A UK GUIDE TO INTAKE FISH-SCREENING REGULATIONS, POLICY AND BEST PRACTICE

With Particular Reference to Hydroelectric Power Schemes

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Contractors

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&
Hydroplan

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PREFACE

The development of hydroelectric energy resources is an important element of the UK government's renewable energy policy. The Government has a domestic aim of a 20% CO_2 reduction compared to 1990 by 2010. The Prime Minister, in his speech last year to the United Nations at the Earth Summit, identified greater use of renewables as one of three principle measures to reduce UK carbon dioxide emissions. Achieving 10% of electricity from renewables by 2010 would contribute approximately 3.4-5.4 MtC/y CO_2 savings in the electricity market, 10% of that necessary to achieve the domestic CO_2 reduction aim, with additional emission reductions from NO_x, SO_x and methane. Renewable sources currently account for 2% of UK electricity supply.

The UK government has provided various incentives to stimulate renewable development, in the form of grants and subsidies. The Non-Fossil-Fuel Obligation (NFFO) raised a levy on fossil-fuel generation that was used to subsidise sales of electricity from renewable sources. Four rounds of contracts (known as NFFO 1,2,3 & 4) to supply the national grid have so far been announced in England, Wales and Northern Ireland, amounting to a potential of contracted new renewable generation capacity of 2,126 MWe[†]. Of this, 43 MWe is hydroelectric. A similar scheme in Scotland, known as the Scottish Renewables Order (SRO), has so far released two rounds of contracts (SRO 1 & 2) totalling 2,316 MWe, of which 30 MWe is hydroelectric.

The development of hydroelectric resources has involved the exploitation of both high- (>10 m) and low-head (≤10 m) water supplies. High-head schemes, usually in mountainous areas, have not, in many cases, resulted in serious conflict with fisheries interests, as upstream fishery resources in headwater streams are of lesser importance than mainstream fisheries, and the high head allows the equivalent power to be generated with much less water use. A 0.5 MWe scheme operating at 50 m head would, for example, require a flow of 1.5 $m^3.s^{-1}$. Low-head schemes, on the other hand, require large flows of water to make them economic. The same 0.5 MWe scheme operating at 3 m head would require a flow of 24.5 $m^3.s^{-1}$, i.e. 16 times larger than the high-head example. This would be constructed on the mainstem or a major tributary of a river system, where it would have the potential to disrupt the movements of migratory species, such as salmon, sea trout, eel and shad, as well as more localised migrations of freshwater species.

Fishery interests are represented by a wide variety of parties, including riparian owners, angling bodies, commercial fisheries, regulatory agencies, fishery scientists and conservationists. These parties recognise ever-mounting pressures on fish and fisheries, as a result of over-exploitation, habitat degradation, pollution and disease. The plight of the Atlantic salmon (*Salmo salar*) is a key concern in relation to UK hydropower development, especially in northern England, Wales, Scotland and Northern Ireland. From the early

[†] MWe = megawatts-electric (as opposed to MW shaft-power).

1970s, annual landings of salmon[‡] have declined steadily, from around 11,000 tonnes, to 4,000 tonnes by the mid-1990s (Source: North Atlantic Salmon Conservation Organisation). If this decline is to be halted, efforts have to be made at any influencable points in the salmon's life cycle. The effective protection of fish by screening at all forms of water intake represents one kind of action that can be taken.

This Guide has been produced on behalf of the Department of Trade and Industry (DTI) in order to clarify the implications for hydropower developers of recent and forthcoming changes in fish screening legislation in England, Wales and Scotland, to review implementation policy by the regulatory bodies and to provide an up-to-date survey of available screening technologies and practice. Its target readership includes hydroelectric operators and developers and their associated engineering and fisheries/environmental consultants, as well as those representing fishery interests. Preparation of the Guide has involved literature searches but has relied heavily upon the cooperation of international specialists in this field. In particular, the authors would like to acknowledge the valuable contributions made by the following: Mr Rolf Hadderingh (KEMA, Holland), M Francois Travade (Électricité de France), Dr Mufeed Odeh (Conte Anadromous Fisheries Research Center, USA), Mr Eamon Cusack (Shannon Regional Fisheries Board, Ireland), Mr Søren Berg (Danish Instiute of Fisheries Research), Mr Wieslaw Wisniewolski (Inland Fisheries Institute in Olsztyn, Poland), Mr Daniel Hefti (Swiss Agency for the Environment, Forests and Landscape) and Mr Shunroku Nakamura (Toyohashi University of Technology, Japan).

In the undertaking of this study, the DTI was keen to ensure that relevant bodies were fully consulted, so that the Guide would be widely accepted. In particular, UK regulatory organisations were consulted concerning their interpretation of the law and implementation policy, and hydroelectric developers and operators were consulted concerning the impact of screening legislation on their business and their preferred means of compliance. Organisations consulted included:

The Environment Agency (EA)
The Scottish Office (SO)
The Association of Scottish District Salmon Fishery Boards (Scotland) and individual Boards (DSFBs)
The Fisheries Committee of the Secretary of State for Scotland
The Department of Agriculture, Northern Ireland (DANI)
The Fisheries Conservancy Board (Northern Ireland)
The Foyle Fisheries Commission
The Association of West Coast Fisheries Trusts (Scotland).
The Freshwater Fisheries Laboratory, Faskally
Scottish Hydroelectric plc

Several of these organisations also reviewed and commented upon the Guide prior to publication. We are grateful to all of them for agreeing to talk to us and, in particular, to those who gave practical assistance or who invited us to

[‡] by all capture methods combined, in home waters and on the high seas

attend meetings. A number of other operators of small hydropower schemes were consulted but did not wish to be mentioned by name.

We hope the Guide will help to clarify legal and policy issues relating to fish screening, lay to rest certain myths surrounding the subject and above all, provide practical information and new possibilities to those involved in fish screening design.

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October 1998.

EXECUTIVE SUMMARY

In the United Kingdom (UK), the abstraction of water, for hydroelectric generation and certain other purposes, is subject to regulations that require screens or other effective barriers to be put in place to prevent entrainment of fish. These arise from:

- *The Salmon & Freshwater Fisheries Act (1975), s. 14,15* (England and Wales)
- *The Salmon (Fish Passes & Screens)(Scotland) Regulations 1994*
- *The Fisheries Act (Northern Ireland) 1966.*

Although each differs from the others in detail and approach, they share a number of key features:

- Fish screens must be fitted and maintained at the owner's expense.
- The screens must be capable of preventing the descent through the turbines of the specified fish species and life stages (salmonid smolts and adults; other species as well in N. Ireland).
- A by-wash (also known as a bypass channel) must be provided, where required, to ensure that fish can continue safely on downstream.
- A 'screen' may be interpreted as any device that will prevent the entry of fish, whether it be a physical mesh or a so-called 'behavioural' screen which uses a deterrent stimulus (e.g. electrical, acoustic or light).

As far as hydropower developments are concerned, the Scottish Regulations apply only to schemes of ≤1 MWe capacity, and not to larger schemes, which are regulated under various separate Acts of Parliament.

This Guide, commissioned by the Department of Trade and Industry (DTI) through the Energy Technology Support Unit (ETSU), has been prepared to assist hydropower developers and owners, and their consultants, in understanding their responsibilities under these fish screening laws, to make them aware of the wide variety of screening technologies available and to present the key design criteria for fish screening systems. The Guide has involved review of legislation and technologies in other countries in consultation with overseas fish screening specialists and is also intended to bring fishery owners and regulators up to date on current best practice. Particular emphasis in the study was placed upon consultations with the UK hydropower industry and the various fishery agencies.

The Guide is divided into two parts. Part A describes the legislation on fish screening and details consultations with regulatory agencies on interpretation of the laws and their implementation policy. It also includes consultations with the hydropower industry and identifies the issues and uncertainties arising from screening legislation, especially in Scotland where new regulations (1994) recently came into force. Recommendations are made which, it is hoped, will provide a basis for smooth implementation of the law where difficulties have arisen in the past.

Part B reviews the currently available screening technologies and comments on their suitability or otherwise for small hydropower applications. In particular, it distinguishes methods that are suitable for low- versus high-head sites. Design criteria for screen location, approach velocity, by-wash design and screen mesh size and other key features are given. The screening technologies described include both physical (i.e. using meshes or grids) and behavioural methods (i.e. using sensory stimuli such as sound, light, turbulence or electrical potential difference). Ways that these can be used to meet regulatory requirements are discussed.

Part A (Screening Law): Conclusions and Recommendations

The advent of new fish screening legislation has given rise to some uncertainty in its early stages. The Regulations in Scotland are in the vanguard of this process and issues relating to the Regulations are beginning to emerge. Changes to the law in England and Wales under SFFA *s*.14 have yet to take full effect (1st January 1999) and will no doubt generate new issues in due course, although the main group affected will be fish farmers. Although there are implications for hydroelectric operators (e.g. the loss of the Ministerial approval process), they are less radical than those arising from the Scottish Regulations.

Perhaps the main effect on hydroelectric operators, as well as water supply undertakings in England and Wales, will be a tightening of enforcement. The Environment Agency have indicated that they wish to ensure that they are not seen to be victimising fish farmers, so will apply enforcement measures uniformly across all categories of user.

In Northern Ireland, the legislation has not changed in the last 30 years and there are no plans to change it at present. It appears to work well and there were no reported problems. Hydro operators in Northern Ireland were keen to see approval gained for behavioural systems, but this will emerge from demonstration of further improvements in the technologies, not from changing legislation or the enforcement process.

Operators of small, low-head (≤10 m) schemes are particularly hard-hit by screening regulations, as the flow of water relative to the power generated is high. This means that large screening areas must be used and that any head-loss associated with obstruction of the flow can have a serious impact on scheme economics. For this reason, operators of such schemes are particularly keen to be allowed to use behavioural, rather than physical screens. Most regulatory agencies indicated that they would not object to the use of suitable behavioural barrier methods, subject to a risk assessment to establish the required performance level, followed by a trial after commissioning to demonstrate that this performance was being achieved.

A particular issue arose from consultations with operators in Scotland, where small schemes were seen to be unfairly disadvantaged relative to larger schemes (>1 MWe) regulated under the Electricity Acts. This was because the Regulations applying to small schemes appear to require screens to be fitted whenever smolts might be present, but no definition of a smolt is given. Hence, the Scottish Office has advised that, until a case tested in court proves otherwise, the only safe legal interpretation is that screens must be in place all year round. On larger schemes, screens are not required to be in place all year round, if at all.

A number of recommendations emerge from the consultations undertaken during this study:

Consultation by Hydro Developers/Operators

The fishery agencies all stressed their willingness to talk to developers/owners/operators about screening and other fishery issues. It is recommended that developers of new schemes involve the fishery agencies at an early stage to avoid later misunderstandings. Owners and operators of existing schemes should also take an early opportunity to discuss whether their scheme conforms to current screening requirements, rather than waiting for the agencies to seek them out during the enforcement process.

Interpretation of the Law

It is important to demonstrate that legislation is being applied uniformly. Where at present there is scope for different interpretations of the law (e.g. definition of a 'smolt' within the Scottish Regulations), it would be helpful for enforcement agencies to reach a uniform policy on how the law should be interpreted and applied, until such times as case law may clarify definitions.

Risk Assessment

The development of a uniformly accepted risk assessment procedure for hydropower screening applications is strongly recommended. Such a procedure would need to be transparent and lead, via a series of clearly understood steps, towards a required level of action, expressed in terms of an acceptable overall scheme bypass rate. This would give a clear indication to developers and operators of what they needed to achieve, and would provide a uniform basis for presenting any case that went to court.

A specific requirement within the proposed risk assessment methodology is to develop improved procedures for predicting the likely mortality rates of fish in small turbines (especially <1MWe). This would require the application of computational fluid dynamics (CFD) techniques to analyse hydraulic stresses in small Francis and Kaplan turbines so that available biological data could be applied, followed by validation of predictions at operating turbine sites.

Part B (Screening Technologies): Conclusions

1. A wide variety of fish screening systems is available to suit different needs, environmental conditions and budgets. New types of screens are continually under development. The full range of options should be considered when planning new fish protection measures.

2. Physical screens still offer the highest guaranteed fish diversion efficiencies and may be the most cost-efficient for very small intakes (<1 cumec). A number of self-cleaning physical screens are available, which reduce manpower requirements, but these are mainly cost-effective on smaller intakes, and are therefore best suited to high-head schemes. Physical screens are only efficient if they are correctly operated, cleaned and maintained, however.

3. Behavioural fish barriers offer advantages in terms of low cost, particularly on large intakes, low maintenance, little or no obstruction to flow and ease of retrofitting. Fish diversion efficiencies are generally lower than for physical screens, ranging from ~40% for bubble curtains to >90% for louvre and certain acoustic barriers. Higher efficiencies may possibly be obtained by operating two systems in tandem. Behavioural systems may

also be used to improve the performance of poorly designed physical screening systems.

4. Behavioural barriers also have a role in certain situations where physical screens are impractical, e.g. where physical screens might obstruct a navigable channel, and where an operator is not obliged by law to fit fish screens but is willing to use a 'no-trouble' behavioural barrier (e.g. on cyprinid waters).
5. The design of bypass (by-wash) facilities is critical to the good performance of any fish screen that is placed within a channel. This is particularly true of behavioural screens, where failure of fish to locate an exit quickly will increase its chances of entrainment. With physical screens, delays may also lead to increased risks of predation or impingement. Improved design criteria now available should reduce these risks.
6. No fish screening system will work if the water velocities from which the fish are required to escape are too high. Existing criteria appear to ensure adequate fish safety but are stringent and require large screening areas to be used, leading to high screening costs. There is evidence that the currently accepted 25-30 $cm.s^{-1}$ escape velocity criterion for salmonid smolts underestimates their true swimming capability and may lead to excessive costs in providing screening structures. It is important that these are kept under review to ensure that costs to operators are not unnecessarily burdensome.
7. For newer screening methods to be fully accepted by fishery authorities, it will be necessary to ensure that test results from varied applications are generated and made available.
8. Failures in screening systems of all types occur mainly due to lack of maintenance or to failure to operate them correctly. This is often due to inadequate manning or operational staff not being aware of how , when and why screening systems should be operated. Occasionally, it is through wilful neglect, owing to the gain in flow and reduced maintenance effort when screens are not in place or not fully seated. It is important that operational staff are trained in the required operation of screens and are made aware of the legal obligation of the owners.

CONTENTS

PART A:

REVIEW OF SCREENING LEGISLATION AND POLICY

A1. INTRODUCTION

Any abstraction of water from rivers, lakes, estuaries or the sea carries a risk of harm to fish that may be present. Legislation within the United Kingdom (UK) to reduce potential harmful effects on fish of water mills, irrigation offtakes and other abstractions dates back to the last century and before.

Regulation of fish screening has never been uniform throughout the countries of the UK. England and Wales form one jurisdiction, Scotland another and Northern Ireland a third, and each is subject to its own particular fish screening laws. Added to this, there may be variations in implementation policy at the local level. These regional differences offer a degree of flexibility to cope with differing conditions, but can make it difficult for operators to understand how they can best discharge their responsibilities under the law. Overall, however, there is a strong degree of communality, both in intent and approach. It is the object of Part A of the report to explain the main legal provisions relevant to hydropower that stand in the UK, to reflect regional and local variations and to show how they are applied.

The issue of fish screening is not unique to the UK and it is of interest to see how other countries deal with the problem, in terms of both regulation and practice. In Europe, we find no consistency of approach. This may stem partly from the fact that most of the fish screening legislation in Europe applies only to migratory salmonids, whereas these have been lost to many of the major European rivers. Possibly for that reason, there has to date been no European Commission directive on the subject. Nevertheless, most countries have some way of regulating the problem of fish entrainment within the planning process for new facilities. There is also much to learn from North America, with hydroelectric power schemes that dwarf any found in Europe, and a very strong degree of regulation.

A2. CONSULTATION METHODS

A large number of individuals and organisations were consulted during the preparation of this report (see Preface). Where possible, face-to-face meetings were held. These included meetings with the Environment Agency (Dr Tony Owen [then] Head of Fisheries, and Mr Jonathan Shatwell, responsible for The Salmon and Freshwater Fisheries Act *s*.14 implementation within the Agency), The Scottish Office (Mr David Dunkley, Inspector of Salmon and Freshwater Fisheries), members of the Secretary of State for Scotland's Fisheries Committee, and members of the Association of Scottish District Salmon Fishery Boards (at a meeting of their Superintendents and Bailiffs organised by The Freshwater Fisheries Laboratory at Pitlochry, April 8th-9th, 1998). Numerous other meetings were held with hydroelectric developers and operators, the majority of whom preferred not to be named. These meetings were often followed up with correspondence and telephone conversations. Where face-to-face meetings were not practical, correspondence took place. Reliance was placed largely on the Internet (e-mail) service for overseas contacts. Questionnaires were used where appropriate; where these were used, copies are provided within the Appendices of the report and are referenced within the text.

Following the preparation of the initial draft of the report, copies were sent to each of the main bodies consulted above for comment. The final version takes account of, as far as possible, the diverse comments received.

A3. REGULATIONS IN ENGLAND AND WALES

A3.1 Applicable Legislation

The main fish screening powers that operate in England and Wales derive from The Salmon and Freshwater Fisheries Act (SFFA) *s*. 14 & 15, and recent amendments to those Sections arising from the Environment Act 1995 that come into full effect from January 1st 1999. The powers relate only to rivers frequented by salmon (*Salmo salar*) and sea trout (*Salmo trutta*). No specific screening regulations apply to other species of fish, although the Hydropower Working Group of the former National Rivers Authority (NRA) (Anon.,1995) suggested "that the developer should be made aware of *s*.2(2) SFFA 1975 which makes it an offence knowingly to kill or injure immature freshwater fish". No case of this kind has been tried, to the authors' knowledge

New construction projects involving water abstraction will generally require application for an abstraction or impounding licence under the terms of The Water Resources Act (WRA) 1991, or possibly a land drainage consent. WRA *s*.158 entitles the regulating body (now the Environment Agency, hereafter "the Agency") to impose conditions on the issuing of a licence. The conditions must be within legal ambit of the Agency, but for example WRA *s*.114, which states "It shall be the duty of the Agency to maintain, improve and develop salmon fisheries, trout fisheries, freshwater fisheries and eel fisheries", along with other provisions of the WRA (see also *s*.2 & 16), would provide adequate justification for most conditions relating to fisheries. Other powers relating to fish conservation derive from The Wildlife and Countryside Act (WCA) 1981, which requires protection to be afforded to species listed under Schedule 5, and from other British and European conservation law (e.g. the 1992 Habitats and Species Directive).

A3.2 Salmon and Freshwater Fisheries Act (SFFA) 1975, *s*.14

A3.2.1 Summary of Screening Measures

As SFFA is the only Act operative in England and Wales that deals specifically with fish screening, and its powers have recently been revised under The Environment Act (EA) 1995, it will be explained in more detail, drawing attention to the changes. A copy of *s*.14 in the original 1975 format and containing the 1995 revisions is given in Appendix I. Section 14 deals with the obligations of scheme owners/operators to provide fish screening. Mention should also be made of *s*.15, which grants powers to the regulating authority to place and maintain screening *at its own cost* where the owner/operator is exempted for reason e.g. of prior rights. Section 15 has not been radically altered by the 1995 Act, other than the relevant power having been transferred to the Agency.

<u>The 1975 version</u>

The earlier Section 14 applied to water or canal undertakings and mills, and required the 'responsible person' (i.e. owner or occupier) to place and maintain, at his own cost, gratings across any channel or conduit where water was diverted from waters frequented by salmon or migratory trout 'for the purpose of preventing (their) descent'. The occupier of any mill constructed on or before 18th July 1923 (the effective date of the SFFA 1923) was exempted from any obligations under *s*.14. The regulating authority was empowered to grant other exemptions as and when it saw fit. The Act also required that no grating should be so placed as to interfere with navigation.

A number of points need clarification:

- "Water and canal undertakings" here mean water supply organisations and canal suppliers. "Mills" include water turbines and any other erection for the purpose of developing water power.
- The term "gratings" may be interpreted as any device which prevents the passage of fish through a channel (Howarth, 1987) and is thus not restricted to physical screening devices.
- "Salmon" means fish of the species *Salmo salar* and "migratory trout" means fish of the species *Salmo trutta* which migrate to and from the sea (also known as 'sea trout').
- "Waters frequented by" means that salmon or sea trout are present in part of the watercourse immediately supplying water to or receiving water from sites specified in the Act. This is taken to refer to naturally occurring populations, not artificially maintained stocks.

The 1975 Act further required that the grating should be "constructed and placed in such a manner as may be approved by the Minister". In other words, plans would need to be submitted to the Minister for approval: provided the gratings were then constructed and operated according to the approved plan, they would comply with the Act (whether they worked or not!).

It should be noted that:

- the provisions of *s*.14 do not apply to water not frequented by salmon and sea trout, hence no provision is made for waters that contain only non-migratory trout or coarse fish;
- no reference is made to particular life stages that are to be screened, although Ministerial approval would determine what was acceptable in terms of, for example, mesh size;
- *s*.14(6) of the Act requires screening to be present all year round, except where prescribed by local byelaw.

Section 15 SFFA is available to the Agency, principally to provide for the necessary protection of fish at sites that are exempted from *s*.14, e.g. mills that have operated since prior to July 18^{th} 1923. The power has rarely been used, owing both to the costs to the Agency for construction and maintenance and the liability that would attach to them, for example, if a power generator lost production as a result of screen blockage.

<u>Revisons under the 1995 Environment Act</u>

The revised *s*.14 differs in a number of key points:

- The term 'grating' is replaced by the term 'screen'; the same broad meaning of the term is retained, but is defined more explicitly to include any device or combination of devices that have the effect of preventing fish descent into an offtake.
- Fish farms have been added to the list of regulated water users, the new *s*.14 requiring them to place screens at the intakes and outfalls of the fish farm.

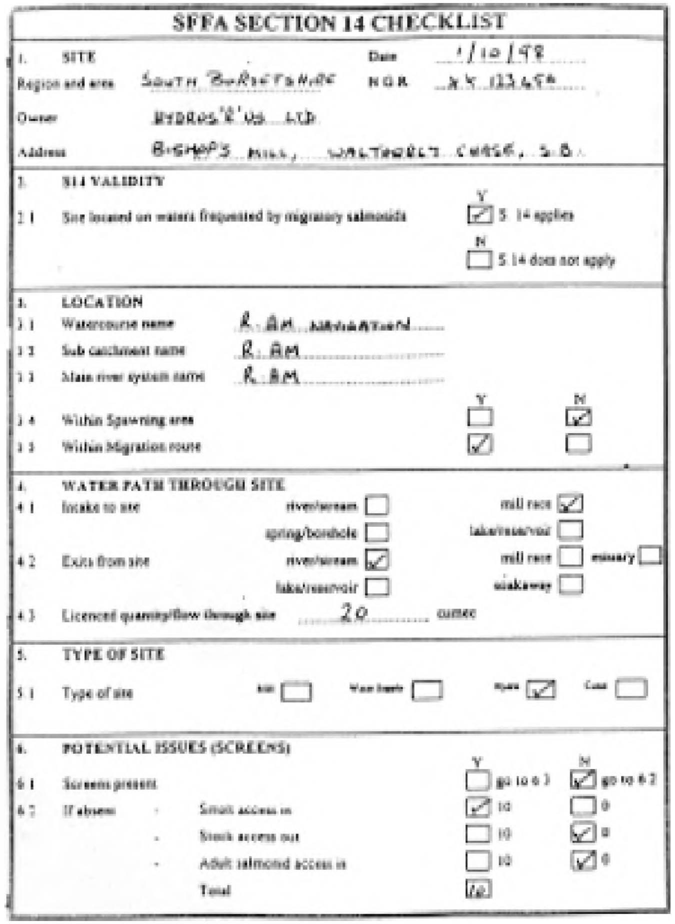
- Where the screens are placed in a channel, a by-wash[‡] must now be provided immediately upstream of the screens to enable fish to return to their waters via the shortest practicable route.
- The requirement for Ministerial or any other regulatory approval has been dropped. The test of compliance is now not whether it conforms to an approved plan or design, but whether it works. The new *s*.14 requires that the screen 'prevents the descent of the salmon or migratory trout' and 'is so constructed and located as to ensure, so far is is reasonably practicable, that salmon or migratory trout are not injured or damaged by it'.

A3.2.2 Implementation Policy

The Agency is keen to demonstrate an effective but transparent implementation of the new *s*.14. In advice to its enforcement officers, the Agency has spelt out its policy. The following items are of particular interest:

1. A standard risk assessment checklist procedure will be used, the results of which will be available to the responsible person/ owner and open to appeal. (This procedure is reviewed below).
2. Full recognition will be 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").
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) 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

[‡] A by-wash, in the sense of the Act, means 'a passage through which water flows'.



SFFA SECTION 14 CHECKLIST

1. SITE Date: 1/10/98
Region and area: SOUTH BORSETSHIRE NGR: XX 123456
Owner: HYDROS 'R' US LTD
Address: BISHOPS MILL, WALTBOREY 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
3.2 Sub catchment name: R. AM
3.3 Main river system name: R. AM

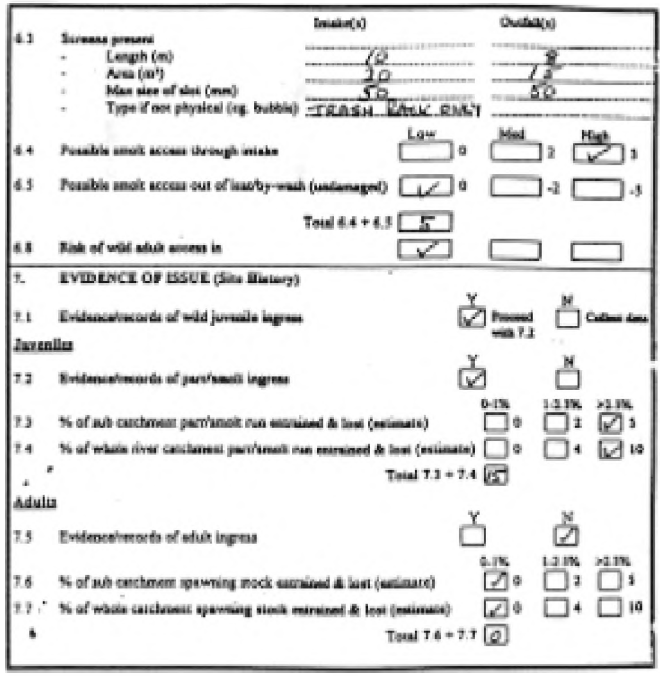
	Y	N
3.4 Within Spawning area	[ ]	[✓]
3.5 Within Migration route	[✓]	[ ]

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 [ ]; estuary [ ]; soakaway [ ]
4.3 Licenced quantity/flow through site: 20 cumec

5. TYPE OF SITE
5.1 Type of site: [ ] [ ] Hydro [✓] [ ]

6. POTENTIAL ISSUES (SCREENS)

		Y		N	
6.1 Screens present		[ ]	go to 6.3	[✓]	go to 6.2
6.2 If absent	- Smolt access in	[✓]	10	[ ]	0
	- Stock access out	[ ]	10	[✓]	0
	- Adult salmonid access in	[ ]	10	[✓]	0
	Total	10			



6.3 Screens present

	Intake(s)	Outfall(s)
- Length (m)	12	8
- Area (m²)	20	12
- Max size of slot (mm)	50	50
- Type if not physical (eg. bubble)	TRASH RACK ONLY	

	Low		Med		High	
6.4 Possible smolt access through intake	[ ]	0	[ ]	2	[✓]	5
6.5 Possible smolt access out of leat/by-wash (undamaged)	[✓]	0	[ ]	-2	[ ]	-5
Total 6.4 + 6.5	5					
6.6 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 [ ]

	0-1%		1-2.5%		>2.5%	
7.3 % of sub catchment parr/smolt run entrained & lost (estimate)	[ ]	0	[ ]	2	[✓]	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 [✓]

	0-1%		1-2.5%		>2.5%	
7.6 % of sub catchment spawning stock entrained & lost (estimate)	[✓]	0	[ ]	2	[ ]	5
7.7 % of whole catchment spawning stock entrained & lost (estimate)	[✓]	0	[ ]	4	[ ]	10
Total 7.6 + 7.7	0					

Figure A1
Example of the Environment Agency's SFFA s14 Risk Assessment Procedure (source: Environment Agency)

INTERPRETATION			
QUESTION	SCORE	RISK	ACTION
6.2 (add scores)	0 ≥10	None. Risk	No visit(s) needed. B
6.4 + 6.5 (add scores)	-5 to 0 >0	Low risk. Risk.	A B
6.8		Low. Medium. High.	A B B
7.3 + 7.4 (add scores)	0 2 to 4 ≥5	Low. Medium. High.	1 2 3
7.6 +7.7 (add scores)	0 2 to 4 ≥5	Low. Medium. High.	1 2 3

KEY	
ACTIONS A B 1 2 3	-X check with evidence section 7. If no issues programmed visit (annual). -X check with section 7. -Programmed Visit (annual). -Monitor each year – action if necessary. -Action needed.
Programmed visit Yearly Monitoring	-Visit yearly to inspect screens/ maintenance. -at parr migration/ smolt run or adult run, as indicated. -visual monitoring or trapping. -inspection of screens.

