble	
	Smolts	**Passive Mesh, Vertical/inclined Bar rack, Coanda, PWWC,** Sub gravel intakes,Rotary Discreen, Modular Inclined, **Louvre, Acoustic, Light,** Bubble	**Passive Mesh, Vertical/inclined Bar rack, PWWC, Coanda,** Rotary Discreen, Modular Inclined, Louvre, **Acoustic, Light,** Bubble	**Passive Mesh, Vertical/inclined Bar rack,** Louvre, **Acoustic, Light,** Bubble	**Passive Mesh, Vertical/inclined Bar rack, Coanda,** Modular Inclined, Louvre, Acoustic, Light, Bubble	
	Adult	**Passive Mesh, Vertical/inclined Bar rack,** Coanda, PWWC, Rotary Discreen, Sub-gravel intakes, Modular Inclined, Louvre, Electric, Acoustic	**Passive Mesh, Vertical/inclined Bar rack, PWWC, Coanda,** Rotary Discreen, Modular Inclined, Louvre, **Acoustic, Light,**	**Passive Mesh, Vertical/inclined Bar rack,** Louvre, **Acoustic, Light,**	**Passive Mesh, Vertical/inclined Bar rack, Coanda,** Modular Inclined, Louvre, Acoustic, Light,	**Vertical/Inclined Bar Rack, Electric**
Lampreys	Juvenile	**Passive Mesh, Coanda, PWWC,** Sub-gravel intakes	**Passive Mesh, Coanda, PWWC**	Electric	**Passive Mesh, Coanda**	
	Adult	**Passive Mesh, Coanda, PWWC,** Rotary Discreen, Sub-gravel intakes, Modular Inclined, Electric, Deep channel bypass?	**Passive Mesh, Coanda, PWWC,** Rotary Discreen, Modular Inclined, Electric, Deep channel bypass?	**Passive Mesh,** Electric?, Deep channel bypass?	**Passive Mesh, Coanda,** Modular Inclined, Electric, Deep channel bypass?	**Vertical/Inclined Bar Rack, Electric**
Eels/Elver	Elver	**PWWC, Sub-gravel intakes,** MLES, Modular Inclined, Electric, Light	**PWWC, Sub-gravel intakes,** MLES, Modular Inclined, Electric, Light	Electric?, Light	**Coanda,** Electric, Light	
	Adult	**Passive Mesh, Coanda, PWWC,** Rotary Discreen, Sub-gravel intakes, Modular Inclined, Electric, **Light,** Deep channel bypass?	**Passive Mesh, Coanda, PWWC,** Rotary Discreen, Modular Inclined, Electric, **Light,** Deep channel bypass?	**Passive Mesh,** Electric, **Light,** Deep channel bypass?	**Passive Mesh, Coanda,** Modular Inclined, Electric, Light, Deep channel bypass?	**Vertical/Inclined Bar Rack, Electric**
Freshwater coarse fish	Juvenile	**Passive Mesh, PWWC, Coanda,** Sub-gravel intakes, MLES, Acoustic, Light, Bubble	**Passive Mesh, PWWC, Coanda,** Acoustic, Light, Bubble	Acoustic, Light, Bubble	**Coanda,** Acoustic, Light, Bubble	
	Adult	**Passive Mesh, Vertical/inclined Bar,** PWWC, Rotary Discreen, Coanda, Sub-gravel intakes, Modular Inclined, Louvre, **Acoustic,** Light, Bubble	**Passive Mesh, Vertical/inclined Bar,** PWWC, Rotary Discreen, Coanda, Modular Inclined, Louvre, **Acoustic,** Light, Bubble	**Passive Mesh, Vertical/inclined Bar,** Louvre, **Acoustic,** Light, Bubble	**Passive Mesh, Vertical/inclined Bar,** Coanda, Modular Inclined, Louvre, Acoustic, Light, Bubble	**Vertical/Inclined Bar Rack, Electric**
Freshwater benthics	Juvenile	**Passive Mesh, Coanda, Blank off bottom,PWWC,** MLES, Light, Bubble	**Passive Mesh, Coanda, Blank off bottom,**PWWC, Light, Bubble	**Blank off bottom,** Light, Bubble	**Passive Mesh, Coanda,** Light, Bubble	
	Adult	**Passive Mesh, Vertical/inclined Bar,** Rotary Discreen, Coanda, PWWC, **Blank off bottom,** MLES, Modular Inclined, Light, Acoustic	**Passive Mesh, Vertical/inclined Bar,** Rotary Discreen, Coanda, PWWC, **Blank off bottom**, MLES, Modular Inclined, Light, Acoustic	**Passive Mesh, Vertical/inclined Bar, Blank off bottom,** Light, Acoustic	**Passive Mesh, Vertical/inclined Bar, Blank off bottom,** Coanda, Modular Inclined, Light, Acoustic	

Key: Items in emboldened typeface are the most suitable choices but those shown in standard typeface may be suitable in some applications

Marine/Estuarine					
Fish species	**Life Stage**	**Large Thermal Power Plant with Onshore Intake**	**Large Thermal Power Plant with Offshore Intake**	**Small Thermal Power Plant / Desalination / Refineries**	**Outfalls**
Salmonids	Smolts	**PWWC screens where feasible; Acoustic,** Bubble ***with*** **Fish Return System otherwise.**	**PWWC screens where feasible; Velocity Cap** *with* **Acoustic, Bubble** *with* **Fish Return System otherwise. Keep opening above bed level.**	**PWWC** alone *or* **Acoustic,** Bubble ***with*** **Fish Return System**	
	Adult				30-50 mm-spaced Bar Rack
Shads	Juvenile				
	Adult				30 mm-spaced Bar Rack
Lampreys	Juvenile				
	Adult				
Eels/Elver	Elver				
	Adult				
Marine/estuarine benthic	Juvenile				
	Adult				
Marine/estuarine demersal	Juvenile				
	Adult				
Marine/estuarine pelagic	Juvenile				
	Adult				

Table 6.2 Screening Techniques Suitable for Marine Sites

6.2 Multiple Solutions and Non-Screening Solutions

It is stressed again that screening is not always the best solution. It may be more economic and/or protective to modulate abstraction to avoid seasons, days or times of the day when fish are most at risk.

In the case of larger coastal abstractions where dozens of species may have to be protected, a single solution may not be adequate. The best solution found to date for sites where PWWC screening is impractical uses a combination of an acoustic fish deterrent, which is very effective against pelagics and moderately effective against demersal species, and a fish return system which is moderately effective for demersal species and offer the best solution for robust benthic flatfishes and rock fishes. The systems therefore complement each other well. This combination of methods is used at several power plants, including Great Yarmouth, Shoreham, Fawley in England and Doel in Belgium. There are numerous other technology combinations that have shown promise and which should not be overlooked. These include bubble/acoustic/strobe-light combinations, electric and acoustic screens, screen and eel-bypass combinations and use of turbulent attraction flow to improve guidance in front of screens. Reference to Table 6.3 may suggest other techniques that could be combined to achieve the best results for the species present.

6.3 Costs of Different Screening Solutions

The costs of installing fish screens or barriers are highly site-specific and will depend on whether the application is new-build or retrofit, what existing structures are present, what ground conditions are like, the degree of exposure to flood- and other damage, whether power (if required) is available and many other factors. Table 6.4 attempts to provide indicative costs of some of the main techniques in use described in section 3 of this Guide. In most cases the costs are for the screening/ barrier hardware only and exclude costs associated with planning and design, consultancy, site investigations and preparation, installation, commissioning and testing. These likely additional costs may inflate the overall project cost considerably.

Type of Screen		Relevant section in text	Salmonids	Shads	Eel & Lampreys	Cyprinids & Other Freshwater Fish	Marine		
							Pelagic	Demersal	Benthic
Physical screens	**Passive Mesh/Wedge-Wire Panels**	3.1.1 & 3.2.2	*****	*****	*****	*****	*****	*****	*****
	Vertical or Inclined Bar Racks	3.1.2	*****	*****	**	***	*****	*****	*****
	Rotary Disc Screen	3.1.3	****	?	?	***	NS	NS	NS
	Smolt Safe'	3.1.4.2	**	NS	?	?	NS	NS	NS
	Coanda Screen	3.1.4.1	*****	NS	*****	*****	NS	NS	NS
	PWWC Screens	3.2.1	*****	*****	*****	*****	*****	*****	*****
	Marine Fish Exclusion System	3.2.4	***	***	***	***	NS	NS	NS
	Modular Inclined Screen	3.3.1	****	NS	****	****	?	?	?
	Labyrinth Screen	3.3.2	*****	****	****	***	?	?	?
Behavioural screens	**Louvre Barrier**	3.4.2	**	?	NS	?	NS	NS	NS
	Bubble Curtain	3.4.3	**	**	NS	**	**	**	*
	Electric Screen (GFFB)-intakes	3.4.4	?	?	?	?	NS	NS	NS
	Electric Screen (GFFB)-outfalls	3.6.3	****	?	****	****	NS	NS	NS
	Acoustic (SPA/Infrasound)	3.4.5	****	****	**	****	*****	****	*
	Acoustic (BAFF)	3.4.5.8	****	?	NS	****	NS	NS	NS
	Acoustic (Ultrasound)	3.4.5.11	NS	****	NS	NS	***	NS	?
	Continuous Light	3.4.6.1	**	**	**	**	NS	NS	NS
	Strobe Light	3.4.6.2	**	***	***	***	NS	NS	NS
	Eel Deep Bypass	3.5.3	NS	NS	***	NS	NS	NS	NS
	Surface collectors	3.5.2	***	?	?	***	NS	NS	NS
	Velocity Cap	3.4.7	**	***	NS	NS	***	**	?
	Turbulent Attraction Flow	3.5.1	**	?	?	?	?	?	?

NS

Key: note that the ratings assume that the systems are designed using the appropriate criteria for the application. Not Suitable ** Low efficiency *** Suitable for some lifestages ****Suitable for most lifestages *****Excellent for most or all lifestages

Table 6.3 Suitability of Screening Techniques for Different Types of Fish

Table 6.4 Approximate purchase costs (£k) for fish screens and barriers. Costs are for equipment only and exclude installation except where otherwise indicated.

Screen or Barrier Type	Inland		Estuarine/Marine		
	$\leq 1\ m^3s^{-1}$	$10\ m^3s^{-1}$	$\leq 1\ m^3s^{-1}$	$10\ m^3s^{-1}$	$50\ m^3s^{-1}$
Positive Exclusion Screens					
Flat Mesh Panel, 12mm	24	50	30	-	-
PWWC Screen, 3mm	50	285	70	430	-
MLES™	160*	1600*	-	-	-
Under-Gravel Filter	160	-	-	-	-
Raked Bar Screen	40	250	40	250	-
Coanda-Effect	13-17	-	-	-	-
Smolt-Safe™ Screen	15		-	-	-
Rotary Disk Screen	130	-	-	-	-
Behavioural Screens					
Bubble Curtain	5	15	5	15	75
Louvre Screen	24	50	-	-	-
Continuous Light	5	20	-	-	-
Strobe Light	10	40	-	-	-
SPA Acoustic Barrier	15	40	15	40-60	80-250
BAFF™ Acoustic Barrier	18	40	-	-	-
Electric GFFB	10	18	-	-	-

* MLES figures are manufacturers estimated fully installed costs in pounds sterling.