Figure A2

Interpretation Sheet for the Environment Agency’s Risk Assessment Procedure (source: Environment Agency) screening arrangements, which are the responsibility of the responsible person or owner.

A3.2.3 The Agency's Risk Assessment Procedure

The Agency has designed two SFFA *s*.14 checklists, one for fish farms, the other for the remaining types of controlled use. The latter, more general one is discussed here. The checklists enable enforcement staff to collect information about the site and to conduct a formal risk assessment based on a checklist scoring system.

The SFFA *s*.14 checklist format is shown in Figure A1. A hypothetical example for a hydro site at Bishop's Mill on the R. Am (Items 1 & 5 on checklist) is shown. The site has two 300 kW Kaplan turbines and is licenced to abstract 20 $m^3.s^{-1}$ from the Am, the mainstem of a moderate salmon river (Items 2 & 3). The water is drawn via a 500 m long mill race, discharging back to the main river (Item 4). At the headrace, trash screens are fitted which have 50 mm bar spacings and are adequate to prevent descending kelts passing through, but smolts pass through the turbines and occasional dead smolts are seen at the tailrace. Water velocity is high at the intake (about 1 $m.s^{-1}$). No by-wash is provided. During a typical spring, about 50% of the main river water flow passes through the turbines and, on the basis of similar turbines tested elsewhere, about 15% of smolts passing through are expected to be injured. In the absence of specific information on mortalities, the precautionary assumption is made that about 7.5% of the main smolt run would be killed by the turbines.

The risk assessment part of the checklist begins with Item 6. In 6.1, screens are absent and the boxes are ticked as shown, "Y" for smolt access in, "N" for adult access. (The 'stock access out' is relevant only to fish farms and is therefore ticked "N" in this case). Item 6.4, 'possible smolt access through intake' is ticked as "high", and possible smolt access out of leat/by-wash as "low", owing to high velocities. Responses to questions in Item 7 yield a maximum score for juveniles (15), as the site draws from the mainstem of the river, and minimum score for adults (0) as none is expected to be entrained. Scores are interpreted as per Figure A2, which results in the conclusion: "action needed".

The procedure may be viewed as simplistic, but has the considerable virtue of being simple to apply and readily understood by all parties involved. In practice, Item 7 ('Site History'), provides the opportunity to incorporate background knowledge about the site and catchment. The procedure has been tested and found to give sensible results on a range of widely differing sites. The Agency expects the procedure to be further developed and adapted in the light of experience.

A feature not included in the procedure was any explicit expression of the level of action merited by the degree of risk. This at present is left as a matter for negotiation between the Agency and the owner/operator.

In practice, for a site identified as 'high risk', a highly efficient physical screening system might be essential to provide the necessary protection, whereas at a 'low risk' site, a behavioural barrier of more limited efficiency might provide adequate protection.

A3.3 Procedure for New Sites

The Agency's *s*.14 procedures detailed above apply only to existing abstractions. Developers applying for an abstraction or impounding licence or land drainage consent under the WRA should expect the Agency to apply a number of tests to determine the need for screening and the specific arrangements that would form part of the *s*.158

Agreement. They would also take into account the views of other statutory consultees, e.g. English Nature or the Countryside Council for Wales, as appropriate.

Table A1 Typical Section 158 Conditions Attached to Abstraction and Impounding Licences

Types of Fish Frequenting Water	Likely Conditions in *s*.158 Agreement
Salmon and/or sea trout	Full SFFA *s*.14 requirements. Performance criteria may be specified, with a requirement to demonstrate that they are met, and an improvement path if they are not.
WCA Schedule 5 species	Appropriate measures to ensure their protection (e.g. physical or behavioural screening, suitably low water velocities, by-washes or other escape routes), and/or: other compensatory mitigation measures (e.g. habitat improvement measures). Performance criteria: as above.
Brown trout, eels and coarse fish	As above but perceived risk to and value of the fishery will dictate the level of protection justified (BATNEEC applies).

Table A1 lists some of the screening-related conditions that might be attached, according to the nature of the fish populations present. As can be seen, within its general policy regarding fish screening, the *s*.158 Agreement gives the Agency almost unlimited scope to ensure that its statutory obligations are met. In particular, it gives the Agency powers to protect fish species other than salmon and sea trout when a new licence is issued. The measures invoked may then be radically different from those detailed in SFFA *s*.14, which may be wholly unsuited to the task. For example, juvenile shad, which migrate to sea from rivers such as the Severn and Usk in summer, at body lengths of around 3-4 cm, would not be protected by screens suitable for salmon smolts of 12-15 cm. Furthermore, shad are extremely delicate and are likely to be fatally injured by contact with a screen, and perhaps may be more effectively dealt with using behavioural methods.

In some cases, particularly where the proposal is unusual or the habitat is regarded as sensitive, developers may be asked to commission background studies prior to the awarding of a licence or consent.

A4. REGULATIONS IN SCOTLAND

A4.1 Applicable Legislation

The regulation of fish screening in Scotland does not lie with a single body, owing to historical development. The Scottish Environment Protection Agency (SEPA) plays no part in fisheries protection. That role falls to The Scottish Office, which appoints an Inspector of Salmon and Freshwater Fisheries, whose role is to advise the Secretary of State for Scotland, and to sixty-two District Salmon Fishery Boards (DSFBs).

Salmon Fishery Districts were established through The Salmon Fisheries (Scotland) Acts of 1862 and 1868, although their present powers arise from The Salmon Fisheries Act 1986. These provided the mechanism for setting up the DSFBs whose responsibilities include the protection and improvement of salmon fisheries within their respective areas. Not all Districts have Boards, and the initiative for their establishment rests with the proprietors. A further summary of salmon, trout and freshwater fisheries legislation in Scotland is given by Anon. (1996), which lists 17 Acts of Parliament, dating from 1804, as well as a number of Scottish orders and regulations. Other useful references are The Scottish Office “Notes for Guidance on the Provision of Fish Passes and Screens for the Safe Passage of Salmon” (Anon., 1995), which is essential reading for developers and operators of small hydro schemes in Scotland, and the report of the Salmon Advisory Committee (1997) entitled “Fish Passes and Screens for Salmon”. The latter document incorporates Anon. (1995).

Early legislation on fish screening in Scotland dates back to The Solway Act of 1804, which required screens to prevent fish being lost to irrigation systems. Further regulations relating to mill wheels were contained in Schedule G of The Salmon Fisheries (Scotland) Act 1868. However, no generally applicable legal requirement for fish screening at water abstractions in Scotland existed prior to the Salmon Act 1986. Section 3 of this Act made provision for screening legislation and gave rise to The Salmon (Fish Passes and Screens) (Scotland) Regulations 1994 (Appendix II). Prior to this, regulation relating to hydroelectric installations was enacted via The Hydroelectric Development (Scotland) Act 1943, which established the state-owned North of Scotland Hydroelectricity Board (Anon., 1996). The Act placed upon the Board responsibility “of avoiding as far as possible injury to fisheries and to the stock of fish in any waters”. Under more recent legislation, The Electricity (Scotland) Act 1979 and The Electricity Act 1989, this responsibility has continued, with each scheme built under the terms of the Acts being required to abide by statutory obligations for fish screening specific to that scheme.

The 1943 Act required the Secretary of State for Scotland to appoint a Fisheries Committee to advise on fishery-related matters, including screening. The Fisheries Committee continues to sit, its current terms of reference as per the 1989 Act. The Fisheries Committee has supplied the following summary of its functions:

The Committee's statutory function is to advise and assist:

(i) the Secretary of State, and

(ii) any person engaged in, or proposing to engage in, the generation of hydroelectric power,

on questions relating to the effect of hydroelectric works on fisheries or stocks of fish. The Committee may give such advice whether asked or not.

Any person engaged in, or proposing to engage in, the generation of hydroelectric power shall give the Committee such information as it reasonably requires.

Any person wishing to construct or operate a hydroelectric station with a capacity of more than one megawatt must apply to the Secretary of State for consent and, before so applying, must consult the Committee.

Additional Functions of the Committee

In addition, the Committee has been asked by the Secretary of State to consider and advise as necessary on the effects that the water systems of thermal and nuclear generating stations may have on fisheries and stocks of fish.

In legal terms, these electricity-related Acts take precedence over the 1986 Salmon Act and other fisheries legislation. As a result, where hydro schemes are concerned, The Salmon (Fish Passes and Screens) (Scotland) Regulations 1994 apply to schemes of <1MWe only. This would include, for example, the majority of small schemes constructed under any Scottish Renewables Order.

A4.2 The Salmon (Fish Passes and Screens) (Scotland) Regulations 1994

A4.2.1 Summary of Screening Measures

The main provisions of the Regulations are:

1. that the owner or occupier of an offtake from a salmon river must ensure that it is provided with a screen at the intake which prevents smolts from passing through it;
2. that where the screen is situated within the offtake, a continuous by-wash should be provided to enable smolts to return to the river by the shortest practicable route;
3. that where an offtake returns water to a river, screens should be provided to prevent the ascent of adult salmon into the offtake;
4. that the screen and by-wash are so constructed and located as to ensure that salmon are not injured or damaged by it.

"Salmon", in the context of the Regulations, means all migratory fish of the species *Salmo salar* and *Salmo trutta*. The Scottish Office advises that the Regulations apply only to rivers that ordinarily support upstream-migrating salmon. Simply stocking a river with juvenile salmon is not, in itself, enough to trigger the Regulations.

A "screen" is defined as a heck or grating or any device that prevents the passage of adult salmon or salmon smolts, hence the Regulations offer no powers with regard to other species.

It should be noted that:

- the Regulations in respect of the screening of offtakes require only that the screens should prevent the passage of smolts, not all life-stages; while no definition of the term "smolt" is given, kelt would clearly be excluded;
- no provision is made for relaxing the requirement at times of the year when smolts are not likely to be passing, e.g. through local bye-law;

- no body, including The Scottish Office, the DSFBs or the planning authority, is empowered to grant exemptions from the Regulations, other than those detailed within the text of the Regulations themselves, *viz.*:

  (i) offtakes which are constructed under Acts which provide for the Secretary of State to make separate provisions for fish screening before approving construction of the scheme, or offtakes constructed for public water supply purposes;

  (ii) offtakes that merely divert water from a river and return it with out obstruction to fish movement (e.g. fireponds in forests or stock-watering channels);

  (iii) overflow outlets or spillways used to discharge excess waters from reservoirs.

[For the exact wording given in the Regulations, the reader should refer to Appendix II].

For offtakes, the construction of which started prior to 1st January 1995, the Regulations took effect from 1st January 1998, and with immediate effect for constructions begun after 1st January 1995.

With regard to the Scottish Border rivers, schemes constructed on the River Tweed (including those parts that are in England) are subject to the Scottish laws, while those on the Border Esk are subject to English and Welsh laws.

A4.2.2 Implementation Policy

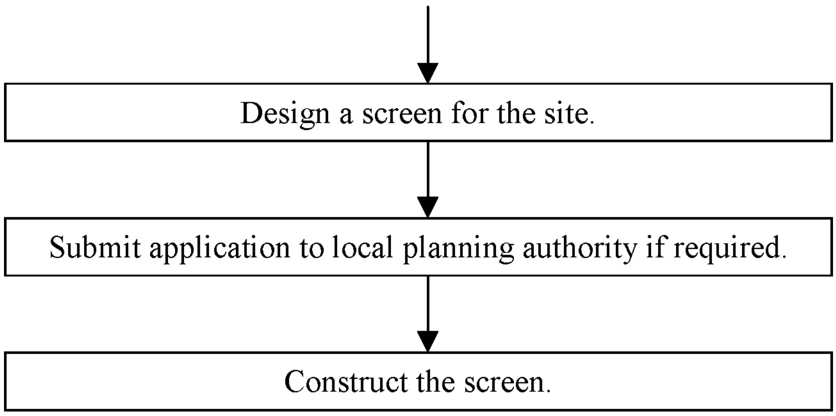
The Regulations have direct effect, i.e. in Scotland there is no regulating agency that has responsibility for enforcement of the Regulations, nor can any agency authorise a particular screen plan or design. The test of compliance lies with the courts of law. Under *s*.3(8) of the Salmon Act 1986 it is open to any person, organisation or agency to bring a prosecution against an owner or occupier who is considered to be in breach of screening regulations. The DSFBs have responsibility for fisheries protection at the local level, and perhaps would be the most likely bodies to prosecute an offender. The Scottish Office has indicated that the role of the Inspector of Salmon and Freshwater Fisheries is more likely to be advisory than direct in such cases. Riparian owners, angling bodies or any others with commercial interests in the fishery might also bring prosecutions.

A number of Boards have indicated that they have plans to inspect sites on a prioritised basis.

A4.3 Procedure for New Sites

Scotland has no abstraction licensing procedure that is relevant to hydroelectric developments, hence that particular mechanism for regulating new abstractions does not exist. For hydroelectric schemes of 1 MWe or larger, The Electricity Act 1989 requires consent from the Secretary of State and appropriate measures can be agreed in consultation with the Fisheries Committee (see Section 4.1, above). In the case of smaller schemes, any requirements for screening should be detected within the planning application process. The Salmon Advisory Committee (1997) provides the following model for this part of the process:

Determine whether the proposed or existing inlet or outlet needs a screen as required by the Regulations, consulting with the District Salmon Fishery Board and/or The Scottish Office as appropriate.



The final step is, of course, subject to planning approval for the scheme. Any such approval is for the scheme design and would not automatically imply that the screen itself complied with the screening Regulations. Only its effective function can demonstrate that.

A4.4 Summary of Consultations with Fishery Agencies in Scotland

A4.4.1 The Scottish Office

The Scottish Office (SO) supported the DTI's initiative on the present project, considering it an opportunity to examine the current legislation and recent developments in screen design.

The Regulations had been drawn up in such a way that a framework had been developed whereby decisions could be taken at a local level, where the fishery in question was best understood. Neither the Inspector, nor anyone within or outwith the SO, exercised any powers of approval. If it was considered that a particular screening system was inadequate, the courts of law would have to decide.

On the issue of the required season for screening of smolt, the SO's formal position was that the only safe legal interpretation of the Regulations was that fish screens should be operated all year round. However, the local DSFBs, who have powers to protect or improve fisheries within their Districts, are best placed to determine local conditions and may decide to enter into agreements with operators on a case-by-case basis.

On behavioural screening, the Inspector indicated that the advent of new methods, such as acoustic screening, held promise for the future, subject to proof of adequate performance.

On the question of whether current standards for screen approach velocity (25-30 $cm.s^{-1}$) were appropriate in view of recent scientific evidence concerning swimming performance, the Inspector considered that a wide margin of safety should be maintained. However, the scientific evidence should be interpreted in relation to the particular conditions pertaining in individual hydro schemes. Where, for example, the distances required for the fish to enter the by-wash were small, higher velocities might be acceptable.

As a general procedure for determining what screen design and operating regime was acceptable for a given site, the Inspector recommended that a comprehensive risk assessment should be carried out. Demonstration that such a procedure had been carried out and that its conclusions had been acted upon would carry considerable weight in supporting the developer's/operator's position.

A4.4.2 The Fisheries Committee

The Secretary of State's Fisheries Committee was consulted during a meeting held on 23rd March, 1988, when Members of the Committee offered their personal views on a range of issues relating to fish screening legislation and practice. These views have been taken into account in the preparation of the present report, which was also submitted to the Committee in draft for comment.

A4.4.3 The District Salmon Fishery Boards

Given the views of The Scottish Office and the Fisheries Committee that the detailed fish screening requirements were best decided at the local level, it was of interest to canvass the views of District Salmon Fishery Boards. Questionnaires were distributed to the clerks of all 62 Boards. Replies were received from only 18 Boards. A summary of the responses is given in Appendix III.

Conclusions from the DSFB Survey

While some degree of varied interpretation of the Regulations by the DSFBs would be both expected and necessary in order to accommodate differing regional conditions, the survey reveals a lack of consensus on the key issue of what constitutes a smolt under the Regulations and hence when screening is required. There was perhaps a consensus that screening should be designed to protect the vulnerable life-stages, based on the known migration patterns and population composition in each river system. This would seem to be a good approach but whether it can be sustained under the existing Regulations depends on the definition of what is a smolt.

A5. LEGISLATION IN NORTHERN IRELAND

A5.1 Applicable Legislation

Screening legislation in Northern Ireland is provided for in The Fisheries Act (Northern Ireland) 1966. This gives overall responsibility for regulation to the Department of Agriculture for Northern Ireland (DANI). The Act also gives two other organisations responsibility for enforcement and conservation at the local level. These are Fisheries Conservancy Board (FCB) and the Foyle Fisheries Commission (FFC). The FFC exercises power only within the Foyle River catchment and is a cross-border authority which owes its origins to both UK and Irish law. Crawford (1994) gave an account of the legal standing of the FFC and its duties. The remainder of the province falls within the FCB jurisdiction.

Fish screening legislation is contained within *s*.59 of the Act. As elsewhere in the UK, other legislation of possible relevance includes the Wildlife and Countryside Act 1981 and directives of European Commission relating to conservation.

A5.2 The Fisheries Act (NI) 1966 *s.*59

A5.2.1 Summary of Screening Measures

Fish screening legislation under this Act (see Appendix IV) is broad in its application compared with that in the rest of the UK, covering all freshwaters from which water is diverted (not only those frequented by salmon and sea trout), and every kind of water abstraction. It is also more prescriptive; that is to say, it states how and when fish screening should be carried out, rather than stipulating the required result. Specific requirements of the Act are:

1. Screens (gratings) should be located at points where the watercourse diverges from and is returned to the river (i.e. inlet screens should be at the entrance to a leat, not within the channel itself).
2. The screens should extend across the full width of the watercourse, and vertically from the bed or sill level to the level of the highest floodwaters. (A return frequency is not mentioned).
3. The bar-spacing of screens placed at the inlet should be ≤5.1 cm, those at the outlet ≤2.5 cm (outlet screen installed prior to 1991 may be ≤5.1 cm: see *s.*59((b)(ii)).
4. During the months of March, April and May, and at any other time when fry of salmon or trout are descending the watercourse, a wire lattice of mesh dimensions small enough to prevent the entry of fry or small fish must be fitted over the entire surface of the screen. (The DANI recommends a mesh size ≤12 mm for this purpose).
5. Section 59 (3) makes it an offence to tamper with or remove screens when they are required by the Act to be in place.

In spite of the apparent rigidity of the legislation, *s.*59(4) allows the regulators substantial scope for exemption, in particular where the Department is satisfied that sufficient arrangements will be made by other means. The law in this case is consequently found to be extremely flexible.

A5.2.2 Implementation Policy

Flexible interpretation of the Act has enabled some particularly innovative approaches to the problem of smolt entrainment in hydroelectric stations in Northern Ireland. An historical feature of the Act contained in *s.*58 requires that, if there is a fish pass in the dam belonging to a mill, the mill sluices should be closed for 24 consecutive hours between Saturday afternoon and Monday morning to ensure that water is available for ascending adult salmon. Nowadays, where water is being used to drive hydro turbines, the Sunday closure rule is arbitrary and to the best advantage of neither the site owner/operator, nor the fish. Instead, although the requirement for 52 days per annum cessation of abstraction is retained, exemptions may be granted that require the generator to close down operations for, say four consecutive weeks during the spring smolt migration season, the remaining days closure being arranged around critical migration flow conditions. Such an arrangement can prove satisfactory to the generator, who may lose less generation by concentrating closures during low spring river flows than by weekly Sunday closures. By protecting smolt migrations in this way during the expected peak season, the regulators have also been more readily able to consider the use of certain behavioural fish barriers (louvre screens and acoustic deterrents) to provide coverage over the remainder of the smolt season

Electric fish barriers have been accepted for use to prevent upstream migrants from entering outfalls at a number of locations and are reported by FCB to be successful when properly maintained.

A5.3 Procedure for New Sites

Northern Ireland has no system of abstraction licensing and any regulation of abstraction is exercised through the planning process (on such developments as may require planning consent). Regulation of abstracted quantities would then be dealt with through planning conditions.

The FFC and the FCB (depending on the region of the proposed development) are consultees within the statutory planning process in Northern Ireland. Before submitting a planning application it would therefore be necessary to discuss requirements with the relevant one of these bodies. They would decide whether or not a proposal met with the stipulated *s*.59 criteria, or alternatively whether it met the purpose of the Act, in which case they might agree to grant an exemption under specified conditions. Meeting the requirements of *s*.59 by one of these means would be essential to the receipt of planning permission.

A6. SUMMARY OF FINDINGS ON SCREENING LEGISLATION

An overview contrasting the provisions of the three main pieces of screening legislation that operate in different parts of the United Kingdom is given in Table A2. A key feature that all three have in common is that scope is provided for using any kind of screen or barrier that is effective in keeping fish out. A number of differences are seen, notably:

- the types of waters and fish species provided for;
- prescription of the times when fish screens are required to be in place;
- the powers of exemption open to regulatory/enforcement bodies.

Legislation in Northern Ireland is perhaps most straightforward for developers/owners. The scheme must either comply in detail with the law as set out in *s*.59 of the Act, or an exemption must be sought to allow another means to be used. The latter is, in effect, an authorisation. This system leaves no doubt as to whether or not the scheme is compliant with the law.

The system in England and Wales, under the new SFFA *s*. 14 legislation, has taken the power of authorisation given in the 1975 Act away from the regulator. The legal test of compliance now is not whether the plans have received Ministerial approval but whether the screen performs its job, and is maintained so that it continues to do so. However, the Environment Agency retains the power of exemption (*s*.14(3) & 14(6)) and chooses to exercise its discretion through a formalised process of risk assessment and by negotiation with the owner/operator. A further discretionary element is provided through the provision to limit through byelaw the times of the year when screening is provided. The law, overlaid with the Agency's policy, would appear to offer a flexible and workable approach.

In contrast, developers/owners in Scotland face more uncertainty. Taken at face value, the new Regulations require 100% effective screens to be in place every day of the year. While The Scottish Office, the Secretary of State's Fisheries Committee and the District

Salmon Fishery Boards indicated that they supported flexibility of approach at the local level, none of these bodies has the legal power to grant exemption. This problem will not be overcome until there is sufficient case law to create precedents. It is important therefore that suitable cases should be tested. The key issue would appear to be:

- What constitutes a smolt under the Regulations?

This alone would be sufficient to determine when screens needed to be in place. The DSFBs proposed a number of definitions. A further list taken from the literature is given in Appendix V. It might be helpful if, prior to any test case reaching a court, the DSFBs reached a consensus on a working definition of the term "smolt" in the Regulations, and whether they were prepared give advice to limit the season for fish screening to periods when smolts were at risk. In the absence of such advice, it would seem that the Regulations impose unfair restrictions on small scheme operators relative to operators of larger schemes regulated under the Electricity Acts. These larger stations benefit from restricted screening seasons, the terms of which are either stated within the relevant Act or have been agreed subsequently with the local DSFB.

The lack of explicit powers to protect non-migratory fish is seen by many fishery specialists as a failing in the fish screening legislation in England, Wales and Scotland. While migratory species (which include e.g. shads, lampreys and eel) are particularly vulnerable, it is well established that many freshwater species, including brown trout and coarse fish, undertake functional migrations within river systems that put them at risk of entrainment. The only existing legal mechanisms to protect these species derive from laws aimed at protecting fish from intentional injury (e.g. SFFA *s*.2), which may be difficult to prove (the term "knowingly" is likely to be open to interpretation), or from the provision to attach conditions to new consents or licences.

A further frustration of fishery bodies in England and Wales is the lack of powers to regulate abstractions that have been in continuous operation since before 18th July 1923. A good number of old abstractions, e.g. on water mills, pre-date this and are thus exempted.

Many would also like to see the legislation in England, Wales and Scotland extended to cover all types of water abstraction.

A7. VIEWS OF HYDROELECTRIC SCHEME DEVELOPERS, OWNERS AND OPERATORS

The survey of the hydroelectric generating industry included both large and small concerns from different regions of the UK and brought a variety of views. A total of ten companies agreed to respond. For commercial reasons, most did not wish to be individually identified, and therefore an overview of replies is presented here.

Q: What do you know about your obligations to fish (and in particular smolt) screening ?

Most respondents appeared to understand in general terms their responsibilities under the law, although, with new legislation in England, Wales and Scotland, there were doubts among some operators of smaller schemes about exactly what was expected of them. Two recurring questions concerned times of the year when fish screens were required to be in place and the levels of effectiveness of any screening system required to comply with the law. Another related to the need to provide screens on rivers not containing salmon or sea trout.

Q: How can you best deliver your obligation?

It was stressed that operating with physical screens small enough to exclude smolts can have a serious impact on generation economics. All those questioned were in favour of using behavioural systems if they could be shown to work effectively. Although sometimes more costly to install, behavioural systems were seen to have lower impact on water flow and to require minimal maintenance. However, none would wish to do so without the sanction of the regulatory authority.

Q: What concerns do you have?

Particular concerns raised were:

- (from owners/operators of small schemes in Scotland) advice from The Scottish Office was that “the safest interpretation of the law” was that fish screens should be in place all year round;
- that insistence on physical screening measures would render smaller schemes uneconomic, especially if required all year round;
- that any move to require screen mesh sizes even smaller than the current standards (12mm x 12 mm or 12 mm x 25 mm) where smaller parr were required to be excluded would make generation practically impossible at most locations;
- the widely used screen approach velocity criterion of 25-30 $cm.s^{-1}$ and its effect on the overall size and capital cost of screening systems, and possible need to widen channels to achieve it;
- (from owners/operators of small schemes in Scotland) that different standards appear to apply to large schemes regulated under the Electricity Acts and those regulated under The Salmon (Fish Passes and Screens) Regulations 1994;
- (again, from owners/operators of small schemes in Scotland) that no guidance is given on the overall bypass efficiency required for smolts, and that, while statements by the fishery interests to the effect that “nothing less than 100%” is acceptable may be a desirable target, it is unrealistic, whatever kind of screen or barrier is used.

Q: What measures are currently in place and how are facilities manned and operated?

Schemes regulated under various Acts of Parliament in most cases operated according to provisions made within the Acts, or subsequent pragmatic agreements made with the regulatory agencies as a result of operational experience. Where smolt screens were operated, they were invariably conventional physical screens, usually with a mesh size of 12 mm x 12 mm or 12 mm x 25 mm. In most cases, the screens were in place for at least three months, usually from April to June; in some cases, they were put in place as early as March and left until as late as October. The screens were normally constructed and operated much as described by Aitken *et al.* (1966), i.e. screens could be withdrawn from slotted frames for cleaning, paired slots being provided so that a cleaned mesh panel could be inserted before the soiled one was removed. During periods of heavy trashing, this procedure was repeated up to several times per day.

Most of the older small (< 1 MWe) schemes that were not regulated by Acts of Parliament but which now fall under one of the instruments of UK screening legislation were not built with fish screening in mind and operated with only trash racks to prevent debris entry into lades and turbines. The trash rack bar spacings ranged from about 25 mm to 75 mm. (The smaller to mid-range of these spacings would prevent kelts entering but not smolts). The owners/operators of these schemes were willing to install fish screens, most not wishing to be seen to jeopardise fish stocks, with smaller ones also fearing that they might be closed down if they did not comply with legislation. However, most had difficulties in seeing how they could meet their legal obligation to screen without the schemes becoming economically unviable. Some had already taken advice and had installed physical screens that were operated over the spring period only, with the agreement of local regulators.

New schemes, largely constructed under the NFFO and SRO provisions, had had the opportunity to take expert advice on fish screening, prior to construction. Where fish screening was required, this was generally provided. Some developers in England and Wales and Northern Ireland had been successful in negotiating the use of non-physical (i.e. behavioural) screens, including louvre and acoustic screens, although not all of these had yet proceeded to construction. The situations where behavioural screening had been approved by the planning authority were generally 'low-risk' for salmonids. In England and Wales, these were located on industrial rivers with marginal or recovering salmon or sea trout stocks. In Northern Ireland, behavioural screens were generally tied in with agreements to cease generation over the peak smolt migration season. In Scotland, no examples of behavioural systems were reported, although at one new site (Blantyre, R. Clyde) that had commenced operation in 1995 and had not been fitted with fish screens, an acoustic barrier had been tested in 1996 (Anon., 1996b). Although the results from this trial appeared promising (73% reduction of smolt passage through the turbine with the barrier operating and 91.5% reduction of coarse fish passage), they were inconclusive owing to the small numbers of fish collected during the trial (210 smolts, 355 coarse fish).

Q: To what extent are you aware of behavioural screening?

Most developers and operators were aware of the concept of behavioural screening, and generally they appeared to be abreast of recent developments in this field.

Q: How do screening requirements effect the economics of your operations?

While few had detailed figures available, two cases described provide some insight. The first is for a small (< 1 MWe), privately-owned, low-head scheme typical of the NFFO/SRO class; the second is Dunalastair, a larger 36 MWe scheme operated by Scottish Hydroelectric plc.