Figures given are based on prices obtained from manufacturers. Three scheme sizes (1, 10 and 50m^3) have been considered where appropriate – generally the smaller schemes are relatively more costly owing to fixed minimum costs. Also, inland and coastal sites have been differentiated. This is important because different materials may be required for use in saline waters (e.g. marine grade stainless steel or Cu/Ni alloy), which increases costs. No figure is shown in cases where screens are considered unsuitable.

7 MONITORING OF SCREEN EFFECTIVENESS: RECOMMENDATIONS FOR FURTHER WORK

7.1 Introduction

From the review of screening technologies presented in section 3 of this Guide, it is clear that many different approaches exist and that there has been much innovation in recent years. The development of new techniques reflects the need to provide cost-effective solutions to suit an ever-widening range of circumstances. Often, a technique has been developed for a specific application but if the results look promising others will want to try it in a different situation. Indeed, it may be arguable that every situation is different and that the performance of every new fish screening system installed should be evaluated at the commissioning stage. In practice, comprehensive scientific testing can be very costly and it makes sense to first answer basic questions on effectiveness from soundly designed generic studies. The site-specific questions hopefully can then be addressed in a much more concise test programme where the regulator deems this necessary. The nature of work appropriate to generic trials and to site-specific commissioning trials is discussed below.

Solomon (1992) proposed that trialling of different fish screens would be best carried out at a purpose-built facility, e.g. on a disused mill leat. He pointed out a number of merits of this approach, e.g. that it would not interfere with operation of an existing abstraction, there would not be issues of operators being unwilling to cooperate with a project aimed at identifying the harm that they are doing and that there would not be operational constraints on the manipulation of flow conditions. While these remain valid issues, the breadth of environments and fish species now being considered mean that a variety of such test sites would be required, covering upland and lowland rivers, canals, lakes/reservoirs and estuarine/coastal locations. Also, it is the experience of the present authors that many site owners recognise the benefits to future business of work being undertaken at their facilities and are willing to cooperate. Cooperation often extends not only to providing access to sites but also to assisting with test facilities and being prepared to manipulate flow conditions to suit experiments. In some cases, successful approaches have been made through trade associations, a route which is to be commended where possible. In particular, operators have shown most willingness to cooperate with regard to trialling behavioural screens, since where they prove suitable, their capital and operating costs would often be lower than for positive exclusion fish screens. Further opportunities may arise at newly developed operational sites when trialling is required as a condition of the planning consent or abstraction, impoundment or land drainage consent.

7.2 Priorities for Generic Trials

The number of techniques now in use could create an almost unlimited agenda for testing in order to cover the different environments, species and lifestages and the possible combinations of techniques. Rather than produce an exhaustive list of possibilities, the aim here is to identify where resources would be best directed to meet current needs. Table 7.1 lists the most promising techniques and identifies priorities for trials along with possible test locations/environments. The choice of techniques is necessarily subjective.

Table 7.1 Proposed Generic Trials Required for Different Screening/Guidance Techniques

Technique	Trial Requirements	Suggested Environment or Location
Flat panel screens	None - well proven	n/a
Vertical bar screens	None - well proven	n/a
Wedge-wire panels	Automated cleaning mechanisms for large installations	River or estuarine site
PWWC screens	Ability to self-clean in different environments	Thames Tideway, Beckton (in progress 2004-5) Stillwaters, especially canals
Coanda-effect screens	None - well proven	n/a
Rotary disc screens	Not currently a high priority	n/a
MLES™ barrier	Await outcome of further trials in USA	n/a
Louvre screens	Suitability for non-salmonids	Small hydropower intake
Strobe lights/bubbles	High priority for eels	Small hydropower intake
Acoustic SPA Acoustic infrasound	Well proven for estuarine power plant; more trials on freshwater needed	Potable water intake
Acoustic BAFF™	Trialled at several locations in UK, Europe and USA but more exhaustive testing needed for a range of fish and for depths >3m	Small hydropower intake
GFFB electric	Merits testing on intakes especially for eel and adult lamprey exclusion	Small hydropower intake
Turbulent attraction flow	Merits testing in conjunction with other physical and behavioural methods to improve guidance efficiency	Small hydropower intake
Adult eel bypass	High priority for eels	Small hydropower intake

7.3 Scope of Work and Costs for Generic Trials

7.3.1 Measures of Performance

Fish screens usually form only part of an overall fish diversion or protection system and it is the performance of the entire system that needs to be proven. Turnpenny *et al*. (1998) used the concept the *scheme passage rate* (*SPR*), defined as:

$$SPR\ \% = 100 * N_{leaving}/N_{approaching,}$$

Where $N_{approaching,}$ and $N_{leaving}$ are the numbers of fish approaching and passing the scheme respectively. Although originally referring to hydroelectric schemes, the definition will apply to any kind of intake or outfall scheme. This concept assumes that all the fish are uninjured when passing the scheme. Where there is a possibility of fish being harmed as a result of the scheme, this needs to be taken into account. Examples of where fish might be harmed are:

- during passage through a pump or turbine;
- as a result of contact with screens or other mechanical components of the system;
- through predation associated with behavioural changes that make fish an easier target for predators.

This can be represented by the following expression:

$$SPR'\ \% = 100(1-P_i) * N_{leaving}/N_{approaching,}$$

Where P_i represents the probability of fish death or injury. Note that within this expression, *SPR'* takes the same value whether a fish is injured or killed – i.e. the worst case is assumed, that any fish injured will not survive.

While the *SPR'* is the most important measure of a screening system's performance, another important aspect is the time taken for fish to pass the scheme. This applies principally to off-channel schemes, e.g. hydroelectric schemes where water is diverted through a mill-leat before being returned to the main channel. Delays can lead to increased risk of predation, but this risk is accounted for in the *SPR'* expression. There may be less clear consequences of delays, for example delayed passage downstream might put them at some ecological disadvantage. It is not realistic to propose targets for passage time, as much will be site-specific and will also depend on the physiological state of the fish, water conditions, time of day, etc. Such effects are virtually impossible to define and the pragmatic course of action is to aim to minimise the time of passage of a scheme. As part of any off-channel screen trial it is therefore recommended that the time taken for fish passage should at least be recorded so that comparisons may be made for different operating conditions or with alternative screen systems tested under comparable conditions.

7.3.1.1 Test Methods

Methodologies for trials should be aimed at estimating the scheme passage rate (*SPR'*) and the duration of passage between predefined scheme entry and exit points. However, it is also extremely helpful to observe fish behaviour in the vicinity of screens and bywashes. Where problems occur or scheme passage rates are below desirable levels, this allows the modes of failure to be identified. A variety of methods can be used.

Table 7.2 lists methods that have been used in different applications and references literature describing the methods.

Table 7.2 Examples of methods used for fish screening system trials

(a) Fish sampling techniques

Technique	Application	Purpose	Reference
Intake/tailrace netting – using trawl-type nets	Sampling fish at water offtakes or hydropower plant	Estimation of numbers of fish passing inlet screen	Wood *et al*., 1994; Turnpenny *et al*., 1996; Hadderingh, & Smythe, 1997 Hadderingh & Bakker, 1998
Canadian screw-trap	Sampling fish in fast-flowing, deep channel	Estimation of numbers of fish passing inlet screen	Spiby, 2004
Electrofishing	Sampling areas behind screens	Estimation of numbers of fish passing inlet screen	-
Collection of fish from band- or drum-screens	Sampling fish at secondary (trash-) screening points, e.g. in power plant or water pumping stations	Estimate impingement rates; compare numbers impingement with/without behavioural technology	Turnpenny, 1993; Turnpenny *et al*, 1994, 1995; Maes *et al*., 2004
Louvre-screen trap	Sampling fish in major flow downstream of intake	Estimate entrainment rate; compare for different screening techniques	Solomon, 1992
Electronic fish counters	Intake and bypass flow counting of smolts and larger fish	Compare fish numbers in screened flow and bypass	Welton *et al*. 2002
Fish trapping with Wolf grid	Sampling fish in bypass channels	Estimation of numbers of fish diverted into bypass	Turnpenny *et al*., 2003b

(b) Fish observation and monitoring techniques

Technique	Application	Purpose	Reference
Video surveillance	Monitoring fish in front of screens & at bypass entrance	To check for evidence of fish impingement, delay or to observe behaviour	Larinier & Travade, 1999
Hydroacoustic monitoring	Intake forebays & bypass entrances	Observe behaviour & estimate relative numbers of fish passing screens or entering bywash	**7.3.2** Iverson, 1999; Johnson *et al*., 2002
Radio-or acoustic-tagging (biotelemetry)	Observing fish movement through or around schemes	Estimation of *SPR* and duration of passage	**7.3.3** Lariner & Travade, 1999
Passive Integrated Transponder (PIT) or Floy tagging	Monitoring fish movement through or around schemes	Estimation of *SPR* and duration of passage using mark-recapture	Larinier & Travade, 1999
Float-tagging	Observing fish movement through or around schemes	Detailed observation of fish behaviour in front of screens and bypasses; estimation of *SPR* and duration of passage	Turnpenny *et al*., 2003

Plate 7.1 Total flow netting at the draft tube of a small hydropower turbine. Here, fish enter a live-car at the cod-end of the net to facilitate removal and to reduce the likelihood of net-induced injuries .

7.3.4 Sampling Fish Post-Screening and in Bywashes

One of the most common methods involves fitting a net to filter the entire intake flow or some portion of it (Wood *et al*., 1994; Turnpenny *et al*., 1996; Hadderingh and Smythe, 1997 Hadderingh & Bakker, 1998). The net is often conical or pyramidal in shape, similar to a trawl net. The mesh size is selected according to the size of fish to be retained. The size of the net will depend on the flow rate and debris load. The force of water can be substantial and such nets should be generously sized and strongly attached. It is normally necessary to be able to shut off the flow to examine the net, but having the net open at the cod-end and discharging into a removable live-car (Plate 7.1) avoids this necessity and creates a more benign holding area for the fish. Alternatively, where space allows, fyke nets can be set in the flow behind the intake to capture all or a sample of the flow. With either approach, catches can be compared with and without the screening measures operating and with alternative screening arrangements.

A newer technique is provided by the rotary screw trap (Plate 7.2). The trap is fixed to a flotation raft and is water powered. The central drum rotates and lifts fish into a holding tank. The trap needs a water depth of ≥1m and works best in water velocities of ~1ms^{-1}. These conditions are usually met in hydroelectric headrace canals, where the trap has been used with some success to test a BAFF™ screen (Spiby, 2004). The screw trap samples only a small proportion of the total channel flow and therefore takes only a sample of fish.