<u>The Small Hydro Scheme</u>

Physical screens (flat panel screens, mesh size 12.5 x 12.5 mm) were installed recently to satisfy the 1994 Regulations. The screen array is fitted within the headrace canal, aligned at an angle of ~30^o to the flow, giving a velocity normal to the screen face of <30 $cm.s^{-1}$. The downstream end of the screen guides fish into a by-wash. The screens are cleaned at least once per day. Even so, build-up of debris on the screens has been shown to immediately reduce the power output of the associated generating units. It has been recorded that on this particular scheme, a 75mm loss in hydraulic head corresponds to a 130KWe loss in generator output. These figures represent a reduction of one-third of the potential output of the scheme. From this figure it can be shown that financial losses due to screening alone amount to £9,900 over a 3 month screening period and would total £39,600 over 12 months. These losses correspond to 8% and 33%, respectively, of the gross income of the scheme operating without screens, for the whole year. If anything, the potential revenue loss is underestimated by this method, as it has been assumed that debris fouling (and consequently cleaning effort) remains constant at the observed spring seasonal rate throughout the year; in practice, fouling would increase in autumn.

In addition to the financial losses associated with the reduction in power generation, additional costs accrue from maintaining the screens. Regular cleaning is essential. It is likely to add approximately 1000 man hours per year to the existing workload, equivalent to a further £5,000 per year. Screen panels also require regular replacement, the average life-span being about 3 years. The capital cost of the system was £12,000 and replacement of damaged screen panels amounts to about £500 per annum. Assuming replacement of the supporting structure after 10 years, annual the screening system, this brings the annual discounted capital cost of screening to around £2,000 per annum.

The total annual cost of all-year-round screening for a small scheme may therefore be of the order £50k per annum, or one quarter of this for a 3 month screening period.

<u>The Large Hydro Scheme: Dunalastair</u>

Scottish Hydroelectric (HE) presented this as probably the worst case within their group of stations. Generally they considered the generation penalty of screening to be low, although by agreement with the Fisheries Committee and DSFBs, the majority of their low-head (<30 m) schemes are not fitted with smolts screens (Anon., 1996).

The screening system at Dunalastair has been described by Aitken *et al.* (1966). The scheme was constructed in 1933 but the original intake screens did not meet the 30 $cm.s^{-1}$ velocity criterion and a new, wider screening arrangement was constructed in 1959. The overall screening area is about 750 m^2. HE estimate the cost of replacing the mesh alone to be about £60k at current prices. The overall costs of maintenance, including manpower, are between £70k and £100k per annum.

Generation loss at Dunalastair caused by hydraulic head loss at the fish screens is estimated by HE to be 2 MWe per machine (there are two turbines), which amounts to an 11% reduction in capacity during the season of screening. At HE sites where screens are fitted, they are put in place from the beginning of March to the end of October (with some local variation).

A8. SCREENING LEGISLATION IN OTHER COUNTRIES

The free passage of fish in river systems has become a major topic on the fisheries agenda of many industrialised nations. Within Europe, a number of cross-border river restoration initiatives are in progress, such as the Rhine 2000 programme, which aims to restore salmon runs to the River Rhine by the new millennium. These programmes recognise the degradation of natural habitat in river systems that has occurred, particularly since the Industrial Revolution, and the loss of continuity of access for fish that has resulted. There has been much interest, therefore, in the means of facilitating both upstream and downstream passage of migratory fish. Recent international symposia on the subject were held in Vienna in 1996[†] and in Monterey in 1997[‡].

[†] International Conference on "Fish Migration and Fish Bypass-Channels", held in Vienna, Austria, 24-26 September 1996.

[‡] American Fisheries Society Annual Symposium, Monterey, California, USA, August 1997.

A number of scientists from other countries provided information on technical approaches to fish screening, which has been incorporated into Part B of this report. The opportunity was also taken to consult these specialists on the screening legislation or other relevant provisions in their countries or regions. This information may be of interest to readers with overseas hydro interests or simply to compare with the domestic situation. Of scientists from some twenty countries consulted those from nine provided information, the salient points of which are summarised in Appendix VI.

From the information supplied, it may be surmised that many countries make some attempt to impose screening requirements on water abstractors, and that this is almost invariably at the abstractors' own expense. It is seen that often the only mechanism enabling regulation is at the planning stage, when planning powers allow screening to be required as a condition of consent. In some countries (e.g. in Switzerland and the USA), rather generalised fish or wildlife protection legislation can be used to enforce the need for screening. It is also evident that operators are being persuaded to provide fish screening measures in order to improve their public environmental image; it is usual for fishery agencies to assist and participate (sometimes financially) in these initiatives.

The provision of formal screening legislation is not unique to the UK, being found at least in Denmark, where it was introduced only in 1994. It is interesting to note that the Danish legislation is highly prescriptive (stating allowable bar spacings, materials, etc.) and stringent compared with that operating in any part of the UK. Nevertheless, it leaves the fishery inspectorate with a degree of discretionary choice and contains cost-benefit element.

A9. TOWARDS A RISK-ASSESSMENT APPROACH TO HYDRO SCREENING SPECIFICATION

A9.1 The Fundamentals

The term "risk assessment" seemed to have a wide base of support amongst the consultees of this study, although it clearly held different meanings. There is a need to develop a common basis for this process. While the development of such a procedure is outside the terms of the present study, it may be helpful to list some of the features that emerged from discussions with consultees that would need to be included for a hydro scheme assessment. No bias is intended in this list with respect to migratory or other categories of fish.

A risk assessment may need to consider the following information:

1. the value of the fish stock in economic or conservation terms;
2. the percentage of the river system's fish stock that must pass the scheme;
3. the percentage of those fish that pass successfully;
4. the additional loss due to other schemes;
5. the significance of given percentage levels of loss in economic and conservation terms.

Each of these items embraces a large number of factors, although in some cases existing data will be available to the assessor. The 'value' of a stock may not be known in quantitative terms, but fishery agencies will generally be able to rank waters within their region according to value. For mainstem rivers and larger tributaries they are also likely to know the approximate spawning escapement, at least in terms relative to the rest of the catchment. The percentage of fish successfully passing the scheme will depend on a number of aspects of the hydro scheme, which will be considered in more detail below. From items 2 and 3, it will be possible to estimate the percentage loss of stock due to the abstraction.

Item 4 is included since e.g. 5% of a smolt run lost to a single scheme on a system might be considered an acceptable loss when a operator's livelihood was at stake, whereas the loss from three or four such schemes on a single system would be rather more significant. With increasing use of whole catchment management techniques, it may be possible to develop a catchment figure for "Total Allowable Loss " (TAL), effectively a quota system, i.e. if TAL was set at 10% of the smolt run, then this would have to be divided among the various abstractors. Such an approach would create a rational basis for risk management and might automatically define Item 5. There are precedents elsewhere in regulation, not only in marine fisheries, where "Total Allowable Catch", or TAC, is set and quotas apportioned, but also in atmospheric emission control, where "Critical Loads" (CL's) are set by government for particular geographic regions. The CL is defined as the maximum allowable deposition of an atmospheric pollutant on a particular region (in units of e.g. $kg.m^2.y^{-1}$), allowable emission quotas being determined by aerial dispersion models. A polluter can only obtain a consent to emit, provided that the model indicates that CL will not be exceeded.

The fifth item is essential for the significance of the loss to be judged, and may come from either a detailed knowledge of the stock dynamics (unlikely) or a professional value judgement (most likely). In the latter case, it is desirable to obtain a consensus view, e.g. within the 'TAL' approach described above.

While the simple approach outlined above may appear to belie the complex reality of the situation, it is important that the apparent complexity should not become an excuse for not bothering to try, nor should the endeavour be allowed to become bogged down in detail. The Environment Agency, within its *s.*14 implementation policy, has developed a simple but workable approach. If looked at carefully, it differs very little from the above. With some refinement, the EA procedure may be suited to wider application for assessment of hydroelectric screening.

It will be noticed that the above process refers to a "stock" as the basic unit of risk assessment. It is intended that the term should be interpreted as widely or narrowly as required. For example, in a mixed salmon/sea trout fishery, it may be desirable to perform two iterations of the assessment, one for each species, basing the final decision on required action on the most sensitive. Equally, it may be desirable to separate spring-run fish from grilse on a salmon river, and so on. An important point that emerged from consultations was that any risk assessment should not 'skim over' important within-stock variation of biological characteristics.

A9.2 Estimating Scheme Passage Rates by Fish

Although the diversion efficiency of a screening system is the key figure of interest when comparing one type of screen with another, the more relevant figure for risk assessment purposes is the overall scheme passage rate. This can be defined as:

$$\text{Scheme Passage Rate (\%)} = 100 * N_{leaving} / N_{approaching} \quad \text{(A1)},$$

where $N_{approaching}$ is the number of fish approaching the scheme from upstream and $N_{leaving}$ is the number that pass the scheme successfully. The fish passing the scheme may comprise three components:

(i) those that pass directly over the weir or spillway and do not enter the generating flow at all;

(ii) those that enter the generating flow but are diverted by the screening system and

(iii) those that pass the screening system (e.g. through large meshes or not deterred by behavioural system) and survive turbine passage.

Turnpenny and Hanson (1997) showed that the Scheme Passage Rate could be determined using the following, more explicit expression:

Scheme Passage Rate (%) = $100*(1 - (P_{gen} . (1 - e) . I)$ (A2),

in which P_{gen} is the proportion of descending fish that enter the generating flow, I is the fish injury rate in the turbine and e is the screen fish deflection efficiency. They gave the example of a high-flow scenario in which 50% of the descending fish passed directly over the weir and a behavioural barrier having a 90% diversion efficiency was used; injury rate in the turbine was 20%. The scheme passage rate then would be 100(1-0.5 x (1-0.9) x 0.2), = 99%. If no fish passed over the weir, then this would amount to a scheme passage rate of 98%.

Reasonable estimates of the injury rates in certain types of turbine can be made from a combination of theoretical predictions of fish strike rates by the turbine blades and results of laboratory investigations into the effects of rapid pressure, hydraulic shear and turbulence (Turnpenny, 1998). All these are conditions that fish may experience during turbine passage. Present empirical data relate only to large turbines (a 9 m diameter reference design was used in the study) and testing of the model on a 0.5 MWe turbine at Blantyre in Scotland (Turnpenny *et al.*, 1995) suggests that it may underestimate hydraulic stresses in smaller turbines, owing to scale effects. Turnpenny and Hanson (1997) proposed that the model merits re-evaluation to ensure more realistic results for turbines of <1 MWe. Such an analysis still remains to be done.

A10. CONCLUSIONS AND RECOMMENDATIONS

The advent of new fish screening legislation has given rise to some uncertainty in its early stages. The Regulations in Scotland are in the vanguard of this process and issues relating to the Regulations are beginning to emerge. Changes to the law in England and Wales under SFFA *s*.14 have yet to take full effect (1st January 1999) and will no doubt generate new issues in due course, although the main group affected will be fish farmers. Although there are implications for hydroelectric operators (e.g. the loss of the Ministerial approval process), they are less radical than those arising from the Scottish Regulations.

Perhaps the main effect on hydroelectric operators, as well as water supply undertakings in England and Wales will be a tightening of enforcement. The Environment Agency have indicated that they wish to ensure that they are not seen to be victimising fish farmers, so will apply enforcement measures uniformly across all categories of user.

In Northern Ireland, the legislation has not changed in the last 30 years and there are no plans to change it at present. It appears to work well and there were no reported problems. Hydro operators in Northern Ireland were keen to see approval gained for behavioural systems, but this will emerge from demonstration of further improvements in the technologies, not from changing legislation or the enforcement process.

Operators of small, low-head (≤10 m) schemes are particularly hard-hit by screening regulations, as the flow of water relative to the power generated is high. This means that large screening areas must be used and that any head-loss associated with obstruction of the flow can have a serious impact on scheme economics. For this reason, operators of such schemes are particularly keen to be allowed to use behavioural, rather than physical screens. Most regulatory agencies indicated that they would not object to the use of suitable behavioural barrier methods, subject to a risk assessment to establish the required performance level, followed by a trial after commissioning to demonstrate that this performance was being achieved.

A particular issue arose from consultations with operators in Scotland, where small schemes were seen to be unfairly disadvantaged relative to larger schemes (>1 MWe) regulated under the Electricity Acts. This was because the Regulations applying to small schemes appear to require screens to be fitted whenever smolts might be present, but no definition of a smolt is given. Hence, the Scottish Office has advised that, until a case tested in court proves otherwise, the only safe legal interpretation is that screens must be in place all year round. On larger schemes, screens are not required to be in place all year round, if at all.

A number of recommendations emerge from the consultations undertaken during this study:

Consultation by Hydro Developers/Operators

The fishery agencies all stressed their willingness to talk to developers/owners/operators about screening and other fishery issues. It is recommended that developers of new schemes involve the fishery agencies at an early stage to avoid later misunderstandings. Owners and operators of existing schemes should also take an early opportunity to discuss whether their scheme conforms to current screening requirements, rather than waiting for the agencies to seek them out during the enforcement process.

Interpretation of the Law

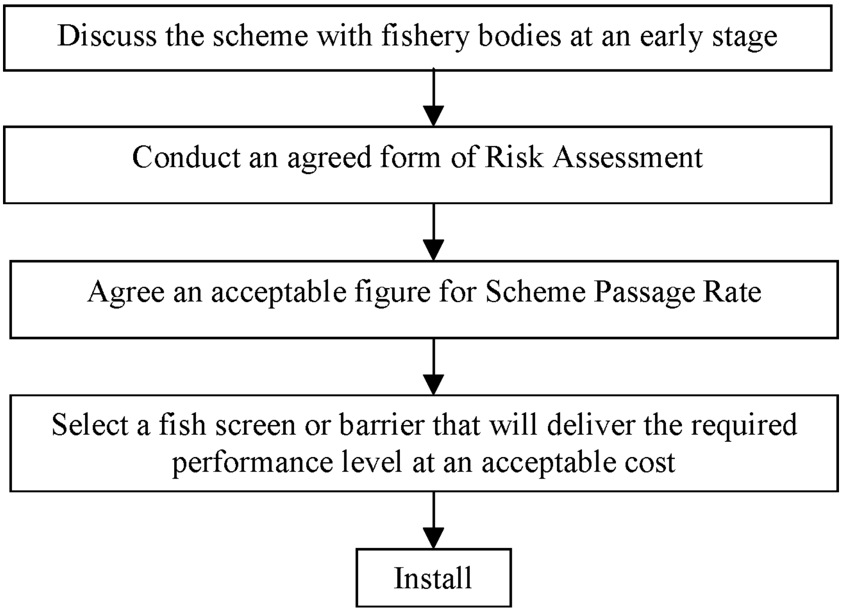
It is important to demonstrate that legislation is being applied uniformly. Where at present there is scope for different interpretations of the law (e.g. definition of a 'smolt' within the Scottish Regulations), it would be helpful for enforcement agencies to reach a uniform policy on how the law should be interpreted and applied, until such times as case law may clarify definitions.

Risk Assessment

The development of a uniformly accepted risk assessment procedure for hydropower screening applications is strongly recommended. Such a procedure would need to be transparent and lead, via a series of clearly understood steps, towards a required level of action, expressed in terms of an acceptable overall scheme bypass rate. This would give a clear indication to developers and operators of what they needed to achieve, and would provide a uniform basis for presenting any case that went to court.

A specific requirement within the proposed risk assessment methodology is to develop improved procedures for predicting the likely mortality rates of fish in small turbines (especially <1MWe). This would require the application of computational fluid dynamics (CFD) techniques to analyse hydraulic stresses in small Francis and Kaplan turbines so that available biological data could be applied, followed by validation of predictions at operating turbine sites.

The following overall model for selecting a screening solution is recommended. The selection of a suitable screen or barrier type is the subject of Part B of this report.



APPENDIX I

THE SALMON & FRESHWATER FISHERIES ACT (*S.*14 &15), AS AMMENDED UNDER THE ENVIRONMENT ACT 1995

Gratings

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

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

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

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

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

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

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

[Screens

14.-(1) This section applies in any case where –

(a) by means of any conduit or artificial channel, water is diverted from waters frequented by salmon or migratory trout; and

(b) any of the water so diverted is used for the purposes of a water or canal undertaking or for the purposes of any mill or fish farm;

and in this section "the responsible person" means the owner of the water or canal undertaking or (as the case may be) the occupier of the mill or the owner or occupier of the fish farm.

(2) Where this section applies, the responsible person shall, unless an exemption from the obligation is granted by the Agency, ensure (at his own cost) that there is placed and maintained at the entrance of, or within, the conduit or channel a screen which –

(a) subject to subsection (4) below, prevents the descent of the salmon or migratory trout; and

(b) in a case where any of the water diverted is used for the purposes of a fish farm, prevents the egress of farmed fish from the fish farm by way of the conduit or channel.

(3) Where this section applies, the responsible person shall also, unless an exemption from the obligation is granted by the Agency, ensure (at his own cost) that there is placed and maintained, across any outfall of the conduit or channel a screen which –

(a) prevents salmon or migratory trout from entering the outfall; and

(b) in a case where any of the water diverted is used for the purposes of a fish farm, prevents the egress of farmed fish from the fish farm by way of the outfall.

(4) Where a screen is placed within any conduit or channel pursuant to subsection (2) above, the responsible person shall ensure that a continuous by-wash is provided immediately upstream of the screen, by means of which salmon or migratory trout may return by as direct a route as practicable to the waters from which they entered the conduit or channel (and accordingly nothing in subsection (2) or (3) above applies in relation to a by-wash provided for the purposes of this subsection).

(5) Any screen placed, or by-wash provided, in pursuance of this section shall be so constructed and located as to ensure, so far as reasonably practicable, that salmon or migratory trout are not injured or damaged by it.

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

(7) Any exemption under subsection (2) or (3) above may be granted subject to conditions.

(8) If any person who is required to do so by this section fails to ensure that a screen is placed or maintained, or that a by-wash is provided, in accordance with the provisions of this section, he shall be guilty of an offence.

(9) In any proceedings for an offence under subsection (8) above, it shall, subject to subsection (10) below, be a defence for the person charged to prove that he took all reasonable precautions and exercised all due diligence to avoid the commission of the offence by himself or a person under his control.

(10) If in any case the defence provided by subsection (9) above involves the allegation that the commission of the offence was due to an act or default of another person, or to reliance on information supplied by another person, the person charged shall not, without leave of the court, be entitled to rely on that defence unless –

(a) at least seven clear days before the hearing, and

(b) where he has previously appeared before a court in connection with the alleged offence, within one month of his first such appearance,

he has served on the prosecutor a notice in writing giving such information identifying or assisting in the identification of that other person as was then in his possession.

(11) Any reference in subsection (10) above to appearing before a court includes a reference to being brought before a court.

(12) The obligations imposed by subsections (2) to (6) above, except so far as relating to farmed fish, shall not be in force during such period (if any) in each year as may be prescribed by byelaw.

(13) The obligations imposed by subsections (2) to (6) above on the occupier of a mill shall apply only where the conduit or channel was constructed on or after 18th July 1923.

(14) Any reference in this section to ensuring that a screen is placed and maintained includes, in a case where the screen takes the form of apparatus the operation of which prevents the passage of fish of the descriptions in question, a reference to ensuring that the apparatus is kept in continuous operation.

(15) In this section "by-wash" means a passage through which water flows.]

Power of water authority to use *gratings* [screens] etc. to limit movements of salmon and trout

16.-(1) A water authority, ~~with the written consent of the Minister~~

(a) may cause a grating [screen] or gratings [screens] of such form and dimensions as they may determine to be placed and maintained, at the expense of the authority, at a *suitable* place in any watercourse, mill *race*, cut, leat, conduit or other channel for conveying water for any purpose from any waters frequented by salmon or migratory trout; and

(b) may cause any watercourse, mill race, cut, leat, conduit or other channel in which a *grating* [screen] is placed under this section to be widened or deepened at the expense of the authority so for as may be necessary to compensate for the diminution of any flow of water caused by the placing of the *grating* [screen], or shall take some other means to prevent the flow of water being prejudicially diminished or otherwise injured.

(2) If any person –

(a) injures any such *grating* [screen]; or

(b) removes any such *grating* [screen] or part of any such *grating* [screen], except during any period of the year during which under a byelaw *gratings* [screens] need not be maintained; or

(c) opens any such *grating* [screen] improperly; or

(d) permits any such grating [screen] to be injured, or removed, except as aforesaid, or improperly opened;

he shall be guilty of an offence.

(3) A water authority, ~~with the written consent of the Minister~~ may adopt such means as in its opinion are necessary ~~as the Minister may approve~~ for preventing the ingress of salmon or trout into waters in which they or their spawning beds or ova are, from the nature of the channel or other causes, liable to be destroyed.

(4) Nothing in this section shall-

(a) affect the liability under this Act of any person to place and maintain a *grating* [screen]; or

(b) authorise a *grating* [screen] to be so placed or maintained during any period of the year during which under a byelaw *gratings* [screens] need not be maintained; or

(c) authorise any *grating* [screen] to be placed or maintained so as to obstruct any conduit or channel used for navigation or in any way interfere with the effective working of any mill;

and nothing in subsection (3) above shall authorise the water authority prejudicially to interfere with water rights used or enjoyed for the purposes of manufacturing or for milling purposes or for drainage or navigation.

[(5) In this section "open", in relation to a screen which consists of apparatus, includes the doing of anything which interrupts, or otherwise interferes with, the operation of the apparatus.]

APPENDIX II

THE SALMON (FISH PASSES AND SCREENS) (SCOTLAND) REGULATIONS 1994

S T A T U T O R Y   I N S T R U M E N T S

1994 No. 2524 (S.119)

RIVER, SCOTLAND

The Salmon (Fish Passes and Screens) (Scotland) Regulations 1994

Made	*23rd September 1994*
Laid before Parliament	*6th October 1994*
Coming into force	
For the purposes of regulation 1(2)(a)	*1st January 1998*
For the purposes of regulation 1(2)(b)	*1st January 2000*
For all other purposes	*1st January 1995*

The Secretary of State, in exercise of the powers conferred upon him by section 3(2)(c) and (f), (4) and (5) and section 10(2) of the Salmon Act 1986(a) and of all other powers enabling him in that behalf, and after having consulted such persons as he considers appropriate, hereby makes the following Regulations:

Citation, commencement and application

1.—(1) These Regulations may be cited as the Salmon (Fish Passes and Screens) (Scotland) Regulations 1994 and shall, subject to paragraph (2) below, come into force on 1st January 1995.

(2) These Regulations insofar as they apply–

(a) to an off-take the construction of which commenced before 1st January 1995, shall come into force on 1st January 1998, and

(b) to a dam the construction of which commenced before 1st January 1995, shall come into force on 1st January 2000.

(3) Subject to paragraph (4) below, these Regulations shall apply to dams in and off-takes from inland waters which ordinarily contain upstream migrating salmon.

(4) Regulations 3 to 7 hereof shall not apply to any dam or off-take–

(a) the construction, extension or operation of which has been authorised, approved or consented to by the Secretary of State (or by any other Minister of the Crown) under the Electricity (Scotland) Act 1979(b), or any enactment repealed by that Act, or under the Electricity (Scotland) Act 1989(c); or

(b) used for the abstraction of water for the purposes of providing a water supply in accordance with the approval of the Secretary of State granted in the exercise of any power requiring him to secure so far as practicable the rights of riparian owners and of other owners of land or salmon fishings.

(a) 1986 c.62.
(b) 1979 c.11; the Act was repealed by the Electricity (Scotland) Act 1989 (c.29), Schedule 18.

Interpretation

2. In these Regulations–

"fish pass" means any fish pass, ladder, fish way or lift or other device which facilitates the free passage, upstream or downstream, of salmon around, over or through any dam;

"off-take" includes a lade;

"operator" in relation to a dam or off-take means its owner or, where another person is in occupation or control of it, that person.

Dams

3. Every–

(a) dam the construction of which commenced on or after 1st January 1995,

(b) mill dam constructed after 28th July 1865, and

(c) portion, of any other mill dam, renewed or repaired at any time after 28th July 1865,

shall be made and maintained watertight by the operator so that no water, which can reasonably be prevented, shall run through it except when necessary to maintain the stability of the dam.

Fish passes

4.—(1) The operator of every dam shall ensure that it is provided with a fish pass which facilitates the free passage of salmon at all times except during any period when, for natural reasons, the flow of the river at the point where the dam is located is so low that salmon would not reasonably be expected to seek passage.

(2) In this regulation "natural reasons" means any reason which is not related to–

(a) the operation of the dam, or

(b) the abstraction of water from the river by the operator of the dam or for a purpose for which the dam was constructed or is being used.

Lades

5.—(1) The operator of every lade shall ensure that it is provided with a sluice to control the flow of water.

(2) The operator shall ensure that the lade and sluice are so constructed as to secure that the quantity of water passing into the lade shall not exceed that which is required for the purpose for which abstraction is made except when it is necessary to do so to prevent damage during high water flow.

Screens

6.—(1) Subject to paragraph (6) below, the operator of every off-take shall ensure that a screen, which prevents salmon smolts from passing through it, is provided at its entrance or within it.

(2) Where the screen is situated within the off-take, the operator shall ensure that a continuous by-wash is provided immediately upstream of the screen, by means of which salmon smolts may return by as direct a route as practicable to the river from which they came.

(3) Where an off-take returns water to inland waters the operator shall ensure that a screen is provided at the downstream outlet which prevents adult salmon from entering the outlet of the off-take.

(4) A screen may be constructed in the form of a heck or grating or in the form of any device which prevents the passage through it of adult salmon or salmon smolts (as the case may be).

(5) Any screen and any by-wash provided in accordance with this regulation shall be so constructed and located as to ensure, so far as reasonably practicable, that salmon are not injured or damaged by it.

(6) This regulation shall not apply to–

(a) any off-take which conveys or channels water to ponds or pools and returns it directly to the river from which it was abstracted, provided that the passage of salmon through the off-take until return to the river is, at all times, unobstructed and the water is not subject to any process, contamination or disturbance which might cause injury or damage to the salmon, or

(b) overflow outlets or spillways used to discharge excess water from reservoirs.

Installation, maintenance etc.

7.—(1) The operator of a dam or off-take shall carry out any work necessary to comply with these Regulations in such manner as to ensure the minimum practicable interruption to the passage of salmon.

(2) The operator of a dam or off-take shall carry out any maintenance of it or of any fish pass, sluice, by-wash or screen in such manner as to ensure the minimum practicable interruption to the passage of salmon.

Revocation and saving

8.—(1) Subject to paragraph (2) below, the regulations with respect to the construction and use of mill dams or lades, or water wheels made by the Commissioners, by byelaw dated 29th April and 19th July, 1865, under section 6(6) of the Salmon Fisheries (Scotland) Act 1862(a) are hereby revoked.

(2) The said byelaw shall–

(a) in relation to lades to which it applies and whose construction commenced before 1st January 1995, continue to have effect until 1st January 1998; and

(b) in relation to dams to which it applies and whose construction commenced before 1st January 1995, continue to have effect until 1st January 2000.

Hector Monro
Parliamentary Under Secretary of State,
Scottish Office

St Andrew's House, Edinburgh
23rd September 1994

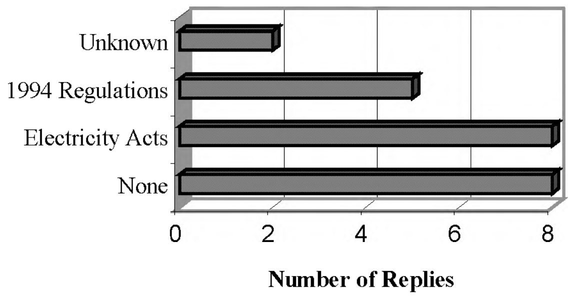
(a) 1862 c.97 (25 and 26 Vict.). The byelaw was subsequently enacted as Schedule G to the Salmon Fisheries (Scotland) Act 1868 (1868 c.123 (31 & 32 Vict.)) by section 10 of that Act. Schedule G was amended by the Salmon and Freshwater Fisheries (Protection) (Scotland) Act 1951 (c.26) Schedule 1 and by the Electricity (Scotland) Act 1979 (c.11) Schedule 11 and revoked by section 41 of and Schedule 5 to the Salmon Act 1986 (c.62). The 1862 Act was revoked by section 41 of, and Schedule 5 to, the said 1986 Act. The byelaw was retained in effect by sections 3(1) and 10(1) of the said 1986 Act.

APPENDIX III
SUMMARY OF QUESTIONAIRE RESPONSES RECEIVED FROM THE DISTRICT SALMON FISHERY BOARDS (SCOTLAND)

The questions are summarised along with a digest of the responses received from the eighteen Boards that participated. Not all Boards replied to all questions, indicating either that they were not relevant to their District or that they had insufficient knowledge to answer the question. Where the total number of responses shown below is less than 18 for a given question, the balance should be taken as a "no comment" response.

Q: Does your Board presently have hydro schemes operating within its area?

Eight of the Boards that replied knew of no hydroelectric schemes within their District. The same number had schemes regulated under the Electricity Acts. Five were aware of schemes within their District that were subject to The Salmon (Fish Passes and Screens) Regulations 1994 but two Boards were uncertain as to whether any such schemes operated within their District.



Q: How would the Board define the term "smolt"?

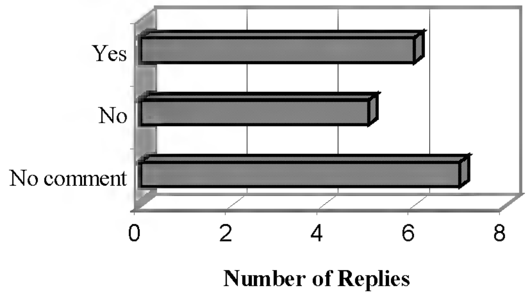
The following definitions were proposed:

- Salmon/ sea trout returning April-June: appearance standard (T L Nelson, Awe Board)
- Salmonid fish average 2 yrs; shoaling behaviour, covered in silver scales; approx. 10 cm fork length (but up to 18 cm), running April-July (R Barnes, Lochy Board)
- Size 15-23 cm, silvery, April/May (P M Fairweather, Fyne Board)
- Phenotypic (March-June) (B Moyes, Tay Board)
- When parr become silvery before entering the sea (Sir W G Cumming, Findhorn Board)
- Salmonid engaged in seaward migration (M Larby, Conon Board)
- According to Allan & Ritter (1975) (W. Midwood, Beauly Board).

The range of replies leaves open the question of whether the term "smolt" applies only to silvery-coloured salmonids of around 10-20 cm in length that migrate seawards during the spring/early summer period, or includes downstream-migrating parr as well. This highlights the problem of interpreting the meaning of a 'smolt' within the Scottish Regulations.

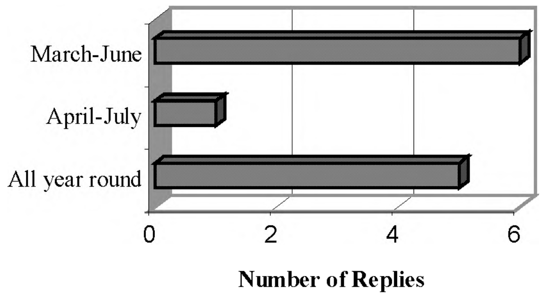
Q: Does the Board consider parr and silvering parr to be part of the total smolt run?

The break-down of replies was as follows:

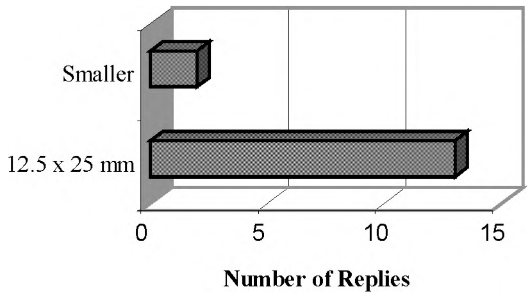


Q: At what times of the year does the Board normally require screens to be in place on existing hydro schemes?

The break-down of replies was as follows:

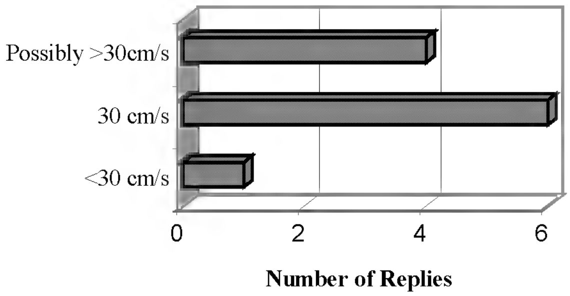


Q: Does the Board accept that a mesh size of 12.5 mm vertical x 25 mm horizontal is acceptable to prevent passage of smolts or is another size preferred ?



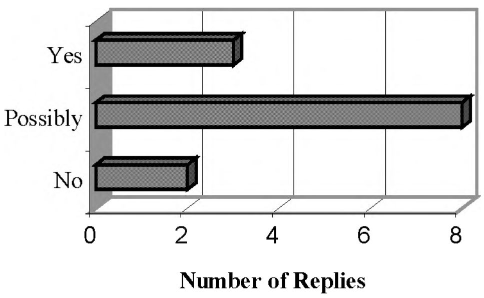
All Boards that replied to this question considered the 12.5 mm x 25 mm mesh to be satisfactory for smolt screening. Two Boards indicated that they would require smaller meshes where parr were to be screened. (Note: The Scottish Office guidance [Anon., 1995] indicates a required mesh size of 10 mm x 10 mm for screening parr down to 8 cm in length).

Q: Does the Board consider a screen approach velocity criterion of 30 $cm.s^{-1}$ to be appropriate for smolt screening, or would the Board wish to take account of recent scientific findings that smolts can sustain higher speeds than this?



The majority of Boards that replied on this question indicated that they would prefer to adopt a precautionary approach and retain a 30 $cm.s^{-1}$ advisory criterion, or less (The Scottish Office Guidance Notes [Anon., 1996] mention 2 body lengths per second, equating e.g. to 26 $cm.s^{-1}$ for a 13 cm fish). Several, however, indicated that they would be prepared to consider higher values if they were substantiated by appropriate scientific data. Other factors were the proximity and efficiency of the by-wash arrangement, as this would determine how long the fish were likely to remain in the intake current.

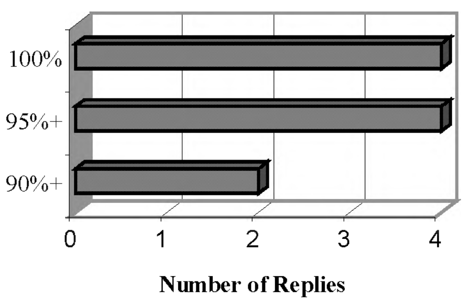
Q: Would the Board accept the use of behavioural screens?



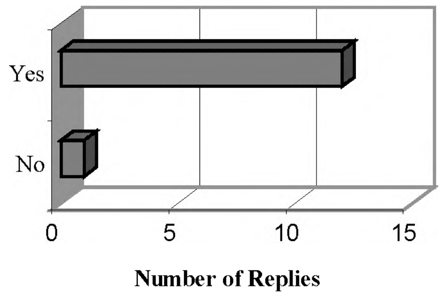
Two Boards said "no". The majority indicated that they would be prepared to consider behavioural screens once they had developed to a stage where they could provide a viable alternative to physical screens in efficiency terms. Three Boards considered that behavioural screens would be acceptable, but would need to be tested once in situ to prove that adequate performance was being achieved.

Q: What percentage of smolts successfully passing a scheme would the Board regard as a minimum?

The breakdown of replies was as follows:



Q: Does the Board consider that further research is required into fish screening, with a view to improving current practice at existing schemes and to the development of more efficient methods and procedures at new schemes?



An overwhelming majority of Boards was in favour of further research, in particular on improvement and proof of effectiveness of behavioural screening methods and of by-wash efficiency.

APPENDIX IV
THE FISHERIES ACT (NI) 1966 (*S*.59)

pliance with paragraph (*a*) or paragraph (*b*) (whichever is applicable) of subsection (1) would have injuriously interfered with the machinery or water power of the mill. PART IV —*cont.*

(4) In this section "mill sluices" means the sluices which admit water to a mill.

Abstraction of water from rivers and lakes

Gratings to be set in watercourses diverted from rivers to prevent entry therein of fish.

59.—(1) Where a watercourse to which this section applies carries water from a [[1]river] [[2]or lake]—

(*a*) there shall be placed, at the points where the watercourse diverges from and returns to the river [[2]or lake], gratings extending across the whole width of the watercourse and from the bottom of the bed or sill thereof to the level of the highest flood waters;

(*b*) the space between the bars of every such grating shall not exceed two inches in any place;

(*c*) during the months of March, April and May and at any other time when the fry of salmon or trout are descending the river [[2]or lake], there shall be placed over the entire surface of every such grating a wire lattice of such dimensions as to effectually prevent the admission of fry or small fish into the watercourse;

(*d*) every such grating and such wire lattice shall be securely fixed in a permanent manner so as to prevent its being removed or opened, and shall be kept in constant repair.

(2) If, in respect of any watercourse to which this section applies (other than a watercourse in relation to which an exemption granted by the Ministry under subsection (4) is for the time being in force), the provisions of subsection (1) are not complied with, the owner or occupier of any premises to which the watercourse leads, or any other person who made, uses or has the care or maintenance of the watercourse, shall be guilty of an offence, and shall be liable on summary conviction to a fine not exceeding one hundred pounds.

(3) Without prejudice to subsection (2), if any person—

(*a*) injures any grating or wire lattice placed in pursuance of subsection (1); or

(*b*) removes any such grating or lattice or part thereof, except, in the case of a lattice, during any period of the year during which such a lattice need not be maintained; or

[[1] Substituted, 1968, c. 31 (N.I.) s. 5 (2).]
[[2] Inserted, 1968, c. 31 (N.I.) s. 5 (5).]

PART IV —*cont.*

(*c*) opens any such grating or lattice improperly; or

(*d*) permits any such grating or lattice to be injured or removed (except as is mentioned in paragraph (*b*)) or improperly opened;

he shall be guilty of an offence.

(4) If in respect of a watercourse to which this section applies—

(*a*) the Ministry is satisfied that sufficient arrangements will be made by means other than those specified in subsection (1) to prevent the admission of fish or fry into the watercourse, and that, having regard to those arrangements, exemption should be granted from the obligations imposed by subsection (1); or

(*b*) where the watercourse is a watercourse constructed for the purpose of conveying water as motive power for machinery, it is proved to the satisfaction of the Ministry that exemption during any period from the obligations imposed by subsection (1) is necessary for the effective working of the machinery,

the Ministry may, by permit in writing, grant such exemption.

(5) Where an exemption has been granted under subsection (4) the Ministry may at any time—

(*a*) revoke the exemption; or

(*b*) vary or revoke any condition for the time being attaching to the exemption; or

(*c*) attach any condition or any further condition to the exemption;

but no exemption shall be revoked nor shall any condition be varied or any condition or further condition imposed unless at least twenty-eight days' notice of the Ministry's intention to make a revocation or, as the case may be, to vary or impose the condition, has been given to the person who appears to the Ministry to be for the time being entitled to the benefit of the exemption, and the Ministry has considered any representations made by him before the expiration of the notice.

(6) This section applies to any watercourse conveying water for the supply of towns, for the irrigation of land, as motive power for machinery, or for any purpose other than the supply of water for navigation . . . .[1]

[1 Repealed, 1968, c. 31 (N.I.) s. 3 (5).]

APPENDIX V

WHAT IS MEANT BY A "SMOLT"? VARIOUS DESCRIPTIONS AND DEFINITIONS

(1) "Juvenile salmon migrating, or ready to migrate, to the sea"
Source: Williamson, Robert (1995) In A Description of the regulations relating to Salmon fishing in Scotland, Appendix B: Brief explanation of some technical words used in the text.
cf. parr, which in above source is explained as "juvenile salmon before they start their migration to sea"

(2) "Fully-silvered juvenile salmon migrating to the sea"
Source: Allan, I R H and Ritter J A J. Cons. Int. Explor. Mer, 37(3): 293-299
In Table 1: Revised terminology list for Atlantic salmon (*Salmo salar* L.)

"Fully-silvered juvenile migratory trout" in
Table 3: Terminology list for migratory trout (sea-trout) (*Salmo trutta* L.)

(3) "A young river salmon when it is bluish along the upper half of the body and silvery along the sides"
Source: Chambers Concise 20th Century dictionary (1985)

(4) "A salmon in its second year when it acquires its silvery scales"
Source: The Concise English Dictionary (1982)

(5) "Fully-silvered juvenile salmon migrating or about to migrate to the sea"
Source: Report of the Scottish Salmon Strategy Task Force (1997), Glossary.

cf. parr, which is described in the above Glossary as:
"Young salmon, at stage from dispersal from redd to migration as a smolt (*q.v.*)"

(6) "Young salmon at the stage it undertakes it's migration to the sea"
Source: Hydroelectric (1996). Hydroelectric development in Scotland and it's effects on fish / Glossary

cf. parr, which is described as:
"Juvenile salmon which spend mainly two or three years in fresh water"

(7) "Fully-silvered juvenile salmon migrating downstream to the sea"
Source: Report of The Salmon Advisory Committee (1988)
Information on the status of salmon stocks / Appendix 3 / Terminology applied to the Atlantic salmon (*Salmo salar* L.)

cf. parr, described as:
"Stage from dispersal from redd to migration as a smolt"

(8) "After a period of growth ranging from one to several years, the parr undergo morphological changes to become smolts. At this stage the fish leave their nursery areas and migrate to sea."

Source: The Salmon Advisory Committee (1991)
Factors affecting natural smolt production / Section 3, Influences of Habitat on Juvenile Salmon, Sub-section 3, Introduction,
Notes on "A brief description of the life history from egg to smolt"

(9) "Before the young fish (parr) migrates to the sea, it takes on a silvery appearance and is known as a *smolt*"

Source: DAFS (1965) Scottish Salmon and Trout Fisheries / Second Report by the Committee Appointed by the Secretary of State for Scotland (sometimes referred to as the Hunter Report) Chapter1, paragraph 8.

cf. fry and parr, which in the same paragraph are described as follows;

"The fry stage is one of very heavy mortality, and only a small percentage survive until the following spring, when they become known as *parr*"

In chapter 1, paragraph 9, of the same source, reference is made to the timing of migration of smolts as follows:

"The smolt migrates to the sea in April, May or June…."

(10) "When the salmon-parr begins to migrate to the sea, usually in March, April and May, they gradually become more silvery in colour and the spots and finger-marks disappear, except the spots on the gill covers, They then become Smolts."

Source: Mills, D. H. and Hadoke, G.D.F. (undated) Atlantic Salmon Facts Identification of Atlantic Salmon: What is the difference between a salmon parr, salmon smolt and a young trout?

Also under Salmon Biology (p.4):

When do they (young Atlantic Salmon) leave the river?

The young fish, now called "smolts", leave the rivers during the late spring. Most will be gone in June.

APPENDIX VI
SUMMARY OF INFORMATION ON FISH SCREENING MEASURES ADOPTED IN OTHER COUNTRIES

France

[Information supplied by M Francois Travade, Électricité de France, Chatou, France].
Legislation in France requires "the free circulation of migratory fish" but does not prescribe precise methods of screening. The local administration can ask the owner to prove the efficiency of upstream and downstream devices assisting fish passage. They can also specify in detail any fish protection measures required at the stage of licensing or relicensing a hydropower plant. All new plant must gain approval for fish passage provisions.
There has been a major programme of fish pass construction on many rivers in France. A large number of fish passes have been constructed in recent years on major rivers such as the Loire and the Dordogne, and on some smaller rivers. This has been a joint effort between industry (mainly Électricité de France) and the government.
Part of this programme has dealt with downstream fish passage issues and research has been carried out into bypass performance and a variety of behavioural screening methods (further information is given in the technical review in Part B).

Republic of Ireland

[Information supplied by Mr Eamon Cusack, Shannon Regional Fisheries Board]

Formal provision for fish screening is made within the Fisheries (Consolidation) Act 1959. Section 123 requires the fitting of gratings to the entry and return points of any watercourse, cut or channel diverted (for whatever purpose) from the main channel of any salmon river. The bars of the gratings must be spaced at no more than two inches (50 mm) and the gratings must extend from the riverbed or cill to the highest floodwater level. During the months of March, April and May, or at any other times when the brood of salmon or trout may be descending, the gratings must be overlaid with a lattice of small enough mesh to prevent the entry of salmon fry or other small fish. The grating or lattice must be kept in good repair and must be secure. Exemptions from these provisions may be granted subject to Ministerial discretion.

Additionally, *s*.124 requires that "*where a turbine or similar hydraulic machine, which may be injurious to salmon in their descent to the sea, is supplied from a salmon river, it shall be the duty of the person owning or operating such a machine to provide, during the time in which such descent to the sea takes place, a grating or other efficient means to prevent the salmon from passing into such a machine*."

There is, apparently, little experience of behavioural screening in the Republic of Ireland.

Holland

[Information supplied by Mr Rolf Hadderingh of KEMA Power Generation, Arnhem, Holland].
No formal screening legislation exists in Holland. For each new hydro scheme or other type of water intake, negotiations take place between the developer and the regional water manager. Abstraction permits are given subject to conditions that require fish protection measures to be fitted. These measures are particularly aimed at protecting

salmon and sea trout, populations of which are being restored in some rivers, and also silver eels. On thermal power stations which withdraw river water for cooling purposes, there is also a requirement to protect other freshwater cyprinid and percid species.
Over 20 years of research into behavioural fish barriers has been undertaken in Holland, including use of electric screens, acoustic barriers and artificial underwater illumination (see technical review in Part B for more details). KEMA have been successful in developing underwater lighting systems for reducing eel entrainment.

Denmark

[Information supplied by Søren Berg, Department of Inland Fisheries, Danish Institute for Fisheries Research, Silkeborg, Denmark].
Denmark does have formal legislation on fish screening and provision of fish bypasses, contained in the "Government Notice on Eelpasses, Downstream Smolt Passages and Fish Screening in Fresh Waters" (Notice No. 657 of 7th July 1994). Some of the key provisions are summarised below.

Downstream Smolt Passage

Section 3

The regional river authorities can require the owner of all obstructions in streams to build a downstream smolt passage, if the obstruction prevents salmonids from migrating and the obstruction is built after 19th July 1898, or if after this date changes have been made to the use or construction of the obstruction.

The owner of the obstruction or weir cannot be required to build the downstream smolt passage if the cost of building the passage exceeds the benefit of building it.

Section 4

A downstream smolt passage is a construction near the water surface at a weir that facilitates downstream passage for young salmonids. The passage is in the form of a tube or similar construction just below the water surface, filled with running water during the months of March, April and May. Minimum water flow is 10 $l.s^{-1}$. The tube must be connected to the stream directly or via a can with a minimum water depth of 20 cm.

Turbines

Section 5

A turbine located at a weir in a stream must be equipped with a grating at the water intake. The grating must be so constructed that all the water flowing to the turbine runs through the grating. Bar spacing must be no more than 10 mm. If possible, the grating should be placed at the beginning of the intake canal. The grating must be placed and constructed in the best possible way to help fish in finding a downstream passage.

All turbine weirs with an upstream fish passage must be equipped with a grating at the outlet or at the end of the outlet canal with a bar spacing of not more than 20 mm, or another construction that prevents fish from swimming into the outlet.

When new gratings are constructed or existing gratings are altered the fisheries inspectorate must approve the construction and location of the grating.

The fisheries inspectorate can in special cases, after consulting the Danish Institute for Fisheries Research, approve bar spacing up to 50 mm on both inlets and outlets.

Fish Farms

Section 6

At a fish farm which is supplied with water from a stream directly or though a canal, there must be placed gratings or similar constructions at all inlets and outlets to facilitate the best possible passage of wild fish past the fish farm. Bar spacing must not be more than 10 mm at the inlets and 30 mm at the outlets.

The fisheries inspectorate must approve new gratings, so that fish passage past the fish farm is secured.

The fisheries inspectorate can set special conditions for another form of fish screening according to local conditions, if other legislation favours another form of fish passage, e.g. as specified in Sections 3 & 4 above.

A few other points that emerged from the questionnaire were:

- The legislation applies to all fresh waters, irrespective of species/ life stages present.
- Abstractions other than for turbines and fish farms are exempted.
- For screens, only metal gratings with vertical flat iron or steel bars (*ca* 5 mm thick and at least 30 mm deep) are approved. Gratings must have horizontal cross bars welded to the back at close intervals (e.g 40-50 cm) to prevent vertical bars from bending when debris accumulates on the grating.
- Iron gratings must be galvanised to prevent fish injury.
- If possible, inlet gratings must be built at an angle of at least 50^{o} to the direction of the water flow in order to guide the fish. The downstream end of the grating must be very close to the bypass facility.
- Screens are required to be in place all year round.
- Behavioural screens can be used, subject to satisfying the inspectorate, although none were being used at the time of reporting.

Denmark has about 100 hydroelectric power stations. The majority of these are very small, privately owned schemes, which supply electricity for one or a few households. When the new legislation took effect in 1995, around 5-10 were closed down to avoid the costs of building new gratings and bypasses. About five more were purchased by government agencies and closed down to allow removal of the weirs and river restoration.

Of 600 trout farms in Denmark, about 25-30 have been bought out and closed by the authorities in order to improve freshwater habitats.

Sweden

Unlike Denmark, Sweden has no formal screening regulations but there is considerable interest in fish passage and screening issues. New developments are required to make provision for upstream and downstream fish passage. Many older hydro plants have no such facilities and power companies are working with government agencies to make improvements.

There is currently a programme under way to improve fish passage on the River Mörrumsån, one of Sweden's best salmon rivers. It has a series of hydroelectric stations, one of which (Upper Hemsjö) hosted the classic studies of fish passage through turbines by Prof. Erik Monten during the 1950's and '60's (Monten, 1985). The experiments are looking at improving bypasses, and modifying hydraulic regimes to assist fish in locating bypasses. Tests of behavioural barriers, including acoustic screens, are being carried out.

Switzerland

[Information supplied by Daniel Hefti, Swiss Agency for the Environment, Forests and Landscape, Bern, Switzerland].

Swiss federal law states that appropriate measures must be taken to ensure that fish are not killed or injured by any kind of installation or plant. The regulations apply to all species and life stages of freshwater fish, and no type of abstraction is exempt from the legislation. No means of achieving fish protection is specified in law, and behavioural screens may be used. Electric screens were identified as being commonly used and successful.

No Swiss research into fish screening was known of by the respondent.

Poland

[Information supplied by Wieslaw Wisniewolski].

There are presently no special regulations to protect fish at water intakes in Poland. It is a legal requirement to equip hydroelectric dams with fish passes and the efficiency of these passes is under observation. There is also a programme of experiments to measure fish mortality rates during passage through turbines. Information has been reported by Bartel *et al.* (1993; 1996).

Japan

[Information supplied by Shunroku Nakamura, Toyohashi University of Technology, Japan].

No formal screening regulations exist in Japan but installations of fish screens have recently begun, both at hydro stations and irrigation schemes. Some 12 species of migratory fish inhabit Japanese waters, including four Pacific salmon (*Oncorhynchus* spp.) species (Nakamura, 1993).

Red coloured trash racks have been commonly used to divert downstream migrants, the concept being that the fish will avoid the red colour. Many other behavioural devices, including electrical screens, air bubble curtains and hanging chains have also been used, but with mixed success, owing to the lack of bypass route being provided in many cases.

USA

[Legislative information from Brown, 1997b].

In the USA, operators of hydropower facilities must obtain a licence to operate from the Federal Energy Regulation Commission (FERC). Section 18 of the FERC licensing procedure requires that the facility has provided a safe environment for fish. The "fish prescription" is negotiated between the operator and various state and federal environmental agencies and the main issue relates to fish passage through turbines.

Brown states that there are 10 million square feet of hydroelectric intake in the USA, consequently fish screening issues are of huge importance.

Every conceivable type of screening solution has been tried somewhere in the USA. The majority of systems still use physical screens but behavioural screens and other solutions such as surface collectors (see e.g. Ferguson *et al.*, 1998) and curtain walls (Odeh and Orvis, 1998) are also used. Increasingly, behavioural systems are being used as an adjunct to other fish diversion methods.

Table A2: A Comparison of Features of the UK's Three Main Instruments of Screening Legislation

	SFFA 1975 *s*.14 (with EA 1995 revisions)	**The Salmon (Fish Passes and Screens) Regulations 1994**	**The Fisheries Act (NI) 1966 *s*.59**
Date of Full Effect	1st January 1999	Current	Current
Main Administering Authorities	Environment Agency	None. (Advice may be obtained from The Scottish Office, Fisheries Committee and District Salmon Fishery Boards)	Department of Agriculture for Northern Ireland, Fish Conservancy Board and Foyle Fisheries Commission
Types of Water Regulated	Salmon and sea trout waters above estuary limits (includes Border Esk)	Salmon and sea trout waters above estuary limits (includes R.Tweed)	All waters above estuary limits
Types of Abstraction Regulated	Public water supply, canal supply, mill and hydropower, fish farm	All but public water supply and exempted, separately-regulated hydropower abstractions and water diversions that return water back to the river without impedance to fish migration	All
Screen Criteria	Any device(s) that exclude(s) salmon and sea trout	Any device(s) that exclude(s) salmon and sea trout smolts	All year round: bar racks of spacing ≤5.1 cm; smolt migration season: a wire lattice small enough to exclude salmon and sea trout fry (≤12 mm square recommended by DANI)
Required Season of Use	All year round, except where otherwise specified in bye-law	All year round, although non-legal agreement may be reached with DSFBs at local level	April to June for smolt screens; period may be extended where migrations are different
Positions of Screens	At the entrance to the offtake or within it	At the entrance to the offtake or within it	At the entrance to the offtake
By-wash Required	Yes	Yes	Not specified
Exemptions	As specified in the Act; others at the discretion of the regulatory authority, subject to findings of Risk Assessment	As specified in the Regulations only.	At the discretion of the regulatory authority, subject to satisfaction that requirements of the Act are being met.

PART B:

REVIEW OF FISH SCREENING TECHNOLOGY AND GUIDE TO BEST PRACTICE

B1. INTRODUCTION

The review presented in Part B is intended to provide designers of water intakes for hydro schemes and other developments with a working knowledge of the design parameters for fish protection screening and of the currently available methods. While conventional passive physical screening systems represent a mature technology, self-cleaning mechanical and behavioural screening are under continual development. The key drivers are the perceived high costs associated with hydraulic losses and maintenance of simple physical screens, against the relatively lower screening efficiencies that can be achieved with present-generation behavioural fish barriers. It is important for designers to keep abreast of new developments in screening and bypass technologies, together with any results from scientific trials of new techniques.

As will be evident from Part A of this report, the theme inherent in the most recent UK screening legislation is not that it should conform to particular design criteria, but that it should be effective. Therefore, no specific design criteria can be given that will comply in all cases with the law. The legislation is designed to encourage a flexibility of approach that will enable effective measures to be provided under very widely differing circumstances of intake design, hydraulic conditions and within other engineering and environmental constraints. The intent of this guide is to summarise the main aspects of screen design, including important aspects such as approach velocity and fish swimming speed considerations, bypass design and selection of an appropriate screening method. While not all these aspects are mentioned in the various instruments of legislation, all are equally important in achieving compliance.

More details on particular aspects of fish screening can be obtained from the references cited within the text or in the reference list.

B2. FISH SCREENING: THE BASIC MODEL

Riverine fish occupy a flow regime that naturally favours downstream movement. During much of the life-cycle, mechanisms operate that prevent fish being washed out by the flow, for example living among marginal vegetation or in riverbed microhabitats. At certain stages, however, functional downstream migrations occur, for example the seaward movements of migratory species, including salmonid smolts (spring/autumn), juvenile shads (summer) and silver eels (year- round), and the dispersal phase of coarse fish fry (summer). Entry of fish into water intakes may be an inadvertent result of concerted downstream migration, or simply a chance event.

The prevention of fish entry into an intake will be referred to as 'fish screening', whatever the techniques used to achieve it. Successful fish screening requires the following three conditions to be met:

(i) there must be some structure or stimulus that the fish can use to detect its approach to the intake and allow it to orientate;

(ii) the water velocity against which the fish must swim to escape (known as the 'escape velocity' must be within its swimming performance capability;

(iii) a suitable escape route or bypass must be provided.

The following three sections describe these requirements in more detail. Certain kinds of screen where these parameters are less important will be discussed. These include spillway screens, drum screens (e.g. the Econoscreen™) and passive pressure screens.

B3. ESCAPE VELOCITIES

B3.1 Swimming Speeds of Fish

B3.1.1 Relevant Measures of Fish Swimming Speed

Fish have two main types of muscle fibre, known as 'red' and 'white' fibres, which function aerobically and anaerobically, respectively. Red muscle receives a steady supply of oxygenated blood from the gills and is used in continuous swimming. White muscle is less dependent on the rate of oxygen supply and can generate short bursts of high power (Beamish, 1978). The swimming speeds attained by freshwater fish, and the lengths of time for which they can be held, depend upon the type of musculature deployed. Beamish (1978) recognised three categories of speed, according to endurance criteria:

- **burst speed** (mainly using white muscle: can be maintained for ≤ 20 s);
- **prolonged speed** (using a combinations of red and white muscle: can be maintained for 20 s to 200 min);
- **sustained speed** (mainly using red muscle: can be maintained for > 200 min).

Burst speeds are not used in routine swimming activity by fish, as the white muscle fibres rapidly become exhausted. Once exhausted, it may take the fish up to 24 h to recover, during which interval their burst swimming capability is compromised. Typically, therefore, burst speeds are used only when the fish are strongly motivated, e.g. for darting at prey and to escape from danger and, in migratory fish, for ascending falls and rapids. When not provided with a suitable escape route, fish will often be drawn into an intake, even though the intake approach velocity may be well below their burst speed potential; only when the water velocity is in the prolonged to sustained swimming speed range of the fish do they move out of danger (Turnpenny, 1988a,b; Solomon, 1992). Consequently, the sustained swimming speed is, in most cases, the safest measure for setting the approach velocity. By the above definition, provided that the velocity is below the maximum sustainable swimming speed, a fish should be able to swim ahead of the screen for several hours. Designs based on prolonged swimming capability may be acceptable in situations where fish are demonstrably capable of finding the bypass route quickly.

There are a few situations where burst speeds may be used to escape entrainment, for example where scaring stimuli are used to deter fish. In such cases, escape may be successful, provided that the escape path is short enough to avoid the fish becoming exhausted. However, given that fish might be already partially spent when they encounter the deterrent system (e.g. following a predator encounter), it is not recommended that burst performance should be used as a basis for intake design.