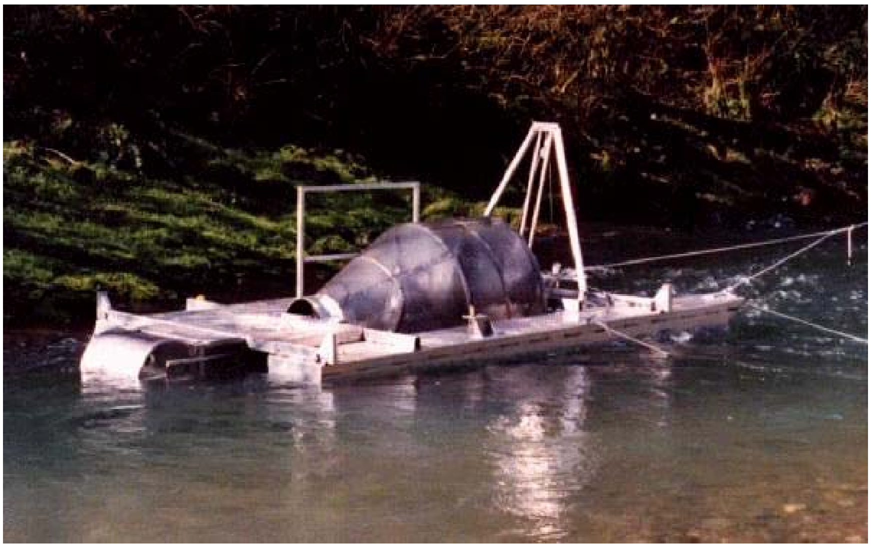

Plate 7.2 A rotary screw trap. Flow rotates the barrel and fish present in the flow are lifted into a holding chamber. The trap takes a small sample of the total channel flow.

Other kinds of fish trap are also useful. The Wolf trap (Plate 7.3) is essentially a dewatering device that can be placed in a bywash channel to remove fish. It comprises a slatted channel floor through which flow passes, leaving the fish to be washed along the surface of the slats and to drop into a tank or cage at the downstream end. It is probably the most widely used style of smolt trap and is ideally suited to monitoring fish entering a bywash (Turnpenny *et al*., 2003b). The louvre screen trap described in section 3 provides a further alternative which appeared to work well, although the version constructed at Walton was a substantial structure that would be more suited to a semi-permanent test facility.

Plate 7.3 A Wolf trap photographed at Halsou, France. Water is strained through a set of parallel rods or slats that run along the length of the channel. These are spaced at about 6mm apart, allowing water to pass through, while fish are flushed along the slats and into a holding tank at the downstream end.

Electrofishing areas downstream of a fish screen can provide useful information about fish ‘leakage’ through the screen. It is not normally used as a quantitative method, as fish may quickly pass beyond reach of the gear, e.g. into culverts or pipes. The presence of fish in quiet areas behind a screen can signal problems with screens.

Sampling on band and drum screens is the most widely used method for assessing entrainment rates at thermal power station cooling water intakes (Turnpenny, 1993; Turnpenny *et al*, 1994, 1995; Maes *et al*., 2004) and potable water intakes (Frear and Axford, 1991). This allows catches to be compared e.g. for ‘on’ and ‘off’ periods with acoustic deterrents, bubble curtains strobe lights, etc.. Care must be taken to allow for any transit time of fish through the system or residence time before fish appear on the screens, which can range from minutes to many hours. Transit and residence time can be estimated e.g. by introducing marked fish into the intake and timing their arrival on the screens, but it may vary according to the swimming abilities of the fish (influenced by species, size, water temperature and other factors) and their behaviours. Once this is known, a suitable gap can be left between test conditions.

Welton *et al*. (2002) devised automated smolt counting methods to simultaneously count fish passing with the screened flow and in the bywash flow during trials of a BAFF™ and bubble curtain system. Counting was performed by crowding the fish into a narrow channel fitted with resistivity counters (Plate 7.4). Time-lapse video recording was used to validate the counters. The relative numbers of fish entering the bypass versus those in the main flow were used to assess screening efficiency.

Plate 7.4 Video and resistivity smolt counting unit used to monitor smolt diverted into a bywash during BAFF™ tests conducted by the Centre for Ecology and Hydrology (CEH) at the River Frome test site in Dorset.

7.3.5 Observing Fish Behaviour

Table 7.2(b) lists methods commonly used for observing fish behaviour around screens and bywashes. While 'hi-tech' solutions such as radio-tracking and hydroacoustics have their place, the value of simple direct observation should not be overlooked. On many schemes, much can be learnt from a few hours personal observation at key points such as along the screen face and at the bywash entrance. Arrays of overhead or underwater CCTV cameras strategically placed can provide much information about how fish react to the screens or behavioural barriers and where points of weakness are. It may be possible to link these to e.g. hydraulic anomalies at those points, allowing corrective action to be diagnosed. As visibility can often be poor, visualisation of fish movements can be aided by fitting brightly coloured or luminous tags to the dorsal fin of the fish. Alternatively, float tags can be used. Turnpenny *et al*. (2003) describes their use in testing a BAFF™ at Hemsjo Nedre hydropower plant in Sweden. For smolt-sized fish (i.e. 12-20cm in length), 12mm diameter polystyrene beads attached by a 0.5m length of fine nylon line are suitable (Plate 7.5). These can be sprayed with fluorescent paint to aid visibility. The tags should be attached very lightly, near to the edge of the dorsal fin membrane, so that the fish can easily pull away from the line if it should become snagged. In a recent performance trial of the angled bar rack and bywash at Stanley Mills hydropower plant in Perthshire (Dr S.C. Clough, personal communication), float tags attached to the smolts were also fitted with miniature chemical lights (Starlite™, Luminasa Europe Ltd). Using this technique, it was possible to observe the movements of smolts released into the headrace, plotting their paths and timing their rate of passage into the bywash. It was demonstrated that Atlantic salmon smolts reacted positively to strong water currents, entering the fastest flowing areas and avoiding contact with the screens.