B3.1.2 Effect of Fish Size

The main factor affecting fish swimming performance within a species is length. Although swimming speeds are often quoted in terms of fish body lengths per second ($bl.s^{-1}$), the number of lengths per second attainable tends to decline with increasing fish length. Wardle (1975), for example, showed that the potential maximum speed achievable by most fish reduces from around 22 $bl.s^{-1}$ for a 10 cm fish, to 9 $bl.s^{-1}$ for a 50 cm fish (temperature 14^{o}C).

B3.1.3 Effect of Water Temperature

Water temperature also has a strong effect on fish swimming performance. At temperatures close to zero, muscle activity is inhibited and fish may become torpid. At higher temperatures, performance is increased, but in warm summer temperatures, muscle activity of cold-water species such as salmon and trout may be inhibited, causing performance to decline. It is important to design intake approach velocities that take account of seasonal temperatures at times when fish will be present or migrating past, for example, springtime temperatures for smolts, and summer temperatures for cyprinid fry or juvenile shad. Where resident fish are involved, the worst case must be assumed (i.e. lowest winter temperature).

B3.1.4 Effects of Other Water Quality Characteristics

Low dissolved oxygen levels in the water may limit swimming performance. In Atlantic salmon, this occurs at values <5 $mg.l^{-1}$, but much lower levels (<2 $mg.l^{-1}$) are necessary to affect cyprinids (Beamish, 1978). In waters that are frequently or persistently subject to oxygen sag, either through pollution or owing to natural causes (e.g. sediment suspension in estuaries), the approach velocity would need to be accordingly reduced.

Similarly, other types of pollutant can inhibit metabolic processes and impair swimming. Where water quality is suspect, e.g. on a heavily industrialised or urbanised river or estuary, the assumed performance of the fish may need to be downrated. Ideally, swimming performance trials should be conducted to measure performance under those specific conditions but otherwise a generous (i.e. 50-100%) safety margin should be added.

B3.2 Swimming Speed Data for Common UK Freshwater and Migratory Fish

There have been surprisingly few comprehensive investigations of swimming performance in UK migratory and freshwater species. The Environment Agency (EA) has commissioned a two-year research project under its National R & D Programme (No. W2-026, reporting in December 1999). The project will review available data and make measurements of swimming performance for selected species.

In the meantime, a brief summary of relevant data is given in Table B1. The available data are patchy and should not be considered definitive.

Table B1 Maximum Sustainable Swimming Speeds of Fish

Species	Fork Length/ Stage	Water Temp. °C	Sustained Swimming Speed $bl.s^{-1}$	Reference
Salmon†	Parr, 57 mm	12.5-19	9.8	Peake *et al.*, 1997
	Parr, 100 mm	12.3-20	7.3	Peake & McKinley, 1998
	Parr, 134 mm	12.5-19	6.2	Peake *et al.*, 1997
	Smolt, 152 mm	14-17.5	7.5	"
	Smolt, 120 mm	12.8-18.5	7.1	Peake & McKinley, 1998
	Kelt	7	2.0	Booth *et al.*, in press
Brown trout†	56 mm	5.5	6.7	Peake *et al.*, 1997
	56 mm	12.5	9.3	"
	210 mm	5.5	5.3	"
	210 mm	12.5	6.0	"
Roach	Fry, 15 mm	20±1.5	6.0	Thatcher, 1992
	Adults, <200 mm	?	4.0	Blaxter, 1969
Chub	Fry,15 mm	20±1.5	4.9	Thatcher, 1992
Dace	Fry,15 mm	20±1.5	5.7	Thatcher, 1992
	100-150 mm	?	4.6	Bainbridge, 1961

B3.3 Escape Velocity Criteria

B3.3.1 Salmon and Sea Trout

A number of authorities have proposed allowable velocities at fish screens. Aitken *et al.* (1966), in a review of screening arrangements in Scotland, referred to limits of 75 to 90 $cm.s^{-1}$ for salmon and sea trout kelts, and 30 $cm.s^{-1}$ for descending smolts and parr. A report prepared for the former National Rivers Authority by Solomon (1992) supported the same 30 $cm.s^{-1}$ limit for smolts, based on sustainable performance of 2 body lengths per second ($bl.s^{-1}$) for a 15 cm smolt. The Scottish Office guidance notes (Anon, 1995a) also suggest a 2 $bl.s^{-1}$ criterion. The Salmon Advisory Committee (1995) recommended a velocity of 25 $cm.s^{-1}$, "except in circumstances where fish can quickly and safely move out of the area of influence of the intake". This lower value may well be appropriate in northern areas of the UK where smolt lengths of around 12 cm are more common but is perhaps unecessarily stringent in the south of the UK, where smolts tend to be larger (~15cm).

The allowable velocity has a direct effect upon the required size and hence cost of a screening structure. At hydropower installations, where flows of water tend to be large compared with most other kinds of abstraction, the economic impact of this decision will be high. Consequently, the validity of such criteria (which are not specified in legislation within the UK at present) should be kept under constant review, in the light of any new scientific knowledge that emerges. Recent Canadian studies (Peake *et al.*,1997; Peake and McKinley, 1998) have shown that Atlantic salmon smolts can sustain speeds of more than 7 $bl.s^{-1}$, for > 200 min (Table B1) and confirm that some earlier studies have underestimated performance. This may be explained in terms of a number of factors. For example, one of the studies (Thorpe and Morgan, 1978) on which Solomon (1992) based

† Values have been calculated from equations given in the papers referenced.

his 2 $bl.s^{-1}$ criterion used hatchery-raised smolts and tested the ability to maintain station on the bottom of a water tunnel, not their swimming ability. The more recent measurements reported by Peake and McKinley (1998) used actively migrating smolts and investigated true swimming performance. They show that swimming performance in smolts is not impaired relative to that found in salmon parr.

Regulatory bodies are unlikely to recommend higher allowable velocity values in the short term (see Part A), preferring to take a precautionary stance. In view of this, designers and developers should be cautious in adopting higher values, except in cases where the required time for fish to locate and enter the bypass entrance is likely to be short. The measurement of smolt swimming speeds under conditions of active downstream migration, using UK fish stocks, merits urgent attention so that operators of abstractions are not subjected to excessive screening costs. Such tests should, ideally, encompass a number of geographically different stocks and should measure the within-stock variance. By this means it would be possible to ensure that approach velocity criteria catered for the weaker-swimming individuals within the stock, not just the best 50%, as would be measured by the commonly-used mean or median value.

B3.3.2 Other Freshwater Fish

Solomon (1992) proposed a maximum allowable velocity of 15 $cm.s^{-1}$ as being suitable for the protection of juvenile cyprinids down to 2 cm in length. This value has generally been adopted as a licensing condition where coarse fish fry might otherwise be put at risk. However, it should be recognised that very small fish are at relatively low risk when passing through many types of hydroelectric turbine and their exclusion would normally be required only where a risk assessment indicated the need. The status of juvenile fish within the population dynamics of the affected stock is also a key factor, as mortalities occurring early in the life-cycle may be balanced by density-dependent effects that cause compensatory improvements in the prospects of surviving fish (Van Winkle, 1977). This means that the loss of a given percentage of the downstream fry run is likely to have less effect than would the loss of the same percentage of fish at the smolt stage.

For older fish, the smolt criterion of 2 $bl.s^{-1}$ or 30 cm.s would be regarded as safe for most species; otherwise, suitable values can be derived from sustained swimming performance data. Where this is done, a suitable margin (say 50%) should be added to allow for intra-specific variations in performance.

B3.4 Escape Velocity in Screening Design

The aim, in specifying a design escape velocity[†], is to ensure that a flow field is created from which fish can readily swim away. The first step is to understand the swimming capabilities of the fish, at the times of the year and under the conditions prevailing when they are likely to encounter the intake. In the following sections, advice is given on the design of the intake flow-field.

B3.4.1 Hydraulic Patterns at Intakes

The simplest and commonest method of estimating the approach velocity ($U_{approach}$) is to divide the expected flow (Q) by the wetted cross-sectional area (A) of the screen or intake channel, i.e.:

[†] The 'escape velocity' (also known as the 'approach velocity') is the velocity perpendicular to the screen face, usually measured 30 cm ahead of the screen (Odeh and Orvis, 1998).

Figure B1

Example of an hydraulic model (Aquadyn TM) used for predicting flow at a water intake. The upper plot shows the speed and direction of flow approaching an intake located at the side of a river channel. The lower plot shows the predicted velocity profile across the mouth of the intake, along the dashed line shown in the upper plot.

$U_{approach} = Q/A$ (1).

This assumes that the water velocity across the channel or screen section is uniform, which, unfortunately, is never the case. Where the water is carried in a straight channel, bed and wall friction effects will tend to reduce marginal velocities, hence mid-channel and surface velocities will be higher than average. In curved channels, inertia will cause a bias towards higher velocities on the outside of the bend (Figure B1). Consequently, certain areas of the screen will experience higher velocities.

Locally higher velocities may not be a problem to fish, provided that they can find adjacent lower velocity areas that are within their sustained swimming capabilities. Fish swimming in front of screens tend not to remain in one fixed position but rather to traverse the face of the screen, probing out areas of lower velocity. Escape routes (i.e. bypasses) should be provided from these lower velocity areas where fish are likely to accumulate. This may require bypasses to be placed on both sides of a channel (Figure B2).

Velocity profiles may be determined in a number of ways. On existing schemes where screens are to be retro-fitted, it is possible to make direct measurements using e.g. a standard propeller-type velocity measuring instrument. Readings should be made under the worst-case conditions (i.e. maximum flow) expected during times of fish passage, at horizontal intervals across the channel and at vertical positions in the water column. For new schemes, proprietary flow modelling software (e.g. AquaDyn™) can be used to predict the velocity profile under different flow conditions (see e.g. Figure B1). This type of software can also be applied to existing intakes to examine different flow scenarios. A rough value can be obtained by calulating the average velocity (Q/A) and adding one third.

Where the flow is not evenly distributed across the screen face, it may be economic to insert flow vanes to improve uniformity, rather than reducing peak velocities by increasing the screening area. This solution is particularly useful to distribute flow near to a bend and where the channel width is expanded to enable a larger screening area.

B3.4.2 Reducing the Escape Velocity by Adjusting the Screen Angle

Many older screen installations, and indeed some modern ones, have screens placed across the river, leat or intake channel, at right angles to the flow. This is the worst possible arrangement for fish protection, as the fish have difficulty in locating any bypass channel provided. The ideal intake would be flush with the riverbank, with a substantial sweeping river flow being left to carry fish on downstream. While many water supply offtakes are of the latter type, most low-head hydro schemes use a large proportion of the available river flow (up to 98%) so that there is no effective sweeping flow.

An alternative arrangement is to angle the screen or barrier relative to the flow to create a virtual sweeping effect that can guide fish towards an escape route, even where channel velocities exceed the swimming speeds of fish. This principle is widely used in screening design. From early work on the louvre fish screen, Bates and Visonhaler (1957) proposed that for a screen placed at an angle ϕ relative to oncoming flow ($U_{approach}$) (Figure B3), the minimum escape velocity (U_{escape}) for the fish is given by:

$U_{escape} = U_{approach} (\sin \phi)$ (2).

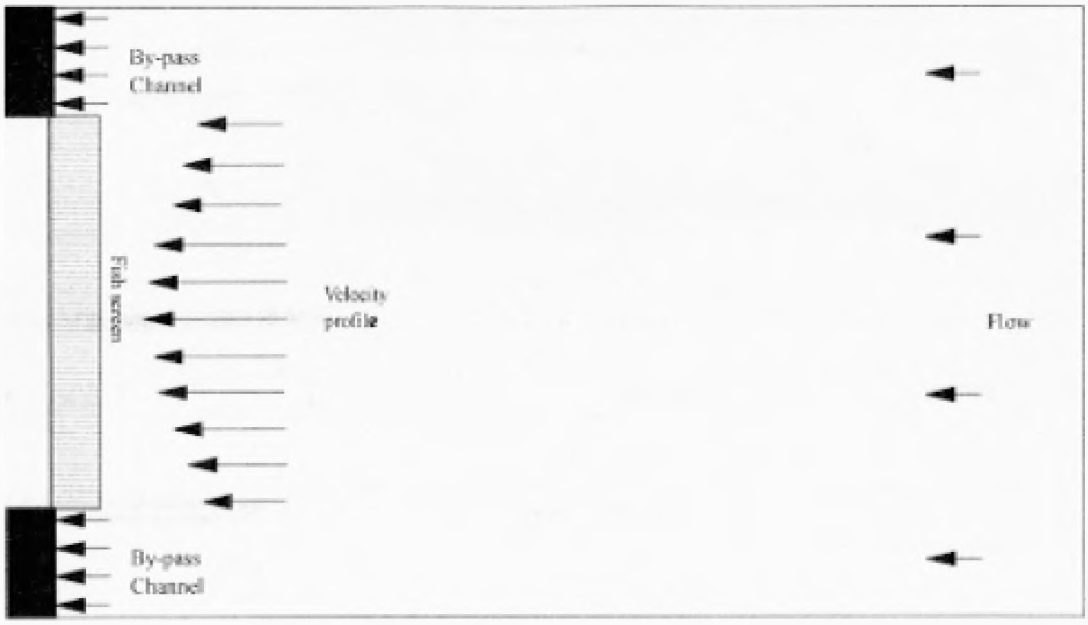


Figure B2 Twin bypass positions for a screen orthogonal to the channel

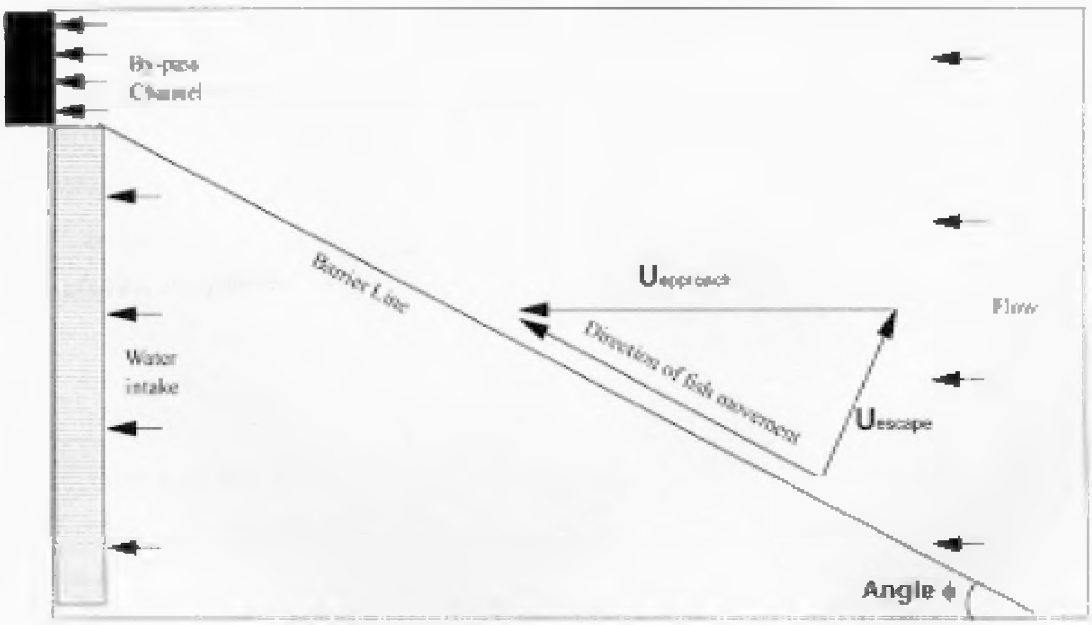


Figure B3 Velocity parameters for an angled fish barrier

Thus, for example, a barrier placed at angle of ϕ=17° across a channel in which the water velocity was 1 $m.s^{-1}$ would reduce the minimum escape velocity to 0.3 $m.s^{-1}$. In this case, the fish would be moved down the line of the screen, towards the bypass, at a rate U_{sweep}, given by:

$U_{sweep} = U_{approach} (\cos \phi)$ (3),

i.e. at 0.96 $m.s^{-1}$. Other values are given in Table B2. The oblique barrier arrangement therefore has the dual advantages of guiding fish towards the bypass and reducing the velocity at which the fish must swim to escape.

In this model, it is assumed that fish will assume the optimum alignment, perpendicular to the screen. This swimming direction allows the fish to maintain its position ahead of the screen while swimming at the lowest possible speed. Pavlov (1989) observed that fish often align themselves ahead of screens at an angle that lies between that of the flow lines and that perpendicular to the screen, implying that they are orientating to a combination of both orientation stimuli. The result would be a higher swimming speed needed to escape and a longer displacement time. However, this situation arises only at relatively low velocities. It should not be taken to be the case at high velocities and the situation described by expressions (2) and (3) should be considered the limiting design case.

Table B2 Values of Velocity Normal to the Screen (U_{escape}) and Sweeping Velocity (U_{sweep}) Relative to an Approach Velocity ($U_{channel}$) of 1.0 for Different Screen Angles to the Flow (see Figure B3).

Screen Angle (ϕ)	U_{escape}	U_{sweep}
10°	0.17	0.98
12°	0.21	0.98
14°	0.24	0.97
16°	0.28	0.96
18°	0.31	0.95
20°	0.34	0.94
22°	0.37	0.93
24°	0.41	0.91
26°	0.44	0.90

B3.5 Swimming Speeds and Escape Velocity: Key Points

- The safe and easy option (although not necessarily the lowest cost option) is to adopt widely accepted standard criteria for fish escape velocity. These are:

  Salmon and sea trout smolts: **2 $bl.s^{-1}$** (30 $cm.s^{-1}$ in England, Wales and N. Ireland; 25 $cm.s^{-1}$ in Scotland).

  Coarse fish fry: **15 $cm.s^{-1}$**

  Coarse fish adults: Use smolt criterion of **2 $bl.s^{-1}$**.

- Otherwise, use sustainable swimming speeds, allowing, say, a one-third safety margin over the measured population average (e.g. for a measured average sustainable speed of 6 $bl.s^{-1}$, set the approach velocity at 4 $bl.s^{-1}$). This may be necessary for other fish species (e.g. brown trout or shad) or life stages or where conditions are unusual (e.g. low dissolved oxygen or high sediment load).
- When applying escape velocities, estimate the maximum screen approach velocities, not the average. Do this by measurement (worst-case flow condition) on existing intakes. Computer hydraulic modelling methods (e.g. Aquadyn™) allow velocity profiles to be predicted and are helpful when designing new screening systems or exploring different flow scenarios on existing ones. Alternatively, calculating the average velocity (Q/A) and adding one third can provide a rough estimate.
- Aligning the screen at an angle to the channel flow can reduce the required escape velocity. A screen aligned at 17^{o} to the flow will, for example reduce the required escape velocity in a 1 $m.s^{-1}$ channel flow to 0.3 $m.s^{-1}$. This arrangement can also be used to guide fish into the bypass channel.

B4. BYPASSES AND OTHER ESCAPE ROUTES

B4.1 Escape Routes

A screen that is placed at the end of a channel with no escape route serves only to trap fish. Although some may find their way out again, many may die through predation or become impinged and injured on the screens. Despite this, many such intakes still exist. Law in all regions of the UK requires the operator of an abstraction on a migratory fish river to provide suitable escape routes adjacent to any screening system so that fish may continue unhindered on their migrations (see Section A). This normally takes the form of a bypass channel (also known as a ‘by-wash’).

The placement of a screen flush at the entrance to a channel avoids the need for a bypass, but a sweeping flow is then required to carry fish downstream. Certain other kinds of screening system mentioned later on require no dedicated bypass structure as such, but *all* kinds require a surplus flow to convey fish downstream

It cannot be over-stressed that where a dedicated bypass structure is used, it is an integral part of the screening system. Often, too little attention is paid to bypass design. Even the best of screens is of no use without an efficient bypass. A good bypass requires thoughtful design and, above all, verification of performance. Only with detailed observation can flaws in the design be identified and overcome

B4.2 Location of Bypass Inlets

The entrance to a bypass 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 B3). 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 bypass 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, say, 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..

Other factors relevant to bypass placement on hydro schemes are the proximity to areas of turbulence and plunging water flows in the headrace, which may make the entrance difficult for fish to detect, and the presence of high levels of underwater noise close to the turbo-machinery. Rotation of the turbine(s) and associated vibrations may give rise to levels of noise within the hearing frequency range of fish that can cause repulsion (Anon., 1996a). Where a bypass is to be positioned close to a turbine inlet, it would be wise to check underwater noise levels before choosing the final position.

B4.3 Design of Bypass Inlets

Most work on bypass design and performance has been carried out on smolts. It is not known how relevant all the following aspects are to other fish, although following the same approach would seem a good place to start.

B4.3.1 Hydraulics

The hydraulic conditions at a bypass entrance are critical to bypass efficiency. Rapid changes of velocity and turbulence may cause fish to avoid entering the bypass (Ruggles and Ryan, 1964; Rainey, 1985; Travade and Larinier, 1992). Transitions should therefore be hydraulically efficient, using, for example, a bellmouth entrance design. Haro *et al.* (1998) compared a bellmouth entrance (Figure B4) with a simple sharp crested weir design. The water in the bellmouth was accelerated smoothly to a maximum value of 3 $m.s^{-1}$ at a rate of 1 $m.s^{-1}$ per metre length. Within the first 30 min after release, signifcantly more Atlantic salmon smolts passed through the bellmouth design than the sharp-crested version. Rapid passage of the bypass 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 effectiveness of a bypass is strongly influenced by the amount of flow used. The larger the flow, generally the more likely the fish are to enter it. The US Fish and Wildlife Service call for a minimum bypass 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 bypass entrance ($U_{entrance}$) and in the main channel ($U_{approach}$) are critical. For louvre screen designs, the ratio $U_{entrance}:U_{approach}$ 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 bypass 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.

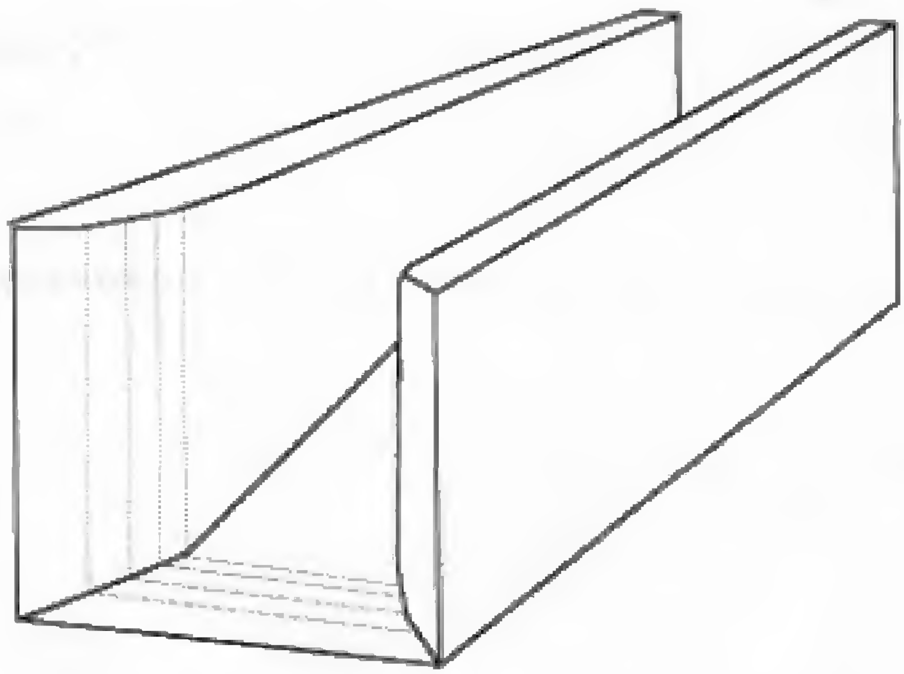


Figure B4

Basic bellmouth entrance design for a bypass channel

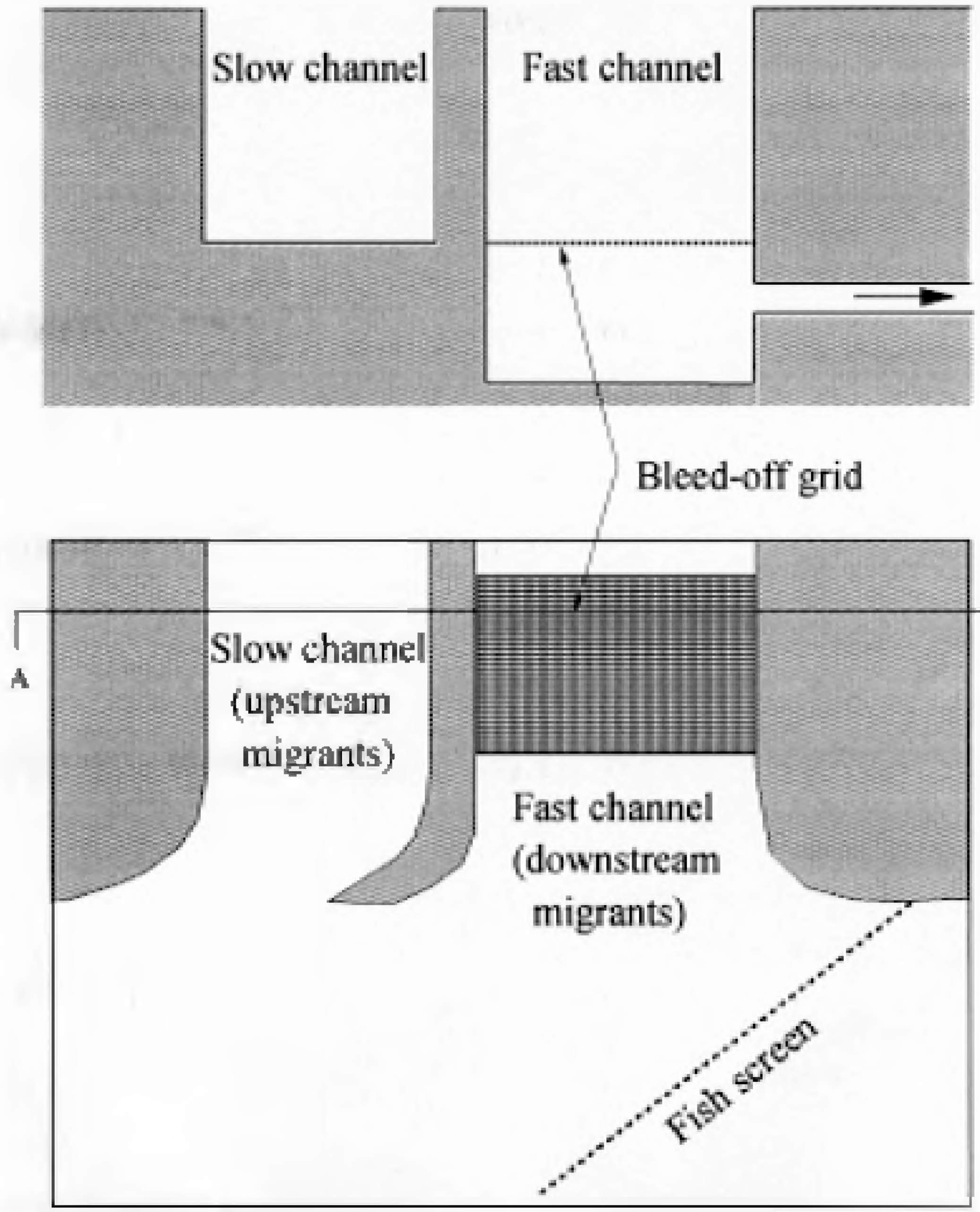


Figure B5

Illustration of a two-speed fishway entrance to handle upstream and downstream migrants. Upper diagram is Section A-A from plan view shown below.

In some cases it is required to use a fishway designed for adult upstream passage as a downstream bypass. The provision of a high-speed zone (1.5-3 $m.s^{-1}$) just downstream of the upper entrance could create a barrier for upstream migrants of weaker-swimming species. This difficulty can be overcome by providing parrallel low and high-speed sections at the upper end of the fishway (Figure B5). The high-speed channel is located to suit downstream migrants and *vice versa*. A grid, e.g. of wedge-wire material, is placed in the floor of the high-speed section to bleed off a portion of the flow, so that the water entering the main fishway is not excessive (Goosney, 1997).

B4.3.2 Sizing

Rainey (1985) reported finding bypass 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.

B4.3.2 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 bypass, 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.

B4.4 Bypass Conduits and Outfalls

Fish handling within the bypass 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 bypass 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.

B4.5 Assessment of Bypass Efficiency

Bypass efficiency may be defined in terms of the proportion of fish approaching the screen that leave via the bypass. A second important parameter, however, is the average time delay between fish reaching the bypass entrance and passing through. In some cases, fish have been observed to make many approaches over a period of hours, before either successfully negotiating the bypass, becoming impinged on the screen or disappearing back upstream. Both aspects should be assessed.

There is no substitute for direct observation of the fish's behaviour at a bypass entrance, visual or using, for example, an imaging sonar system. Other methods of fish tracking, e.g. using float tags, radio tags, sonic tags and PIT[1] tags (see e.g. Anon, 1996a) can yield useful data on passage routes and rates. They may not give detailed information about reactions to fine-scale hydraulic and constructional anomolies, whose modification might lead to enhanced fish passage.

B4.6 Bypasses and Escape Routes: Key Points

- Bypass entrances should be located close to the downstream end of a barrier or screen, preferably within 1-2 m.
- The greater the bypass flow, the better the efficiency. For hydropower installations, at least 2% of the rated turbine flow should be used in the bypass.
- The entrance velocity should be equal to or greater than the main channel velocity.
- The bypass entrance should be at least 30-60 cm wide, and extend preferably to the full channel depth, or as deep as is feasible.

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[1] Passive Integrated Transponder tags

- The entrance profile should use a hydraulically-effficient, flared 'bellmouth' shape. The water should be accelerated smoothly to around 1.5-3 $m.s^{-1}$; an acceleration rate of ~1 $m.s^{-1}$ per metre length has been shown to be effective.
- The entrance should blend visually, from the fish's aspect, with its surroundings to eliminate visible discontinuities. It may be useful to inspect this with an underwater TV camera, or diver.
- The bypass return chute should be smooth and free of sharp bends; it should discharge fish into sufficient depth of water to avoid mechanical shock.
- The performance of a bypass should be checked to ensure its efficiency. A poor bypass will cause delay and may put fish at risk of impingement (on physical screens) or entrainment (past behavioural screens).

B5. FISH SCREENS AND BARRIERS

B5.1 Types of Screen and Barrier

So far as the UK regulations are concerned, fish screens may take the form either of a mechanical screen or grill, or of a behavioural barrier, so long as it prevents the entry of fish. The essence of a behavioural barrier is that it presents an aversive stimulus which acts as a deterrent to fish entry.

Both categories of fish screen can take many different forms and these are briefly reviewed below. Along with a description of each are given details of the types of applications and environmental conditions in which they have been found to work best. These are intended to aid readers in the selection of an appropriate screening method for their particular application. Some methods may work outside the range of parameters given but expert advice should be sought.

Not all the methods described are likely to be suitable for hydroelectric applications in the UK. Some are too costly, especially for NFFO/SRO-level applications; others are suited more to small-flow applications, such as water supply intakes, but these may have application to high-head schemes. A wide range of techniques is shown for completeness.

Summary tables are provided below the descriptions for the majority of screening technologies. These summarise typical applications for which they are suitable and the range of flow conditions at which they work best. In many cases, they could be used to cover larger or smaller flows than indicated, but another method might be more practical or economic. Capital and maintenance (including running) costs shown are intended to be indicative only. These are shown as cost per cumec to allow comparison. For screens which are largely maintenance-free, a small cost has been shown to reflect time for e.g. a monthly inspection visit. For screens where the approach velocity is important, value of of 0.3 $m.s^{-1}$ has been assumed. However, costs for a given scheme may vary substantially from those shown, owing to the installation methods required for different locations, variations in water conditions, and so on.

B5.2 Mechanical Screens

B5.2.1 Static Screens

Passive Flat Panel Screens

Static screens 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 (Figure B6) (Aitken *et al*., 1966). One or more such panels are inserted into vertical slots in a fixed supporting structure, which has an overhead walkway and lifting gear to enable 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. Suitable systems can be designed for any size and most configurations of intake. In a good design, the screen should be aligned flush with the riverbank, or else at an angle to the flow to assist in guiding fish towards a bypass (see Section B2.3) positioned at the downstream end of the screen (Figure B3). The angle (ϕ) 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. The size of individual panels used is determined by the overall screening area and by practical considerations of handling.

The mesh can be made from one of a number of materials but mild or stainless steel are the most common. Scottish HydroElectric has tried a number of materials and now uses stainless-steel, as the ease of cleaning and extended life-expectancy outweigh the initially higher capital costs. Weldmesh is their preferred form of screening material, being easier to clean and cheaper to produce than e.g. a woven mesh. Plastic meshes, used at some continental power stations for cooling water screening, are probably not sufficiently robust and are not normally used for this type of application. Low cost and weight are an advantage, but lifespan is likely to be reduced, especially where a high degree of fouling occurs. The amount of debris reaching the fish screen may be lessened by placing a coarser trash rack in front of it, without affecting smolt passage. In this case a bypass 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).

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 given shape and size:

$M = L/(0.0209L + 0.656 + 1.2F)$,

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 Figure B7, 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 B8 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 used and is generally accepted by the District Salmon Fishery Boards (see

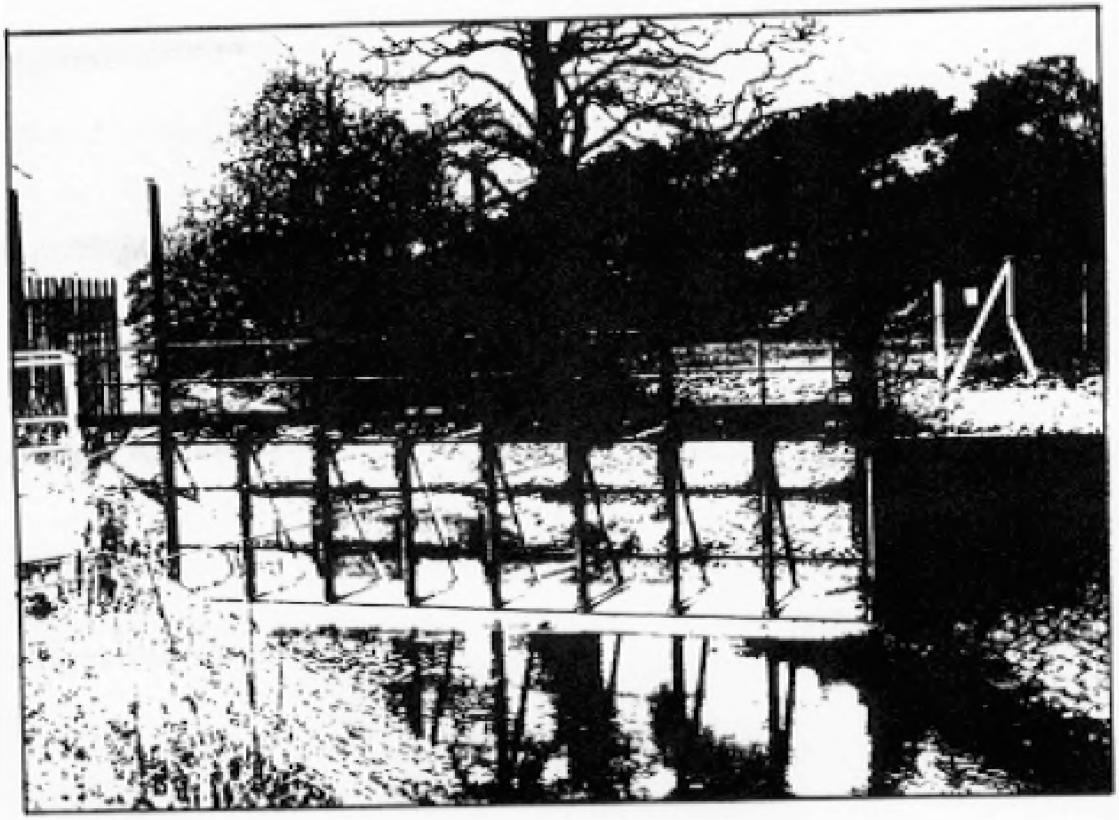


Figure B6
Angled flat-panel smolt screen in a headrace canal.

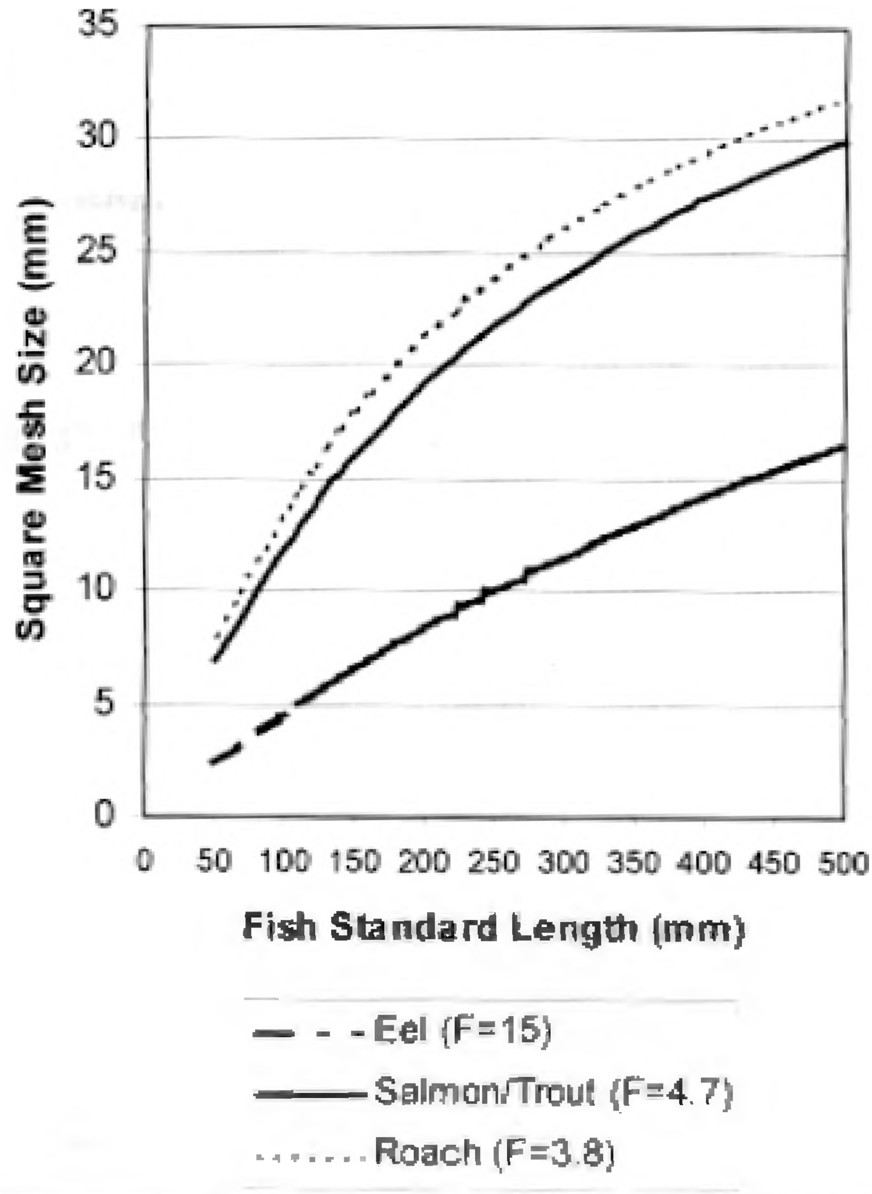


Figure B7
Square mesh apertures required for excluding fish of different species and sizes.

Part A). Appropriate sizes for other species and life stages can be estimated from the formula or curves given above.

FLAT PANEL SCREENS	
Recommended uses	Versatile screens used in almost any situation that allows panels to be removed for cleaning.
Range of flows	All.
Capital cost per cumec	£3k-£4k
Maintenance cost per cumec	£0.5k per annum
Maintenance requirements	Daily or more frequent manual cleaning.
Optimum diversion efficiency	Near 100% if kept clean and panels are seated; high efficiency subject to good bypass attraction.
Causes of losses of efficiency	Blockage, poor fit, worn seals, overtopping.
Problems in use	Some debris materials can be difficult to remove.
Benefits	Low technology, high efficiency
Reported Examples	See e.g. Aitken *et al.*, 1966

Passive Wedge Wire Cylinder Screens

The wedge-wire cylinder screen (Turnpenny, 1989; Solomon, 1992) offers a low-maintenance passive screening system suitable for small abstractions, e.g. on high-head hydro schemes. This type of screen is manufactured from V-profile stainless steel wire, wound in a helix around a cylindrical former. The thickness of the wire and the pitch of the helix can be selected to give the required gap between adjacent strands. The apex of the V-profile points towards the inside of the cylinder so that any particles either bounce off the outside of the screen or pass through without jamming. A slot width of ~3 mm is normally used, and is therefore capable of keeping out fish of almost any size. A compressed air outlet inside the screen allows debris collected on the surface to be backflushed periodically.

Wedge-wire cylinder screens are very effective from the fish protection aspect and are considered by many to be ‘best available technology’. They are suitable, for example, in inter-catchment transfers, where fish down to egg and larval sizes need to be excluded. Unfortunately they tend to be impractical or uneconomic at abstraction flows of more than a few cumecs (Turnpenny, 1989). Of around 40 presently installed in the UK, the majority are rated at well below 1 cumec. They are also prone to clogging unless there is sufficient residual cross-flow (i.e. downstream velocity in riverine applications) to carry away backflushed weed and debris. Problems may be experienced where the screens are not adequately immersed for backflushing to be effective over the whole screen area; the top of the screens needs to be immersed by a depth of at least one diameter.

PASSIVE WEDGE WIRE CYLINDER SCREENS	
Recommended uses	Potable and industrial water supply, cross-catchment transfer; possibly high-head hydro.
Range of flows	< 5 cumec but multiples can be used.
Capital cost per cumec	From £26k
Maintenance cost per cumec	£0.5 k per annum
Maintenance requirements	Self-cleaning by means of air backflush. Need occasional scrub.
Optimum diversion efficiency	100%
Causes of losses of efficiency	Inadequate crossflow to carry away debris; insufficient immersion depth.
Problems in use	None with careful design
Benefits	Self-cleaning; exclude egg or larval size with small slot size (e.g. ≤3 mm).
Reported Examples	Common in the UK on public and industrial water supply offtakes (Solomon, 1992)

The Eicher Passive Pressure Screen

The Eicher screen is designed to fit directly into the intake penstock of a turbine and comprises a flat wedge-wire panel placed obliquely across the flow (Figure B8). Fish are guided up the slope of the screen into a pressurised bypass pipe which diverts them to the downstream side of the dam. Wert *et al.* (1987) described laboratory testing of the device in which the screen was angled at 10.5^o to the flow and the main conduit velocity was 1.5-3.0 $m.s^{-1}$. Bypass velocity was 1.2 times the main conduit velocity. Tests with juvenile Pacific salmon showed no significant loss of scales following passage, nor delayed mortality within 72 hours.

Cramer (1997) described the testing of an Eicher screen that was retrofitted at the TW Sullivan hydro plant in Oregon, USA. Over half a million Pacific salmon (*Oncorhynchus* spp.) were examined for scale loss and injury between 1991 and 1995. The average injury and descaling rates were 0.44% and 1.81% respectively. At this installation, the screen is pivoted such that it can be flipped into a reverse-flushing position for cleaning. This operation takes 19 minutes and may be repeated several times per day. Fish pass through the turbine during this process, hence protection is not complete. Average overall fish bypass rates were estimated to be from 82% to 92%, depending on species. No precise cost information was given, but the capital cost for one turbine was of the order of millions of US dollars.

Another example was reported by Matthews and Taylor (1994) at Puntledge Dam, British Columbia (Canada), which has a 24 MWe powerhouse (flow 27.5 $m^3.s^{-1}$). Previously, turbine-caused mortality accounted for >60% of the juvenile anadromous fish run. The Eicher screen is fitted into the penstock. Cleaning is achieved by rotating the screen on a trunion that runs horizontally along the mid-line of the screen allowing it o be back-washed. A first year of testing indicated that fish mortality was reduced to about 1%. Some "teething" problems were reported with screen cleaning. When operated at partial load, debris collected in the forebay; this hit the screen in one slug when the plant was

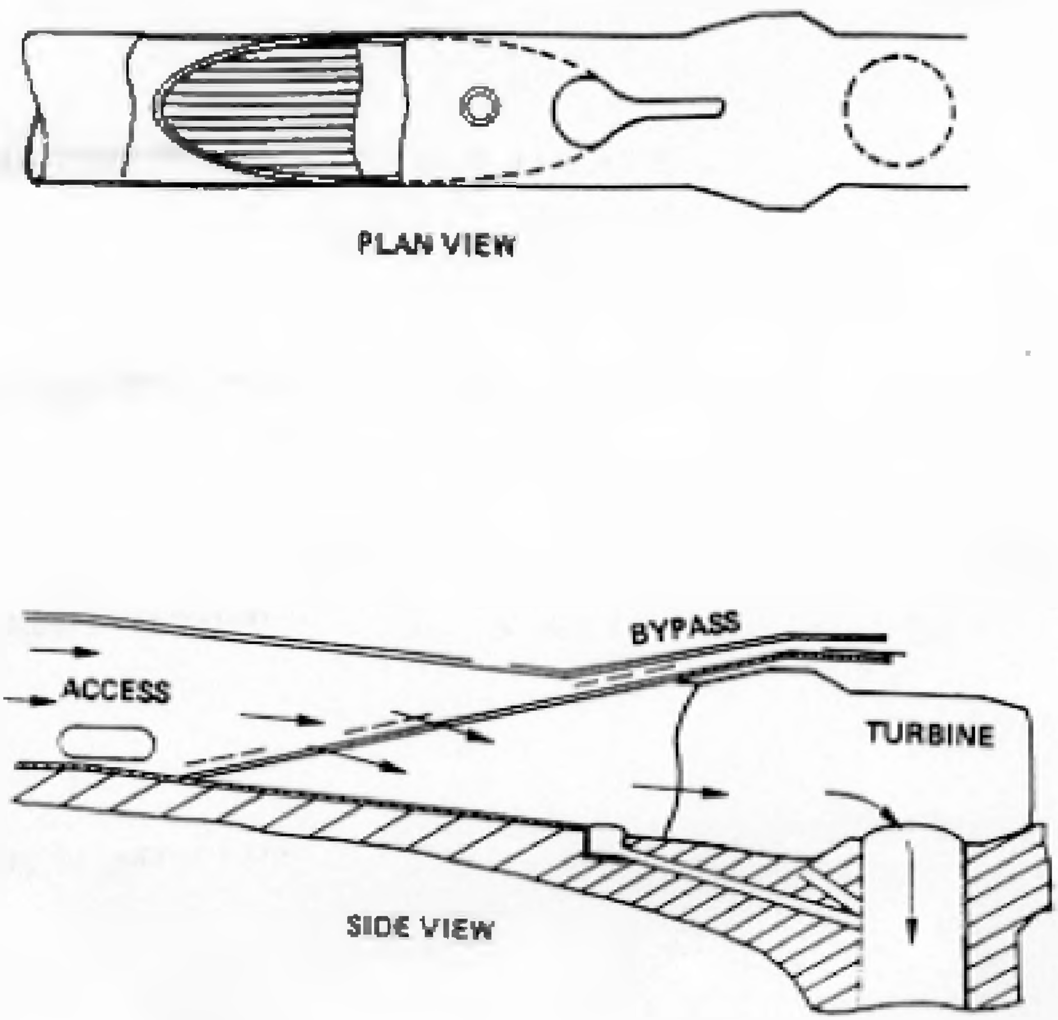


Figure B8

The Eicher passive pressure fish bypass screen, shown as it might be applied to a hydro-electric turbine inlet.

The same principle should be applicable to screening any type of conduit (after Wert, Casey and Nece, 1987).

brought up to full load. A second problem arose from accumulation of black fly (simulid) larve and pupae on the screens, necessitating perioding pressure-washing. The total cost of the project, including evaluation was US$4,750,000.

The Eicher screen is also available in a rectangular form for use in headrace canals. Here, the screen is tilted in see-saw fashion to effect backwashing. Again, fish protection may be lost during the backwash cycle.

THE EICHER PASSIVE PRESSURE SCREEN	
Recommended uses	Fish screening in hydro channels and penstocks. Likely to be far too costly for small hydropower plant.
Range of flows	All
Capital cost per cumec	£100k
Maintenance cost per cumec	£2k per annum?
Maintenance requirements	Self-cleaning arrangement by tilting screen to reverse-flush.
Optimum diversion efficiency	~90%
Causes of losses of efficiency	Fish leakage around screen and loss of screen function during cleaning cycle.
Problems in use	Debris accumulation at low discharges; biofouling.
Benefits	Self-cleaning; low fish injury rates
Reported Examples	TW Sullivan hydro plant in Oregon, USA (Cramer, 1997); Puntledge Dam, BC, Canada (Matthews & Taylor, 1994)

Under-Gravel Intakes

These are sometimes known as *porous dyke* intakes. The principle is that water is drawn through lengths of perforated pipe which are buried beneath beds of gravel, or from collection pits overlaid by metal (often wedge-wire) grids which support the gravel. Solomon (1992) gives design details. From figures given by Solomon for the Ibsley intake on the Hampshire Avon (Wessex Water Services), a filtration area of 40 m^2 of gravel is required for every cumec (1 m^3s^{-1}) of water abstracted. Periodic cleaning of the gravel, which becomes progressively blocked by sediment, is achieved by reverse-flushing.

This method is suited to clear, fast-flowing waters only. Given the required filtration area, undergravel intakes are unsuited to most hydropower applications but a low-cost version might suit small, high-head schemes. Clogging e.g. with leaves might be a problem.

UNDER-GRAVEL INTAKES	
Recommended uses	Water supply intakes from gravel bed rivers. Possibly suitable for high-head hydro.
Range of flows	<1 cumec
Capital cost per cumec	£160k
Maintenance cost per cumec	(Not applicable)
Maintenance requirements	Reverse pumping to backflushing silt.
Optimum diversion efficiency	100% assumed
Causes of losses of efficiency	Gravel washout?
Problems in use	Siltation risk.
Benefits	Good aesthetics; environmentally compatible.
Reported Examples	Ibsley potable intake, Hampshire Avon, Wessex Water (Solomon, 1992)

Raked Bar Screens

These are vertical or inclined bar screens with moveable tines or raking systems. Back- and front-raked systems are available, but the former necessarily lack horizontal braces and are not recommended for closely-spaced bars. An option that can be considered for the exclusion of smolt-sized fish is to use fine spaced front-raked bar-screens across the face of the intake. These are custom-made e.g. by Brackett Group Ltd, with bar spacings as small as 12 mm, and 2 m is a typical unit width. The Brackett Geiger Climber Screens™ have no permanently submerged moving parts (as with back-raked screens) and the electrical driving machinery is well above water level. The rake is carried well clear of the screen on its down-travel (avoiding the trash compression problems of some rakes) and pulls trash up and over the top of the screen into a skip or onto a conveyor. A travelling rake mechanism that is shared amongst several screens is not recommended by the manufacturers for screens with bar spacings as small as 12 mm, as the required frequency of cleaning may not be achieved. This makes it an expensive option.

RAKED BAR SCREENS	
Recommended uses	Use as a self-cleaning replacement for flat panel screens, but too costly to be considered for hydro applications.
Range of flows	All.
Capital cost per cumec	£25k
Maintenance cost per cumec	£0.3k
Maintenance requirements	Self cleaning; occasional servicing.
Optimum diversion efficiency	Up to 100%
Causes of losses of efficiency	None known.
Problems in use	None known but bar spacings <38 mm unusual
Benefits	Eliminates manpower.

Reported Examples	None known with bar-spacing ≤12 mm; screens with larger spacings (e.g. 38 mm) are common as hydro and water intake trash racks throughout the UK.

Spillway Screens

This type of screen has been used in the USA for more than a decade but only recently have examples emerged in the UK. 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, whence 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.

Coanda-Effect Screens

The best-known example of this approach is the patented Coanda-effect screen, named after Henri-Marie Coanda who discovered the effect, which describes the tendency of fluids to follow a surface. Brown (1997a) described their application to small hydro intakes, and it is from this paper that the following information is taken. A wedge-wire screen is installed along the ogee-shaped spillway as shown in Figure B9. A curved 'acceleration plate' at the top of the weir stabilises and accelerates the flow. As the flow passes over the screen, the shearing action of the bars, combined with the Coanda effect, deflects a proportion of the water through the screen. The separation of the wedge-wire bars is 1 mm or less, so that all fish, including young fry, are carried over. As well as other debris, the screen also excludes silts, sand and gravel, depending on the bar spacing used. Where siltation is an issue, Brown suggests that this may reduce costs of sediment trapping arrangements.

There are certain design limitations of the Coanda-effect screen. Brown quotes a capacity of 0.14 cumecs per metre width of weir crest but points out that any limitation imposed by river width can be overcome by positioning the screens on a side-channel weir. Head loss is also a constraint, the screen normally requiring at least 1.2 m operating head, although a recent example used a head differential as low as 0.75 m (A. Brown, Dulas Ltd, Pers. comm.). Brown gives an application chart, from which the minimum viable operating head for a 100 kWe scheme is around 25 m. This would make Coanda-effect screens generally unsuitable for low head, run-of-river schemes.

The performance of Coanda-effect screens appears to be good in all respects. Monitoring of an installation in Wales over an 8-month period verified the screen capacity, self-cleaning performance (including leaves) and resistance to icing. In the USA, the level of fish protection has been shown to be good, except under low flow conditions when there is a risk of fish not being flushed off the screen. This possibility can be reduced by restricting flow to a narrower portion of flow in dry weather.

Brown puts the cost of Coanda-effect screens at US$24,000 (~£15,000) per cumec, making this an expensive option other than on high-head schemes.

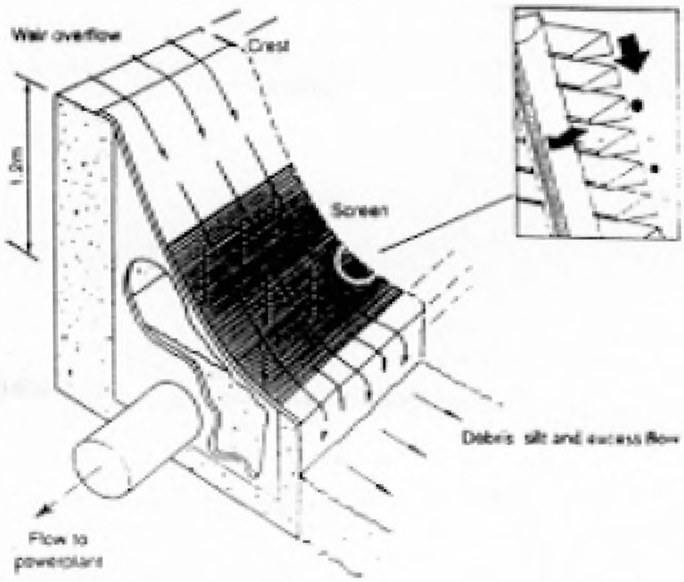


Figure B9

Coanda effect screen mounted in the downstream face of a weir with penstock leading directly from collection chamber (from Brown, 1997).

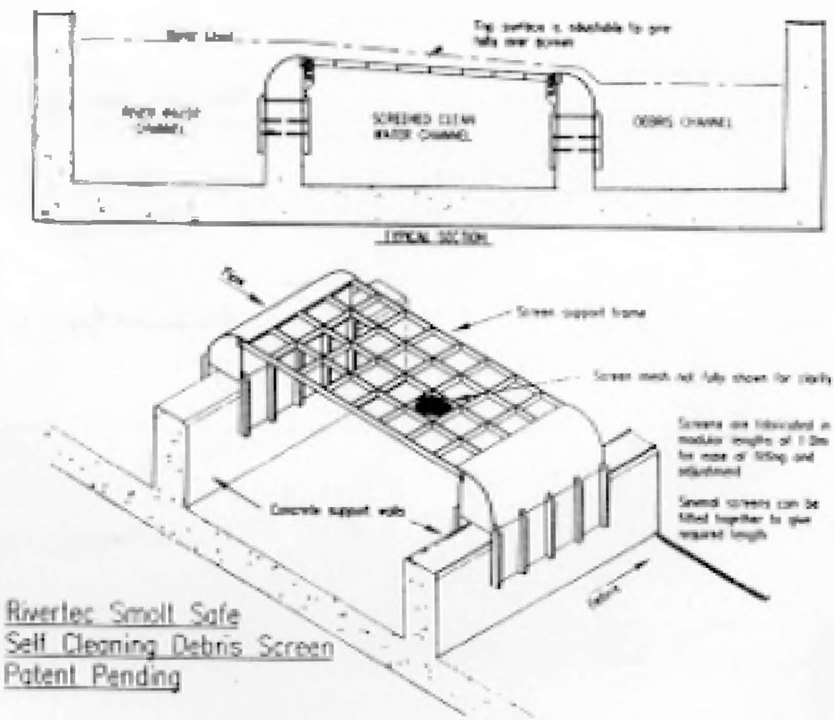


Figure B10

The "smolt-safe" screen

COANDA-EFFECT SCREENS	
Recommended uses	High-head hydro and other uses that can afford to lose ~0.75-1.2 m head at the screen. Minimum viable head for a 100 kWe hydro is 25 m.
Range of flows	0.14 cumecs per m width of weir
Capital cost per cumec	£15k
Maintenance cost per cumec	£0.25k per annum; additional risk of storm damage.
Maintenance requirements	Exposed area of screen may need adjusting in low flows.
Optimum diversion efficiency	Up to 100%
Causes of losses of efficiency	When there is insufficient flow to fully wet the open screen area.
Problems in use	None known.
Benefits	Self-cleaning, low maintenance, low risk to fish, low silt ingress, no moving parts, no power required.
Reported Examples	Wales: Brown (1997a).