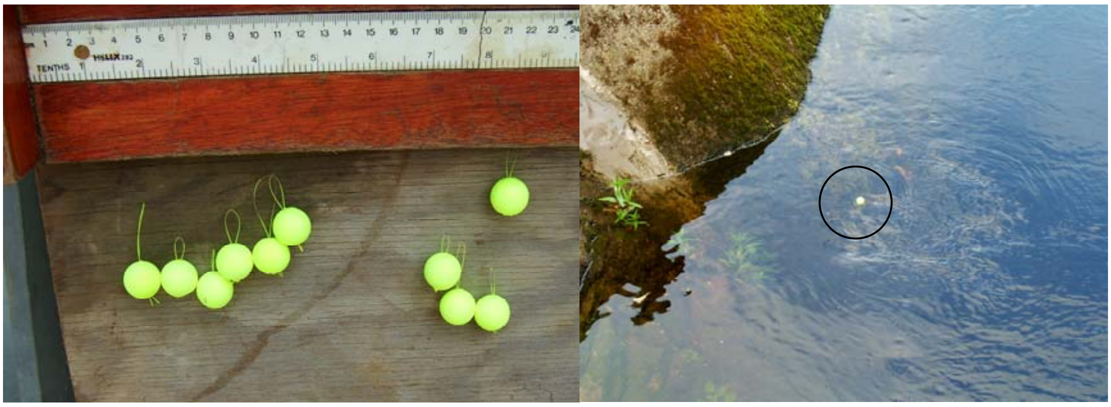

Plate 7.5 Fluorescent polystyrene float tags as used to follow close-range movements in front of screens and bywashes. The left-hand photograph shows a number of floats prior to attachment; the right hand side shows one as viewed in the water (inside black circle).

Hydroacoustic methods have been used extensively in the USA to observe detailed movements of fish at large dams (e.g. Iverson, 1999; Johnson *et al*., 2002) but these methods are costly and somewhat experimental and to date have not been used routinely in the UK.

Radio- and acoustic tracking provide useful techniques for making observations on a larger scale, i.e. to monitor fish passage of an entire scheme or network of schemes (Turnpenny *et al*., 1996), rather than fine detail close to screens and bywashes, although quite fine resolutions (± a metre or so) can be achieved in some circumstances (Larinier & Travade, 1999). Numbers of fish that can be economically used with these methods may be limited, in which case they may be augmented by cheaper tagging methods using PIT or Floy tags. The latter types are normally used in mark-recapture programmes, results being derived e.g. from the numbers of recaptures obtained in bywash and discharge net samples from a known number of tagged fish released (Larinier & Travade, 1999).

7.4 Site-Specific Commissioning Trials

Generally it is advisable to conduct at least a brief assessment of the performance of a screening system following installation or modification. This should be scheduled as part of the commissioning process. It is highly desirable to consider safe access and sampling requirements at the design and construction to facilitate future monitoring. Regulatory agencies may require provision to be made for fish trapping or counting in bywash channels. For example, following consultations with the Environment Agency, a recent planning application for construction of a small hydropower plant on the Yorkshire

Ouse includes provision of a removable Wolf-grid in the bywash channel and a fish holding chamber. At another site where commissioning trials were required, the failure to provide safe access for sampling proved costly when extensive temporary scaffolding was needed.

Trial methods for site-specific commissioning may be selected from any of those identified in section 7.3 but for cost reasons the simpler methods are to be preferred., e.g. trapping, video surveillance or float-tagging. For regulated applications the methods will need to be agreed with the appropriate agency in advance.

8 KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

8.1 Review of recommendations from Solomon (1992)

In advice to the National Rivers Authority, Solomon (1992) made a number of recommendations in respect of fish screening. These are summarised below, along with an indication of progress made since 1992 and comments on their current relevance. The words shown in quotation marks are paraphrased from Solomon's.

8.1.1 *"A national database on abstractions should be developed to include details of fish protection stipulations and measures actually fitted."*

A national database of some 48,000 abstractions now exists but details of fish protection stipulations and measures are not included. <u>This remains a need.</u>

8.1.2 *"Staff should be provided with a concise legal summary of legislation pertinent to fish screening and enforcement and that there should be a broadening of existing legislation to include all types of abstraction and all species of fish."*

Following formation of the Environment Agency in 1995, powers under SFFA 1975 were transferred to the Agency and a national training programme on fish screening techniques and legislation for enforcement staff was undertaken. This Guide provides further information on the subject for the benefit of regulatory agencies and the public.

Powers to extend the scope of screening as proposed have been recommended in the recent Fisheries Legislative Review. At present they have not been enacted in law. However, a review of SFFA s.14 & 15 under the Environment Act 1995 extended its power to include fish farm intakes and outfalls.

8.1.3 *"Operators should be required to fit appropriate fish screens whenever possible on new and existing abstractions, subject to provisions of the law."*

Since 1995, the Agency has carried out a national SFFA s.14 enforcement programme at Regional and Area levels. Many intakes that were formerly not provided with fish protection screening have now been retrofitted with screens or alternative measures (e.g. behavioural technologies), including some that were not legally obliged to do so. This has been undertaken following the Agency's Risk Assessment approach detailed in section 4.2. See also point 8.1.8 below. In England and Wales, provision of fish appropriate screening is also now addressed through conditions attached to abstraction and impoundment licences under the Water Resources Act.