The 'Smolt Safe'™ Screen

The Smolt Safe screen (patent pending) is manufactured by Rivertec of East Sussex (Mr AL Woolnough, Fishway Engineering, pers. comm.). The principle is broadly similar to that of the Coanda-effect screen (Figure B10). In the configuration shown, the weir is constructed flush with the bank of the river and water is carried off sideways over 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 B10 was constructed for a distillery where there is a large amount of waterborne debris and has been in service for three years. 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. It is also claimed that the screen has operated for periods of up to two months without requiring attention.

As for the Coanda-effect screen, there are constraints on operation. The manufacturers specify an operating flow range of 0.5 to 5 cumecs, which would limit its use to either very small or high-head hydro schemes. However, there seems no reason in principle why larger flows should not be accommodated, given suitable space and arrangement of the civil works. The application chart may therefore be similar to that for the Coanda-screen given by Brown (1997a). A second constraint is that at least 25% of flow is required for washover. Thus, for a 5 cumec draw-off, at least 6.25 cumecs initial river flow would be required.

THE 'SMOLT-SAFE' SCREEN	
Recommended uses	Water supply offtakes from weirs; high-head hydros.
Range of flows	0.5-5 cumecs; >25% excess flow needed.
Capital cost per cumec	From £12k.
Maintenance cost per cumec	£0.25k per annum; additional risk of storm damage.
Maintenance requirements	Brooming down every month; pressure-washing every 6 months.
Optimum diversion efficiency	Up to 100%
Causes of losses of efficiency	As for Coanda-effect screen
Problems in use	None known. Prototype has run for 3 years and coped with logs, leaves, etc.
Benefits	Self-cleaning, no moving parts, no power required.

B5.2.2 Mobile Screens

Band and Drum Screens

Band screens comprise a vertical 'conveyor' belt of articulated mesh panels, through which the water is drawn (Figure B11). Ledges or 'fish buckets' carry any impinged fish to the top of their travel, from where they may be backflushed back to the river. Hence they are suitable only for more robust species or life stages, not for smolts. Band screens are less robust than raked screens and more liable to damage by debris. They are therefore seldom used for screening at the primary intake interface.

Drum screens are similar in principle to band screens but use a rigid rotating mesh drum instead of the articulated belt arrangement.

Both types are commonly found on water treatment plants and thermal power station cooling water inlets, where they are used to screen debris from water supplies. In general, they would not be selected primarily for their fish protection merits, but where they are used the design can be optimised to minimise the risk of fish injury (Love *et al*., 1987).

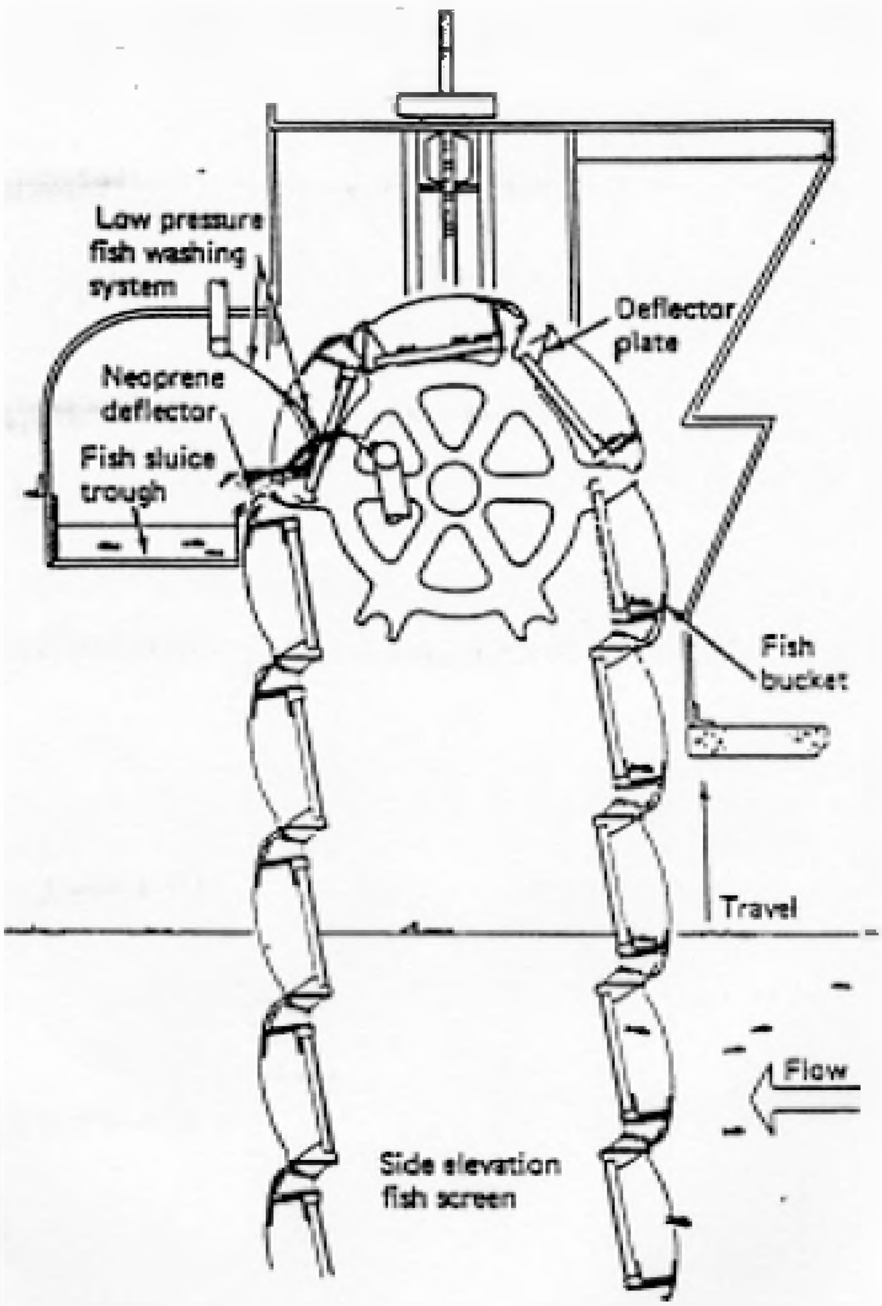


Figure B11

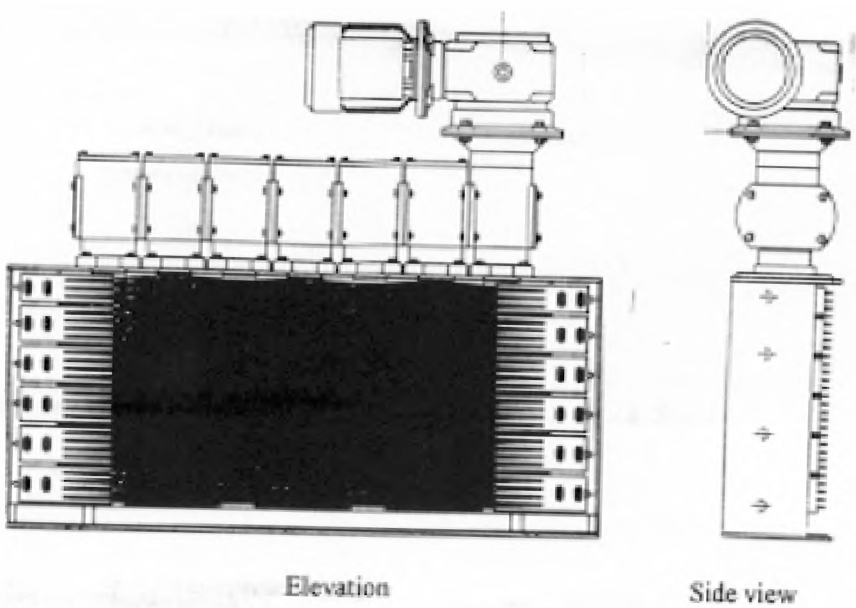
Sectional view of a band screen fitted with fish buckets

BAND AND DRUM SCREENS	
Recommended uses	Primarily for debris removal from water supply and cooling water intakes. Can be modified to improve handling of robust fish species with subsequent return to river.
Range of flows	Multiple screens deal with any flow.
Capital cost per cumec	(not primarily a fish screen)
Maintenance cost per cumec	-
Maintenance requirements	Annual mechanical servicing.
Optimum diversion efficiency	Depends on species. Probably low for smolts; high for benthic species.
Causes of losses of efficiency	Poor design; excessive backwash spray pressure; excessive debris.
Problems in use	None known.
Benefits	Fish return from drum or band screens may avoid the need for special fish diversion screens.
Reported Examples	Sizewell 'B' Power Station, Suffolk (Turnpenny, 1994)

Rotary Disk Screens

Developed originally for application in sewage treatment plants, rotary disk screens (Figure B12) have been used for intake screening applications. These screens again are placed across the primary face of the intake. They use vertical stacks of thin plastic or stainless steel disks with suitable spacing (typically from 2-10 mm) to exclude the critical material or fish. Adjacent columns of disks interleave and all columns rotate in the same direction. The system is driven by electric motors (e.g. 1 per 5 columns), the motor being placed above flood level or in a submersible housing. Debris is passed along the array from one disk stack to the next, until it has reached the end of the screen, where it should be carried away by the flow; hence the direction of rotation must be co-ordinated with the direction of river flow. Vibration of the rotating disks may also discourage fish impingement, although this does not appear to have been investigated.

A rotary disk screen located at Testwood raw water intake, Hampshire (Southern Water Services Ltd) is the largest so far built in the UK for a water intake. It comprises four modules, located side-by-side, each having a screening area of approximately 1 m vertical x 1.2 m horizontal, and handling a maximum flow rate of 40 MLd^{-1} (0.46 m^3s^{-1}) at a screen approach velocity of 0.35 $m.s^{-1}$. The Testwood screen was designed to keep out smolts and uses plastic disks with a 9 mm gap. The installation was completed in March 1997 at a cost of around £200k. Operating costs are relatively low, with a power consumption of 4.4 kW (4 x 1.1 kW motors). Operational experience so far shows mixed success. In 1997, the screen experienced problems during the weed-cut season when *Ranunculus* strands became wrapped around the spindles. The screen was removed over the autumn/winter 1997/8 period to avoid leaf-debris problems. Future operation is likely to be confined to the smolt season and there are plans for a possible extension of the screen to five panels in order to reduce the draw of weed towards the screen (Mr R.



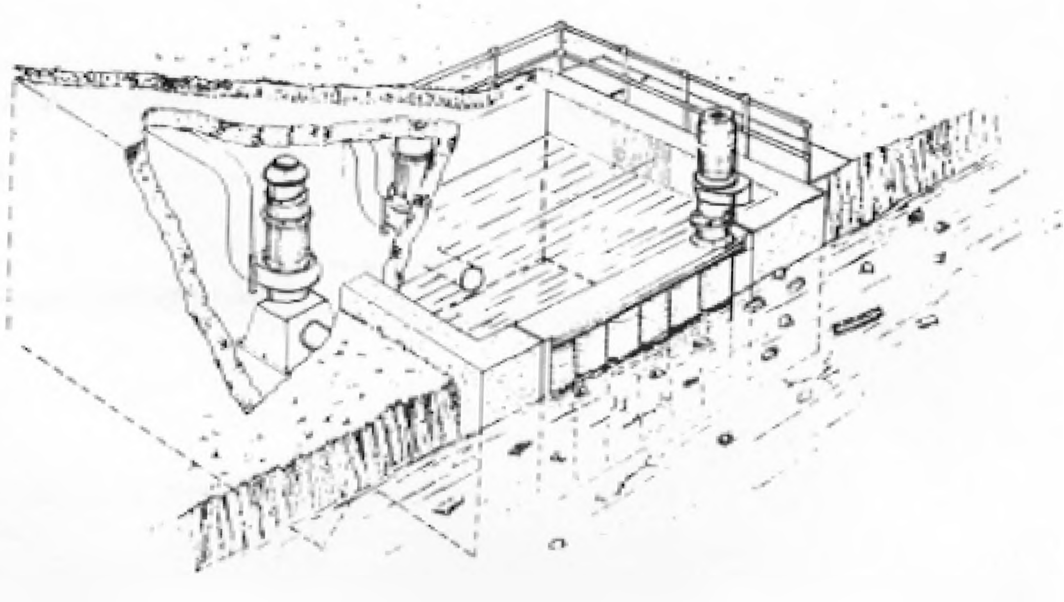


Figure B12

The Rotary Disk Screen

Edbury, pers. comm.). When a similar screen was tested at Restormel in Cornwall, it is said to have suffered problems of leaf blockage (Dr D.J. Solomon, pers. comm.).

The maximum screen depth available for a single unit is 1 m. Where a greater screen depth is required, it is possible to stack units to whatever depth is needed, by placing them in steps, the deeper ones being in front of the shallower ones. This staggered arrangement is necessary to accommodate the drive shafts and motors. Although the gap between disks can be as small as 2 mm, the number of units required rises in inverse proportion to the gap size to compensate for the reduced porosity.

The rotary disk screen has limited appeal for large intakes, owing to the number of screening units required to achieve low approach velocities and consequent high cost. The self-cleaning properties of the screen also appear to be in doubt where certain types of debris are involved. The concept is sometimes attractive to engineers, as the physical attributes of the screen often make it suitable as a direct replacement for conventional trash racks at sites where intake velocities are already low.

THE ROTARY DISK SCREEN	
Recommended uses	Water supply intakes.
Range of flows	Generally <5 cumecs
Capital cost per cumec	£126k for 30 cm.s^{-1} velocity
Maintenance cost per cumec	£1.5k per annum
Maintenance requirements	Removal of strands of vegetation when screens become overwhelmed.
Optimum diversion efficiency	Not tested. Should be high with close disk spacing, provided openings are clear.
Causes of losses of efficiency	Clogging by weed may increase approach velocities.
Problems in use	Weed wraps around spindles.
Benefits	Easy to retrofit in place of trash racks.
Reported Examples	Testwood Pumping Station, Southampton (see text.).

The 'Econoscreen™'

This device (Figure B13) has been described by Solomon (1992) and is a self-powered, self-cleaning rotating drum filter screen. The screen is highly effective in situations where it can be properly deployed, with a steady flow of water past the screen to make it rotate, and into which the impinged debris can be washed off. These conditions are best met when the abstraction rate is a small fraction of the main river flow. Otherwise the screen will need to occupy a substantial part of the river width. In use, it is found to be highly reliable, with virtually no maintenance or running costs. Units have been operating for 7-8 years on their original bearings. Monitoring of fish caught in a smolt trap located downstream of one unit revealed no damage or scale loss to smolt (R.J. Hornsby, University of Lancaster, unpublished MSc Thesis).

The Econoscreen is available in standard sizes for abstractions of 0.1 – 0.5 m^3.s^{-1}, although larger sizes up to 1 m^3.s^{-1} have been built. Although some 10-20 units have been installed in Britain, none so far has been used for hydropower. Its potential for use in hydropower is limited to small, high-head schemes.

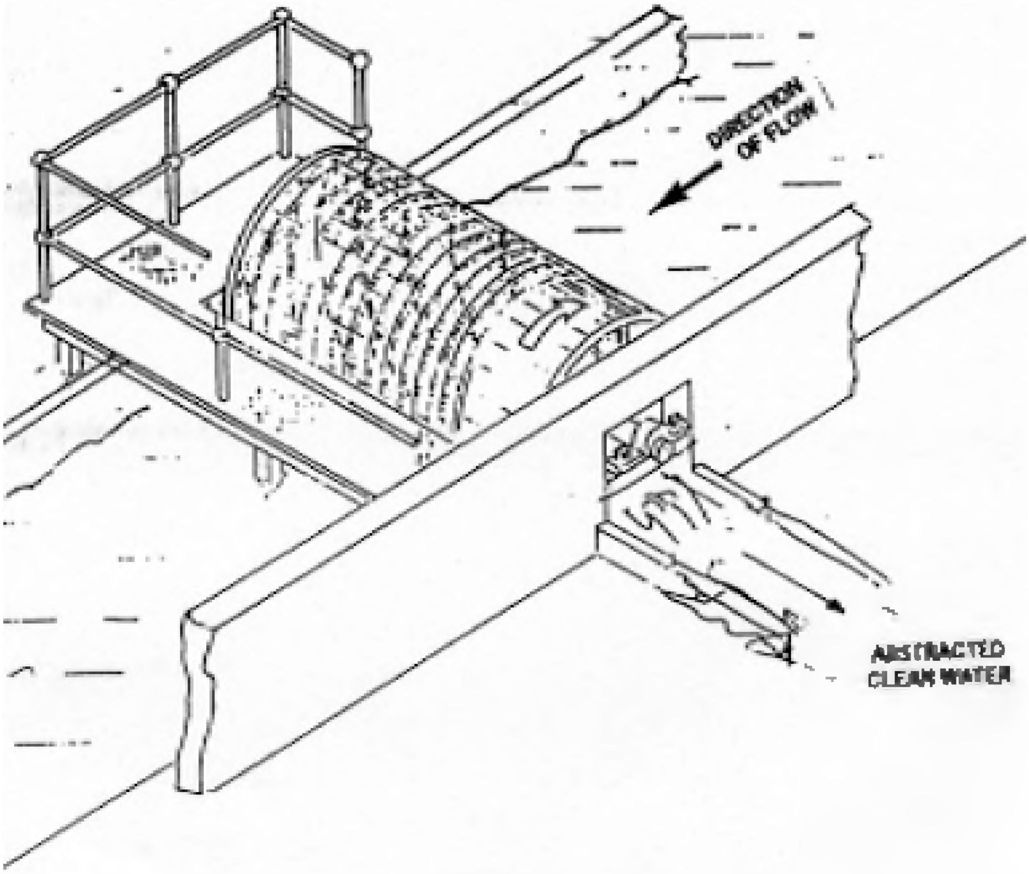


Figure B13

The Econoscreen

THE 'ECONOSCREEN'	
Recommended uses	Small abstractions from river channels, e.g. industrial supply, small potable supply. Only suited to high-head hydropower.
Range of flows	0.1- 1 cumecs
Capital cost per cumec	£12k.
Maintenance cost per cumec	Negligible.
Maintenance requirements	Low: occasional replacement of main bearings.
Optimum diversion efficiency	100%
Causes of losses of efficiency	None reported. Large debris preventing rotation?
Problems in use	None apparent.
Benefits	Self-cleaning, self-powered, reliable.
Reported Examples	British Steel plant, Workington; fish hatchery, Carlisle (Solomon, 1992).

B5.3 Behavioural Barriers

B5.3.1 Electric Barriers

Electric fish screens were developed in the 1950s and 1960s, with the MAFF Fisheries Laboratory undertaking much of the development. MAFF electric screens were subsequently installed at a number of sites, particularly of potable water intakes, across the UK. Electric tailrace screens were also used at several hydroelectric stations. Most have now been removed following doubts about their effectiveness and safety but with more recent designs they remain a potentially useful option, especially for tailrace screening.

The MAFF-type electric screens use an array of vertical electrodes, normally set about 15-30 cm apart and of alternating electrical polarity, arranged across the intake entrance, from top to bottom of the water column. When energized, they create a local electric field that is repellent to fish. The potential difference experienced by a fish depends upon the source voltage and the size of the fish, larger fish being exposed to a proportionately greater voltage. A problem with electric screens is that a field which is strong enough to repel small fish may tetanise or stun large fish and cause them to be drawn into the intake. There have been problems of fish electrocution at some sites and a Scottish Office report describes them as 'disappointing and ineffective' (Anon., 1995a). Solomon (1992), who reviewed screening methods for the National Rivers Authority, agreed with this view.

A more modern version of the electric fish screen is manufactured by Smith Root Inc. (SRI) of the United States, and is known as the Graduated Field Fish Barrier (GFFB). A detailed account of this particular electrical barrier is given here as scientific investigations have shown it to perform well under favourable conditions, with low risk to the fish and to public safety.

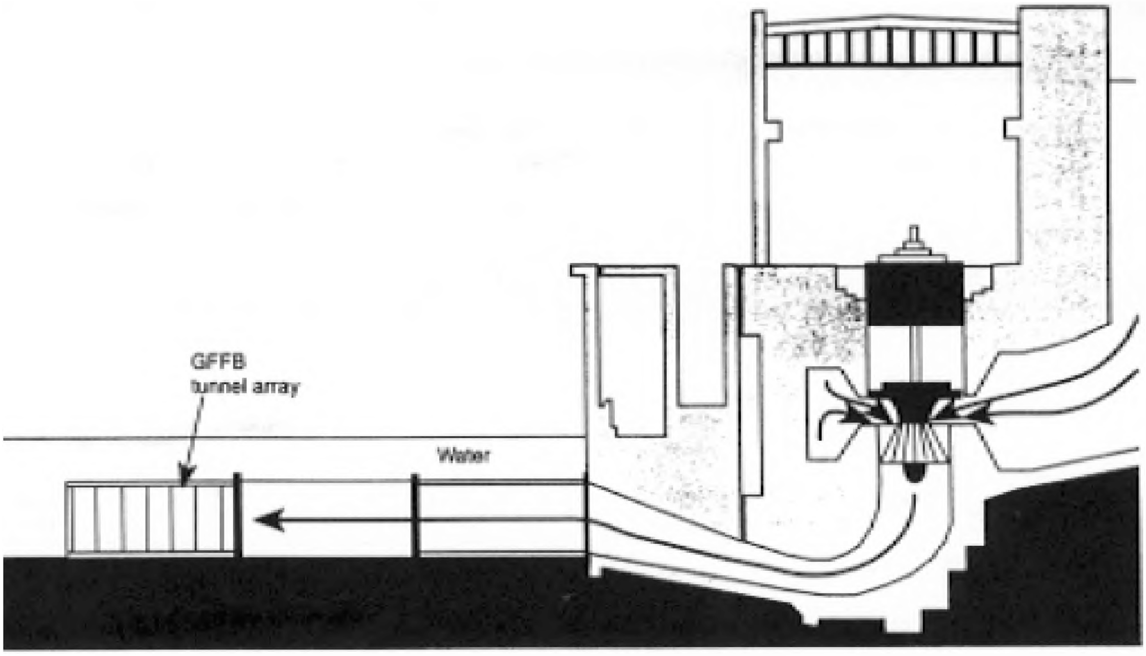
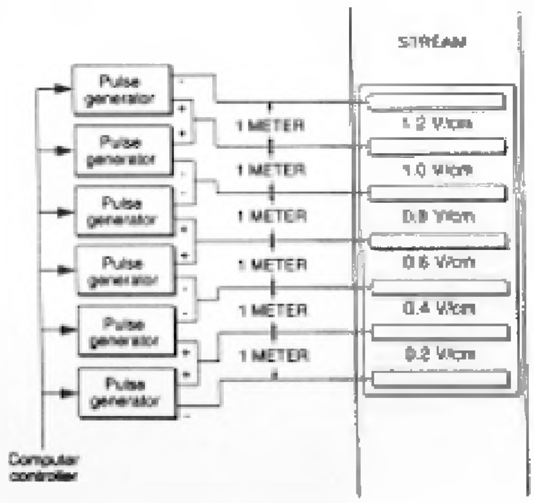


Figure B14

The Graduated Electric Fish Barrier

(a) Tailrace Barrier Installation.



The Graduated Electric Field Barrier

(b)Typical graduated electric field (Smith-Root Inc)

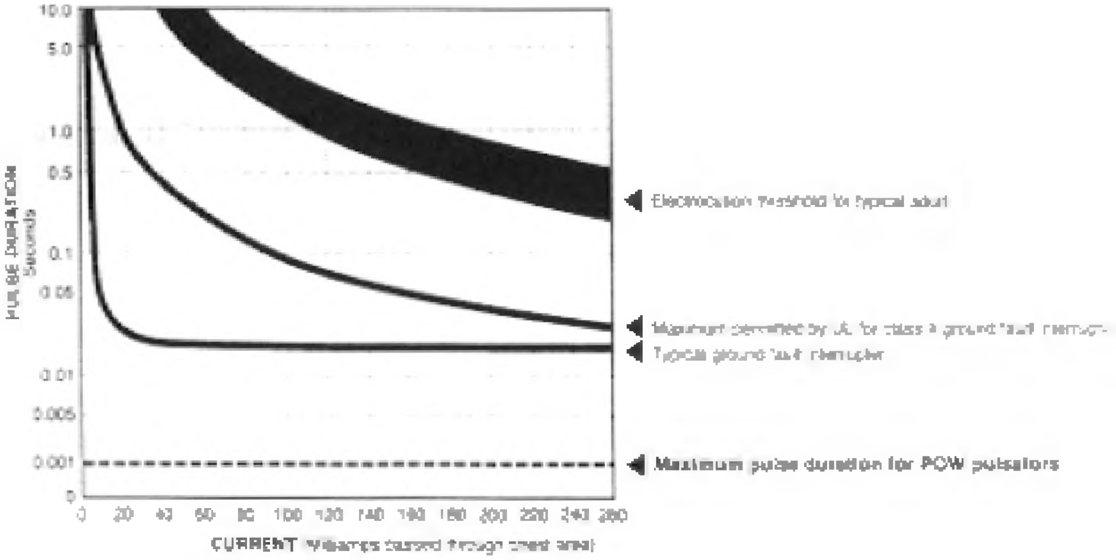


Figure B15

Effects of an electrical pulse on humans passed through the chest

Adapted from the handbook of electronic safety procedures, 1982 Edward A. Lacey

(Smith-Root Inc)

Like other types of electric barrier available, the GFFB uses short pulses of DC current but it differs in that it energises a parallel array of electrodes placed e.g. across the bed of the channel such that the voltage increases progressively as the fish penetrates the barrier. Thus, larger fish will turn back before the field is strong enough to stun them, while smaller fish will eventually reach a part of the field that repels them. Figure B14 shows how a series of electrical pulse generators is used to achieve the graduated voltage field. Figure B14 gives a number of possible alternative electrode configurations for intakes and outfalls. The GFFB has been mainly used for preventing upstream movements of fish, where a minimum water velocity of 0.6-0.9 $m.s^{-1}$ is required to carry fish downstream out of the field. The maximum operating depth in which a uniform field can be generated is about 5 m. The barrier has also been tested as a means of preventing downstream migration into hydroelectric inlets, although SRI offer an alternative version known as the Downstream Guidance System (denoted GFFG) for this purpose; the latter differs in having an abrupt leading field edge which is intended to invoke a startle response.

Evaluations of the GFFB have been reported by Rozich (1989), Seelye (1989), Anon. (1990), Hilgert (1992), Demko *et al.* (1994), Barwick and Miller (1994). The reports cover a wide range of species, of different applications and of potential biological effects. Installed in optimum conditions, the GFFB appears to provide a highly effective barrier against a wide range of species. Changing environmental conditions such as water depth can compromise performance but the most recent developments enable the electrical field to be regulated automatically to cope with such fluctuations.

Physiological effects were also investigated in some of these studies. As exposure to electric fields can harm fish, experiments have sought to evaluate a variety of possible effects under worst case conditions. Thus, Hilgert (1992) exposed adult coho salmon (*Oncorhynchus kisutch*) for ten second periods in field strengths of 0.2 to 0.9 $V.cm^{-1}$ and observed no signs of injury. He commented that exposures of that duration to such field strengths would rarely occur as deterrent effects of the barrier are observed at much lower voltages. He also examined effects of a similar treatment on gamete production and observed no reduction in egg viability or early development.

The GFFB appears to have considerable potential for preventing fish entry into tailraces of hydroelectric stations and for other applications where upstream migrants are to be prevented from entering cul-de-sacs. Barwick and Miller (1994) report promising results also from experiments which attempted to simulate downstream migration conditions in a hydroelectric headrace canal. The canal was 1 m deep and 2 m wide, and therefore was small compared with most applications. A mixture of North American fish (including salmonids and clupeids) was introduced into the canal while water was being pumped at a velocity of 0.2 $m.s^{-1}$ across the GFFB. The GFFB was operated at 10 pulses per second. For the tests, fish were concentrated at one end of the 24 m long canal, and observed over the following 2 h test period with the screen energised. The percentage of fish not crossing the energised barrier during pumping was 83% or more. The required field minimum strength was stated to be 1.5 $V.cm^{-1}$. While these results are encouraging, the small channel size and low velocity presented rather favourable conditions compared with those at most hydroelectric projects. Fish in a migratory phase of the life-cycle, such as smolts, might also react differently. Further testing would therefore be required prior to full-scale hydroelectric intake screening application.

There appears to have been no comparable testing of the GFFG form of the barrier.

Human safety is a major concern when using electrical barriers. SRI have produced the information shown in Figure B15 to illustrate the low level of risk associated with the GFFB and GFFG discharges. Safety can be further improved by isolating the barriers from human access, a precaution that is strongly recommended.

GRADUATED ELECTRIC BARRIERS	
Recommended uses	Fish containment and prevention of upstream migration into tailraces. Results less predictable for intakes.
Range of flows	All, but max. depth ~5m.
Capital cost per cumec	£0.7k – 1.0k
Maintenance cost per cumec	Negligible.
Maintenance requirements	Negligible.
Optimum diversion efficiency	80-100% for upstream blockage.
Causes of losses of efficiency	Excessive water depth (>5m) over electrodes.
Problems in use	None evident.
Benefits	Reduces head-loss on turbines.
Reported Examples	Various locations in North America (Rozich, 1989; Seelye, 1989; Anon. 1990; Hilgert, 1992; Demko *et al.*, 1994; Barwick and Miller, 1994).