8.1.4 *"R & D should be commissioned to investigate the timing, mechanisms and extent of migrations of 0+ and older coarse fish to assist in better defining periods when abstraction might be stopped."*

The Agency has commissioned work on coarse fish migrations (see review by Lucas *et al*, 1998: EA Technical Report W152). Other UK research has also since contributed to this field (see e.g. Smith, 1998; Turnpenny *et al*, 1998b). However, while knowledge in this area has improved, regional and between-river differences in seasonal timing are not well known and further research into geographic differences would help to refine operating agreements. There will nevertheless remain a need to retain flexibility in such agreements to allow for inter-annual variations.

8.1.5 *“R & D should be commissioned to investigate distribution and dispersion dynamics of coarse fish to aid in sympathetic siting of intakes (including diurnal patterns, swimming depths, etc.).”*

No significant advance has been made in this field and further research is required.

8.1.6 *“R & D should be commissioned to investigate population control mechanisms in 0+ fish to assess impact of losses at various life-stages.”*

Work by Smith (1998) and Turnpenny (1999) used the Equivalent Adult Value (EAV) concept (section 2.2), which enables comparisons of impacts of various life-stages but omits any density-dependent population control effects.

Given the inherent difficulties in quantifying the compensatory capacity associated with density-dependent effects (Van Winkle, 1977), it is probably more useful to assume that no compensation takes place and act accordingly. The Equivalent Adult approach is an effective tool for this purpose. While this has been used by Smith (1998) and Turnpenny (1989) to make some attempt at quantifying population level impacts, both authors were aware that the outputs are only as good as the life-history data entered into the analysis. Such data (age-specific mortality and reproductive rates, sex ratios) are presently sparse and are likely to be somewhat specific to particular river conditions, fish communities and even years. The most pressing research need in this context is therefore to assemble life-history data sets for particular species. This might best be done in the first instance by investigating benchmark communities representative of key habitat types (lakes, upland streams and rivers, lowland streams and rivers etc.). The benefits of such research would no doubt spill over into other areas of fisheries biology and management and therefore might be funded from multiple sources.

8.1.7 *“R & D should be commissioned to investigate screen slot and mesh sizes suitable for different species and lifestages.”*

Earlier work reported by Turnpenny (1981) is considered to provide an adequate basis for calculating mesh size for the majority of species, based on the body-length/body-diameter relationship (‘fineness ratio’). Further work is however needed to clarify the more complex relationship between slot-width, channel velocity, fish body length and exclusion efficiency for PWWC screens. This area is currently being researched in the USA and any new data from those studies should be investigated before commissioning new UK work. As the PWWC screen is one of the most important screening techniques currently available, good information on these aspects is essential and work should be commissioned if data are not found elsewhere.

8.1.8 *“R & D should be commissioned to investigate the extent of fish entrapment at intakes in England and Wales.”*

Some work in this field, described in section 2 of this Guide, has been undertaken since Solomon’s (1992) recommendations, particularly pertaining to thermal and hydropower generating plant. As the main large-volume water abstractors, there remains a need to investigate potential impacts from power plant abstractions, either through commissioned R & D or owner-funded studies. The latter currently account for most of the studies carried out in this field, usually as a result of conditions attached to operating licences but in some cases volunteered by the owners. Future work should concentrate in particular on designated fish species (see section 1.2), especially lampreys, on entrainment of fish eggs, larvae and fry that are usually not fully represented in power station sampling and on other species of conservation interest such as sea trout, smelt and eel.

The little work that has been carried out at potable water and fish farm abstractions (e.g. at Walton on Thames and the Hampshire Avon – section 2) suggests that impacts on coarse fish through fry entrainment are potentially large and significant (Turnpenny, 1999), although the importance of high entrainment counts is hard to judge in the absence of a clear understanding of the population dynamics. All evidence indicates that redistribution movements of fry in rivers put large numbers at risk of entrainment and the absence of data on fry movements in particular water bodies should not be used as an excuse for not taking adequate screening measures to protect fry. Wherever possible, through legislative provisions or voluntary cooperation, owners should be encouraged to ensure protection of all life stages of fish. This may be best achieved through screening measures, or through temporal modulation of flow to avoid abstraction during periods of high entrainment risk.

8.2 Additional Recommendations for R & D

The need for adequate site trials of different existing screening technologies was addressed in section 7, where the purpose of the proposed studies was to test the suitability and efficiency of different techniques for the variety of species and applications of interest. The aim here is to consider particular gaps in either our understanding of impacts or the armory of available techniques not covered in previous discussion. Some are identified below. Undoubtedly others will become apparent when looking into individual project applications.

8.2.1 Juvenile fish mortalities and injuries in hydroelectric turbines

Section 4 refers to techniques used to quantify fish mortalities in turbines. Numerical modelling techniques have been validated on fish of smolt size and larger and appear to provide adequate predictions of mortality rates for impact assessment purposes (Turnpenny *et al.*, 1998, 2000). Theory and empirical laboratory evidence (Turnpenny, 1988) indicate that mortality rates due to blade strike - the major cause of injuries in smolts- are relatively much lower in small fish (<20g) than for smolt-sized fish. This results from the larger surface area-to-mass ratio in small fish, which causes the water to drag them around the blade's leading edge, whereas the momentum of larger fish makes collision more probable. The present STRIKER turbine fish injury model developed by Turnpenny *et al.* (2000) does include terms to account for pressure flux and turbulence (shear stress) effects, which may also contribute to fish injury risk, but the empirical data used were derived for smolt-sized and larger fish, therefore they may be unreliable in application to juveniles.

At present, no lowland river hydropower schemes in England and Wales are known to provide screening of sufficiently small mesh opening to prevent the entry of coarse fish fry. For low-head, run-of river schemes the inherent hydraulic head-loss caused by low porosity screens make them impractical and uneconomic. From theory it has been assumed that fry mortalities would be negligible. There is now an urgent need to test this assumption through monitoring at operational lowland river sites and to modify predictive models as necessary.

8.2.2 Eel and lamprey screening and guidance methods

These elongate, thin-bodied fish are poor swimmers and present particular problems with regard to fish screening. Where it is practicable to use fine-meshed or wedge-wire screens, it has been shown that both species can be effectively screened down to juvenile sizes. At large abstractions, especially at thermal and hydropower generation sites, small aperture screens are not always practicable; these species are particularly at risk of blade strike during passage through hydroelectric turbines. While a number of behavioural guidance techniques have shown promise, none is currently sufficiently developed to recommend.

The main contenders for behavioural guidance of these species at present are:

- strobe lights
- low-frequency sound
- water currents
- electric fields.

All of these methods should be investigated, individually and in combination. Juvenile and adult eels and lampreys should be included in tests. Tests would best be carried out in the headrace of one or more small hydropower stations where hydraulic conditions are relatively well controlled. A number of suitable sites have been identified.

One further technique of interest is the bed-level eel bypass channel such as installed at Backbarrow hydropower scheme on the R. Leven in Cumbria and elsewhere in Europe (see section 3.5.3). It is not clear how effective this device is, nor whether it could be improved with better hydraulic conditions but available evidence suggests that it is at least partially effective under some flow conditions. This method merits further consideration as an adjunct to other screening and guidance methods. In particular, it will be necessary to observe the detailed behaviour of eels confronted with this type of bypass and to be able to manipulate the dimensions and geometry of the structure. Such an approach would lend itself to testing in a laboratory flume or raceway, where the behaviour of eels and lampreys could be observed.

8.2.3 Behavioural Barriers in General

Owing to the potential cost savings and ease of use, there is considerable interest from operators in using behavioural barriers as an alternative to positive exclusion fish screens for a wider range of species. This is particularly true of low-head run-of-river hydropower schemes, which use large volumes of water and where screening costs are comparatively high and hydraulic losses may limit generating revenues (see Turnpenny *et al.*, 1998a). Although behavioural techniques have advanced, scientific trial results are still limited and regulatory agencies are reluctant to accept their use in many situations. The cost of conducting scientific trials to a sufficiently rigorous standard can be too high for individual operators of small schemes to bear and therefore further generic testing is recommended. Sites of existing or proposed schemes on the rivers Trent (e.g. Beeston), Yorkshire Ouse (e.g. Linton), Thames (various) and some Scottish rivers may provide suitable locations.

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10 GLOSSARY

The following are definitions of certain words and abbreviations used in this Guide:

AFD – 'Acoustic fish deterrent system' – a behavioural screen or barrier exploiting the hearing sensitivity of fish.

Acoustic barrier – Barriers which exploit the hearing sensitivity of fish.

Approach velocity – The velocity of water approaching the screen.

Attraction flow – A water flow which attracts fish to a desired area.

Backflush – Reverse of flow to wash off debris from the screen.

BAFF – 'Bioacoustic fish fence' – a combined sound and bubble curtain screening system.

Behavioural barrier or screen – A fish deterrent system which works by stimulating the senses of fish either by repulsion or attraction mechanisms.

Benthic – Bottom dwelling fish.

Biofouling – the build up of aquatic organisms on a substrate.

Bubble curtain or barrier – A wall of bubbles used to deflect or guide fish.

Bypass – A channel or pipe which allows fish to pass by the obstruction unharmed via an alternative route.

Bywash – Synonymous with 'bypass' (see above) but more commonly used in Britain

Channel velocity – The velocity in front of the screen measured axial to the flow channel.

Coanda effect – Principle of how fluids follow a surface identified by Henri Coanda in 1910.

Diadromous – Migratory species that move between the sea and freshwater and vice versa.

Epibenthic – Species that normally live close to the bed.

Escape velocity – The water velocity perpendicular to the face of the screen.

Entrainment – The drawing-in of fish of any lifestage at a water intake

Euryhaline – Species with a wide tolerance of salinities

GFFB™ – 'Graduated field fish barrier' – a form of electric screen which presents an electric field of increasing intensity (voltage) as the fish gets closer, generated by means a series of separate pulse generators

Impingement – The accidental pinning of fish onto the surface of a screen by the water current

Infrasound – Sound with a frequency of less than 20Hz

Kelt – Stage in a salmon life cycle just after spawning.

Lithophilous – Requiring gravel on which to spawn.

MLES – 'Marine life exclusion system' – a water-permeable geotextile barrier.

MSSS –'Maximum sustainable swimming speed'

Phototaxis – Movement in relation to light.

Pinhead fry – Newly hatched fry.

PWWC – Passive wedge wire cylinder – a type of fine aperture screen suitable for fish exclusion down to fry size

Retrofit –Addition of equipment to existing facilities.

Rheotactic – Movement (of fish or other animal) in relation to flow.

SAC – 'Special area of conservation'.

Shear (hydraulic) – Differential velocity field in water

Smolt – Young salmon of 2 or 3 years old.

SPA – 'Sound projector array' – uses arrays of underwater transducers to produce a diffuse field of sound.

SSSI – Site of Special Scientific Interest

Strobe light – High intensity, short duration light pulses.

Teleost – A bony fish.

Transformer – Recently metamorphosed pre-adult lamprey

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