B5.3.2 Bubble Barriers

The bubble curtain is the most elementary form of a behavioural barrier. At its simplest, it comprises a perforated tube laid along the riverbed, through which compressed air is forced. The rising curtain of air then forms a wall that, under optimal conditions, will deflect fish. Their reaction may result from a number of stimuli emitted by the curtain, including reflection of light by the bubbles and underwater noise and vibration.

Solomon (1992) cited fish deflection efficiencies for bubble barriers in laboratory tests of up to 98%, falling to between 51% and 80% in darkness or high turbidity levels (showing that reflected light is only partially responsible for their function). Such evidently good results should be treated with caution, however, since laboratory experiments are invariably of short duration and seldom reflect the opportunities for fish to habituate with continual use. In the field, results have been much more mixed and efficiencies are typically much lower. For instance, in experiments carried out with a bubble curtain at Heysham Power Station (Lancashire), fish entrapment was reduced by 36% (Turnpenny, 1993). There have been few rigorous experiments to determine efficiencies in the field.

In the authors' own experience, bubble curtains work best in flowing channels where they are placed at a shallow angle (~12°) to the bank, thus relying only upon a glancing contact of the fish to deflect them across the channel. An example is shown in Figure B16, a photograph of an operating bubble barrier constructed by the former National Rivers Authority at Walton-on-Thames Waterworks. Pavlov (1989) drew a similar conclusion on the basis of studies in eastern Europe. The task to which they are most suited is one of deflecting down-migrating fish such as smolts and 0-group coarse fish.

In static or slow-moving water with resident populations, bubble curtains are usually much less effective. Liu and He (1988) conducted experiments into the adaptation of fish to bubble curtains and showed that efficiency fell sharply with prolonged experimental duration. This finding no doubt accounts for the poor effectiveness of bubble curtains often found with field applications. An attempt by the Environment Agency to use a bubble curtain to exclude juvenile coarse fish from Blackdyke Pumping Station in Lincolnshire, where water is abstracted from a virtually static channel, was initially successful in reducing entrainment but the effect wore off within a few weeks (R. Handford, pers. comm.).

Some design criteria for bubble curtains are given in Table B3. These were used in the construction of the bubble curtain at Heysham Power Station, and in the Walton-on-Thames bubble barrier, both of which were considered successful applications.

Table B3 Bubble Curtain Design Criteria

Feature	Requirement
Bubble tube material	Galvanised iron or PVC pipe
Bubble tube diameter	Length ≤3 m: 28 mm Length>3m: 50 mm
Hole size and spacing	2 mm @ 25 mm centres or 1 mm @ 6 mm centres
Air supply rate	3 $l.s^{-1}$ per metre length of barrier
Supply pressure (at point of immersion)	(0.2+D/10) bar, where D is water depth in m. A blower capable of ~0.50-0.8 bar pressure is suitable for most purposes, provided supply losses are kept low.

The use of a strong flow of air, as indicated, is crucial to effective performance. The most economical way of generating the air supply will depend on flow rate and depth, and any application is best discussed with a supplier of compressed air equipment. For use in water of <2 m depth, a simple rotary blower, as used e.g. for aeration on fish farms, will deliver a large flow of air at sufficient pressure. For deeper water applications, multi-stage blowers can be used to deliver higher pressures.

The behaviour of bubble curtains in flowing water should be fully appreciated before attempting to install one. Bubbles larger than 2 mm rise through the water column at a rate of about 0.25 $m.s^{-1}$. In determining the position for a bubble barrier, the surfacing line should be calculated, according to the likely velocity regime. This will vary depending on river discharge, so that if the barrier is intended to guide fish into a bypass channel, the width of the mouth needs to accommodate any variation in surfacing position. Alternatively, two or more bubble pipes may be laid, being switched from one to the other according to flow conditions (see e.g. Anon., 1996a). Turbulence may also destroy the integrity of the bubble curtain, allowing fish to find gaps, so that areas of uniform flow should be selected for placement of the barrier. Finally, the bubble plume itself may generate self-destructive turbulence. The situation may be likened to the flame of a candle, which has a lower, laminar flow region and a turbulent region above. Some fine-tuning of air flow may be required to ensure a uniform curtain of bubbles.

The cost of a bubble barrier is relatively low, although large, deep-water installations can be expensive, both in terms of capital costs of the compressor and housing, and of power requirements.

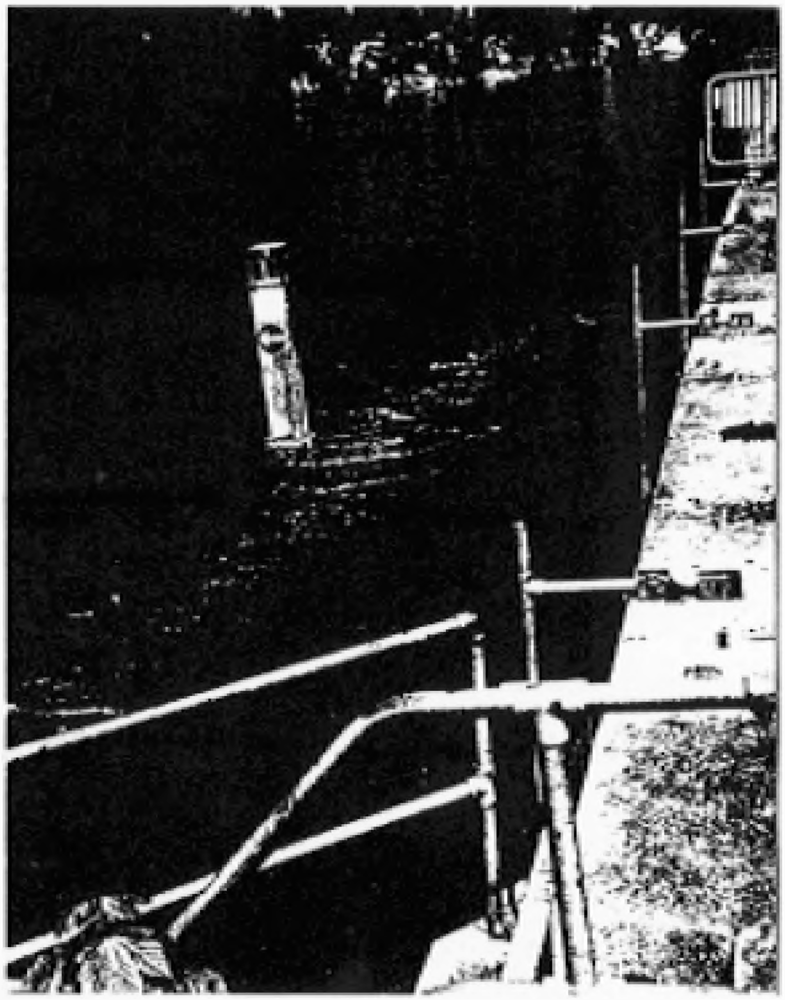


Figure B16
A bubble barrier at Walton-on-Thames waterworks

BUBBLE CURTAINS	
Recommended uses	Low-cost, low efficiency screening method for large flows. May be used to augment other methods.
Range of flows	All. Suited to flows > 5 cumecs
Capital cost per cumec	£1.2k
Running cost per cumec	£0.25k
Maintenance requirements	Removal and cleaning of bubble tube at least annually.
Optimum diversion efficiency	40%
Causes of losses of efficiency	Blockage of bubble tube, especially when turned off for periods; water turbulence may disturb curtain integrity.
Problems in use	Varying flow conditions effect lie of the curtain.
Benefits	Low cost, no hydraulic loss.
Reported Examples	Walton-on-Thames waterworks (Solomon, 1992); Heysham Power Station (Turnpenny, 1993)

B5.3.3 Louvre Screens

The louvre screen (Figure B17) is a semi-physical barrier that offers low resistance to water flow but high fish deflection efficiency (>90%) when installed under optimum conditions (Aitken *et al.*, 1966; Solomon, 1992). It is best suited to installation in a channel, and may be inclined at angles of 10^o to 30^o to the flow, depending on the channel velocity (see Section B3.4.2), although 10^o to15^o is usually quoted as optimal. Louvre slats are orientated at 90^o to the flow and spaced at 15 cm centres, with flow straighteners at 45 cm centres. Efficiency may be improved by reducing the slat gaps to ~5 cm near to the by-wash exit. Water velocity in the channel can be in excess of 1 m.s^{-1}, subject to the escape velocity being low enough for the species in question; velocity in the bypass entrance should be around 1.4-1.5 times that in the channel.

The deflection principle of a louvre screen is that current vortices are set up between the slats (Figure B14) so that an approaching fish senses a shearing flow (i.e. different velocities across different points along its body) and avoids it. The fish therefore swims a little way ahead of the screen and is guided into the by-wash.

As the screen has physical elements exposed to the water flow, trashing can occur, although to a lesser extent than mesh screens. Access must therefore be provided for cleaning. Solomon (1992) makes the suggestion that placing a conventional coarse trash rack (through which fish could pass) upstream of the louvre barrier would obviate this problem. A separate kelt by-wash would then be required, unless the bar spacing were ≥100 mm.

Louvre screens were first developed during the 1950s but, despite promising results, they have been little used in the UK and Europe. In North America, louvre technology is more widespread and still being installed. Goosney (1997) described a 170 m long floating louvre screen that was being installed at the Grand Falls hydroelectric plant in Canada during 1997. The floating arrangement allowed the screens to be removed outside the fish migration season.

LOUVRE SCREENS	
Recommended uses	Mainly used in hydroelectric canals and thermal power station cooling water channels.
Range of flows	All. Suited to flows > 5 cumecs
Capital cost per cumec	£3k
Maintenance cost per cumec	Low, if mounted behind trash rack.
Maintenance requirements	Removal of larger debris, unless site downstream of trash racks.
Optimum diversion efficiency	90%
Causes of losses of efficiency	Low approach velocities at reduced water flows limit vortex formation and hence efficiency drops.
Problems in use	None evident.
Benefits	Low head loss and high efficiency; small debris such as leaves have no effect.
Reported Examples	Grand Falls hydroelectric plant, Canada (Goosney, 1997).

B5.3.4 Artificial Illumination

Artificial lighting can be used to help fish orientate to the structures around them and can help to reduce impingement on screens, especially where the problem occurs mainly at night. Even in relatively turbid waters, artificial lights can provide orientation information but the range of effect will be diminished. An effective way of using lighting for orientation is to place the lamps behind some structural element (e.g. a trash rack) so as to throw it into silhouette, which will achieve the maximum visual contrast (Turnpenny, 1988). The velocity close to the bars needs to be low enough for fish to escape for this to work.

To minimise reflective loss at the surface and to reduce light “pollution”, the lamps are normally placed underwater. The lenses then need frequent cleaning (perhaps every week or so in dirty or eutrophic waters) to maintain their effectiveness, and this may increase the cost considerably where mechanical recovery systems have to be provided to withdraw the lights for cleaning, and will also increase manpower costs. The most common arrangement is to place an array of lights in an arc surrounding the intake entrance, where velocities will be low enough for fish to escape.

Lights attract some species of fish, a feature used in Mediterranean light-fishing (Ben-Yami, 1976), which therefore can increase the risk of entrapment. Other species show negative phototaxis and can be repelled from intakes using strong underwater lighting (Hadderingh, 1982). Experiments on Pacific salmon (*Oncorhynchus* spp.) reported by Nemeth and Anderson (1992) suggest that this may also depend on the illumination level, with dim lights attracting and bright lights repelling. Therefore the artificial lighting approach tends to be unpredictable.

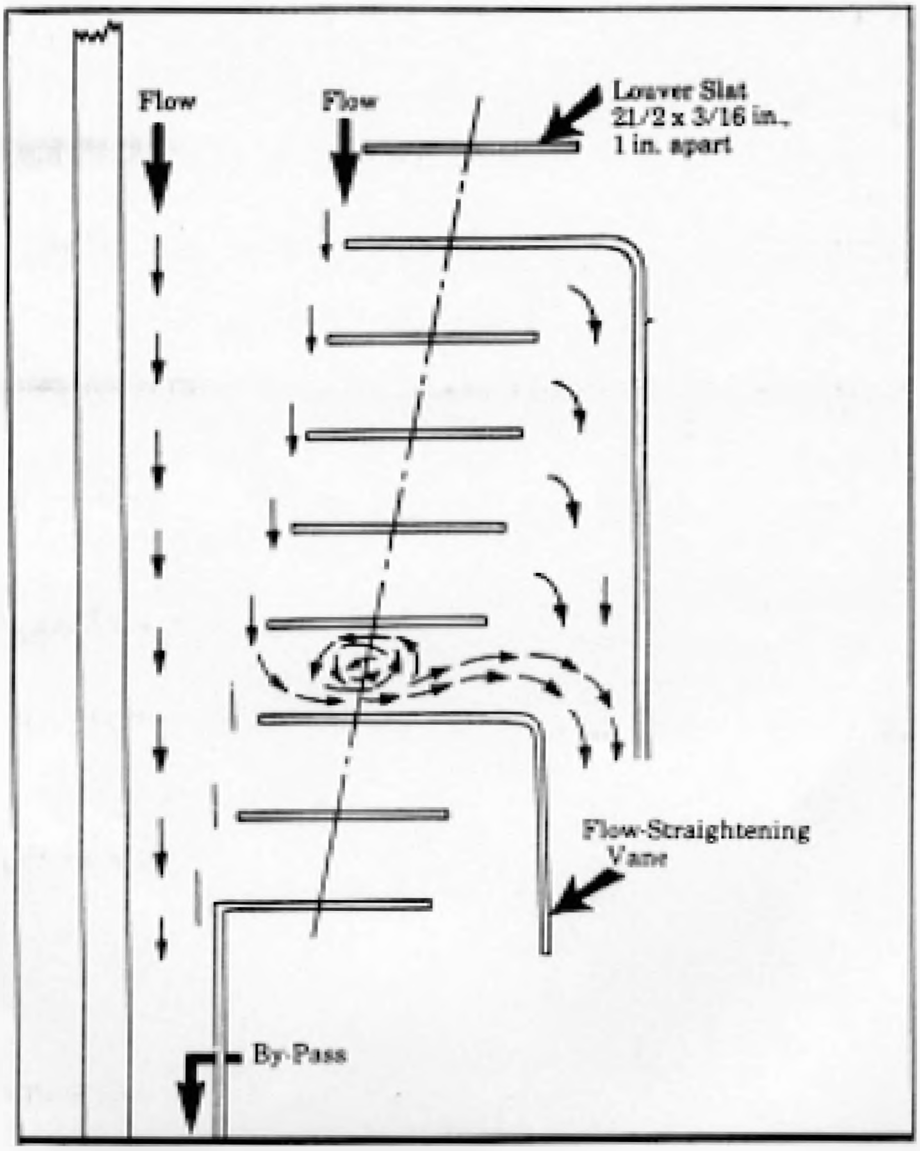


Figure B17

Vortex generation using a louvre screen

(after Bates and Visonhaler, 1957)

Flashing lights tend to be more consistently repellent and some moderately successful applications with strobe lights that use xenon discharge tubes have been reported.

B5.3.4.1 Continuous Light Systems

Continuous illumination has been tested extensively in the Netherlands, particularly to deflect eels (Hadderingh and Smythe, 1997). Eels show strong negative phototaxis and positive rheotaxis, but their tendency to follow water currents at intakes can be discouraged by placing lights in the flow. These can be incandescent lights, mercury vapour lights or fluorescent lights. Recent trials have mainly used the latter (specified as 36W, PL-L Philips, spectrum with peaks at 440, 550 and 610 nm). Deflection efficiencies at thermal and hydroelectric power stations have ranged from 25% to 74%.

CONTINUOUS LIGHT SOURCES	
Recommended uses	Eel deflection from hydro and other large water intakes. May be used to augment other methods.
Range of flows	All. Suited to flows > 5 cumecs
Capital cost per cumec	£2k
Running costs per cumec	£0.36k per annum
Maintenance requirements	Regular raising of the lamps for lens cleaning; replacement of bulbs as needed.
Optimum diversion efficiency	70%+
Causes of losses of efficiency	High turbidity; lens fouling; hydraulic conditions.
Problems in use	Frequent maintenance means system must be provide to raise lights for attention.
Benefits	No hydraulic loss. Few other methods work with eels.
Reported Examples	Amer power station, Holland (Hadderingh and Smythe, 1997).

B5.3.4.2 Strobe Light Systems

Solomon (1992) and Brown (1997b) reviewed fish deflection experiments involving xenon strobes. Best results appear to be obtained when operated at flash rates of >200-400 per minute. Laboratory tank trials have shown consistent avoidance response by salmonids and other freshwater species to strobe lighting, whether in ambient light or dark conditions. In field trials at hydroelectric and other water abstractions, overall scheme bypass efficiencies ranging from around 50% to 95% have been reported, although these figures are not necessarily direct assessments of deflection efficiency.

Strobe lights can be used in conjunction with other behavioural devices to increase the level of fish protection. Combinations with bubble curtains may enhance the effectiveness of both, as the light can be projected onto the bubble sheet. In the UK this approach was tested at Walton-on-Thames raw water intake, where it was estimated to have reduced smolt entrainment by 62.5% (Solomon, 1992).

A problem with earlier strobe systems was that the lifespan of the xenon discharge tube was limited to a few weeks of operation. Modern tubes, however, will last for a year or more when correctly driven.

STROBE LIGHTS	
Recommended uses	General fish deterrent suitable for hydros, thermal power stations and other large flows. May be used to augment other methods.
Range of flows	All. Suited to flows > 5 cumecs
Capital cost per cumec	£3.5k
Running cost per cumec	£0.36k per annum
Maintenance requirements	As for continuous lights.
Optimum diversion efficiency	60% if used with bubble curtain.
Causes of losses of efficiency	Reactions of different species/ life stages vary according to flash rate. Optimum for one species may not be for others; other effects same as for continuous light.
Problems in use	As for continuous lights.
Benefits	As for continuous lights, but higher efficiencies may be obtained.
Reported Examples	Power stations in Holland (Hadderingh and Smythe, 1997) and USA (Brown, 1997b).

B5.3.5 Acoustic Barriers

Solomon (1992) made reference to the use of underwater sound stimuli for fish deflection purposes. At the time of his writing, acoustic fish deflection systems were in their infancy, but he nevertheless concluded that acoustic fish diversion systems were 'perhaps the most promising' of the behavioural methods available. In the past six years, there has been considerable development and testing of acoustic deflection technologies. These can be divided into three categories according to emission frequencies: audible range (i.e. to humans: 20 to 20,000 Hz), infrasound (<20 Hz) and ultrasound (>20,000 Hz). Each has different applications and limitations.

B5.3.5.1 Audible-Frequency Systems

The hearing range of most fish falls within the audible range to humans, maximum sensitivity lying in the sub-3 kHz band (Hawkins, 1981). Audible frequency deterrent systems mostly exploit hearing sensitivity in the 20 to 500 Hz range. Key factors for successful fish deflection are (Lambert *et al.*, 1997):

1. the sound signal should be within the above frequency spectrum;
2. the nature of the signal should be repellent to fish;
3. the sound level received by the fish at the required point of deflection should be sufficiently above ambient noise level (at least ten times, or >20dB).

Other factors, including sufficiently low escape velocity and presence of an escape route also apply.

Two methods of generating an acoustic barrier are presently in use. One uses arrays of underwater loudspeakers or "sound projectors" to produce a diffuse field of sound that will block fish movement. The other uses sound sources coupled to a bubble curtain to produce a discreet "wall of sound" (strictly known as an "evanescent" or rapidly decaying field) that can be used for more precise guidance of fish, e.g. into a bypass channel. The choice of method depends on the intake configuration and bypass facility.

Sound Projector Array (SPA) Systems

A recent summary of their use at hydroelectric water intakes was provided by Lambert *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. In particular, the Energy Technology Support Unit (ETSU), Harwell, funded work 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 could be 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 (*Alosa fallax*) and various cyprinid and percid species.

The first permanent acoustic deterrent system in the UK was installed at the Foss flood relief pumping station, York (Environment Agency; capacity 32 $m^3.s^{-1}$). Sound projectors were placed behind the trash racks. The sound emitted served both to drive out fish that had accumulated in the pump wells during periods of inactivity and to keep at bay fish present in water upstream of the screens. The system achieved overall 80% exclusion (Wood *et al.*, 1994). The values for individual species were as follows:

Species		Efficiency	Significance
roach (*Rutilus rutilus)*	-	68%	$P<0.001$
perch (*Perca fluviatilis*)	-	56%	$P<0.05$
chub (*Leuciscus leuciscus*)	-	87%	$P<0.02$
bleak (*Alburnus alburnus*)	-	72%	$P<0.05$
bream (*Abramis brama*)	-	74%	$P<0.05$
All species	**-**	**80%**	**$P<0.001$.**

A similar, but even larger sound system was tested in the cooling water intake at Hartlepool nuclear power station (capacity 34 $m^3.s^{-1}$) on the River Tees estuary. This was intended to reduce the entrainment of sprat (*Sprattus sprattus*) and herring (*Clupea* *harengus*). The trials, which took place over a two month period, demonstrated reductions by 60% of sprat and by 80% of herring (Turnpenny *et al*, 1995).

The sound signal used in both of the above cases comprised a sweep of frequencies from 50 to 500 Hz, repeated 4-5 times per second (Figure B18). Source levels were of the order 174 dB re 1 µPa @ 1m. Other effective signals have been developed; these have in common the characteristics of rapidly changing in either frequency or amplitude, or both. Pure tones, either pulsed or continuous, were found to have the least effect on fish behaviour (Turnpenny *et al.*,1993).

A SPA acoustic deflection system comprises the following elements: an electronic signal generator, one or more power amplifiers and an array of underwater sound projectors, plus connecting cables. Power requirements are modest (around 1-2 kVA for an eight-unit SPA) so that running costs are low. A typical arrangement of sound projectors is shown in Figure B18. Normally, sound projector units are located along the front face of the intake, suspended about 1 m below the surface at no more than 3 m spacings. The maximum spacing of 3 m minimises interference between the emissions of adjacent sound sources.

The optimum number and positioning of sound projectors can be determined using an acoustic model such as "PrISM" (Subacoustech Ltd) to predict the resulting sound pressure. This also accommodates information on the geometry and bathymetry of the intake area and adjacent structures, and ensures that surface, bank and bottom reflections are taken into account in the final system design. After commissioning, measurements can be taken to confirm the field and ensure that there is no risk of blocking passage in any adjacent river channel that is required to be passable by fish.

Sound projectors are electro-mechanical devices and at least annual 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. Hence, it is necessary to ensure that easy retrieval is considered.

ACOUSTIC SPA BARRIER	
Recommended uses	Versatile fish barrier suitable for water supply and low- and high-head hydro intakes, etc.
Range of flows	All. Suited to flows > 5 cumecs
Capital cost per cumec	£1.1k (based on 20-60 cumecs)
Running cost per cumec	£0.17k per annum (as above)
Maintenance requirements	Inspection/ servicing (1-2 per year)
Optimum diversion efficiency	80%
Causes of losses of efficiency	Other sources of background noise (e.g. pumps); cable damage
Problems in use	None, provided sound projectors and cables are fully protected from debris.
Benefits	Simple to retro-fit; low maintenance; no hydraulic losses.
Reported Examples	Foss Pumping Station, York (Wood *et al.*, 1994) and Hartlepool Power Station (Turnpenny *et al*, 1995).

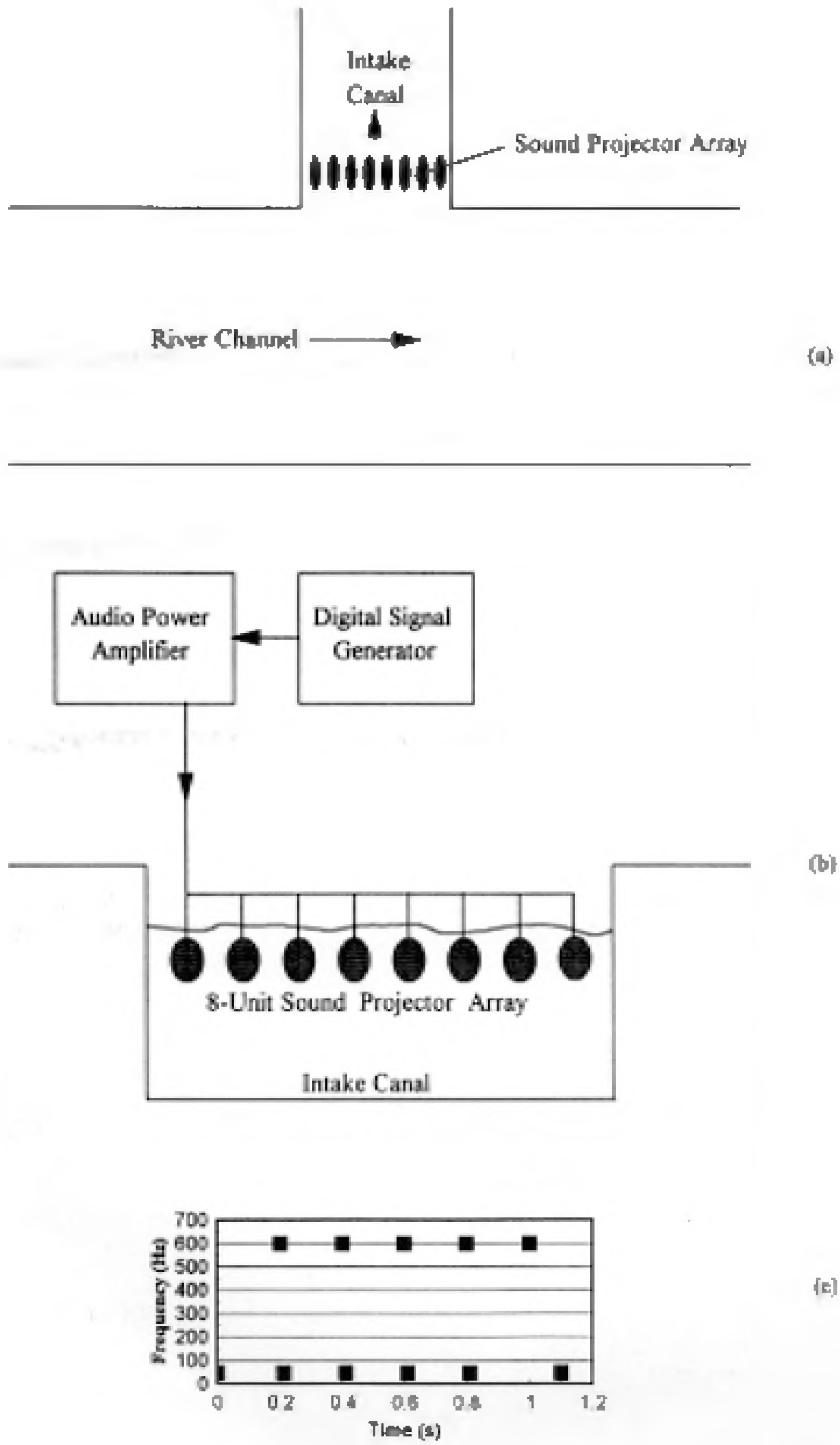


Figure B18
The "SPA" Acoustic Fish Barrier. (a) & (b) show typical deploymentof a system at the entrance of an intake canal; (c) shows the waveform of one type of deterrent signal

Evanescent Sound: The Bio-Acoustic Fish Fence

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 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 wave 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 B19). 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 freqency 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 bypass channel.

The BAFF has been under test in different applications for several years and is now commercially available. A trial undertaken at Blantyre, a small (575 kW, 20 $m^3.s^{-1}$ flow) hydroelectric plant on the R. Clyde, Scotland, yielded a barrier deflection efficiency for smolts of 74% and 92% for coarse fish (Anon., 1996a). Calculated in terms of the overall scheme passage efficiency, these figures rise to at least 96% for smolts and 99% for coarse fish. Unfortunately, only small numbers of fish (210 smolts, 355 coarse fish) passed the scheme during the trials and therefore the reults were not considered conclusive.

More extensive testing of the BAFF has been carried out by the Institute of Freshwater Ecology (IFE), as part of the Environment Agency's National Research and Development Programme. Trials of different configurations were made over a three-year period at their Rivers Laboratory on the R. Frome, Dorset (Welton, *et al.*, 1995 and unpublished). The largest BAFF tested was 20 m in length and was placed obliquely across the main river channel, so as to divert down-migrating smolts into a disused mill leat, thence through an electronic counting and video recording system. Numbers passing down the main river channel could be monitored as they passed over a weir, also with fish counting and observation facilities. Estimated diversion efficiencies into the mill leat over the 3-year trial period ranged from 88% to 100%. Secondary barriers were also provided within the leat system to divert fish into a narrow bypass channel. Efficiencies here were lower, around 70% at night and 40% during daylight. Lower efficiencies associated with these barriers appeared to be due in part to unsatisfactory bypass entrance conditions. Visual observation of smolt schools approaching the barrier revealed that fish were diverted by the BAFF towards the bypass but were reluctant to enter the bypass. Some schools were seen to make several attempts at passage over a number of hours but gradually detected gaps around the edge of the bubble curtain allowing some to pass through. Differences between day and night efficiencies appeared to occur when short segments of the bubble curtain became blocked due to biofouling, allowing fish to find

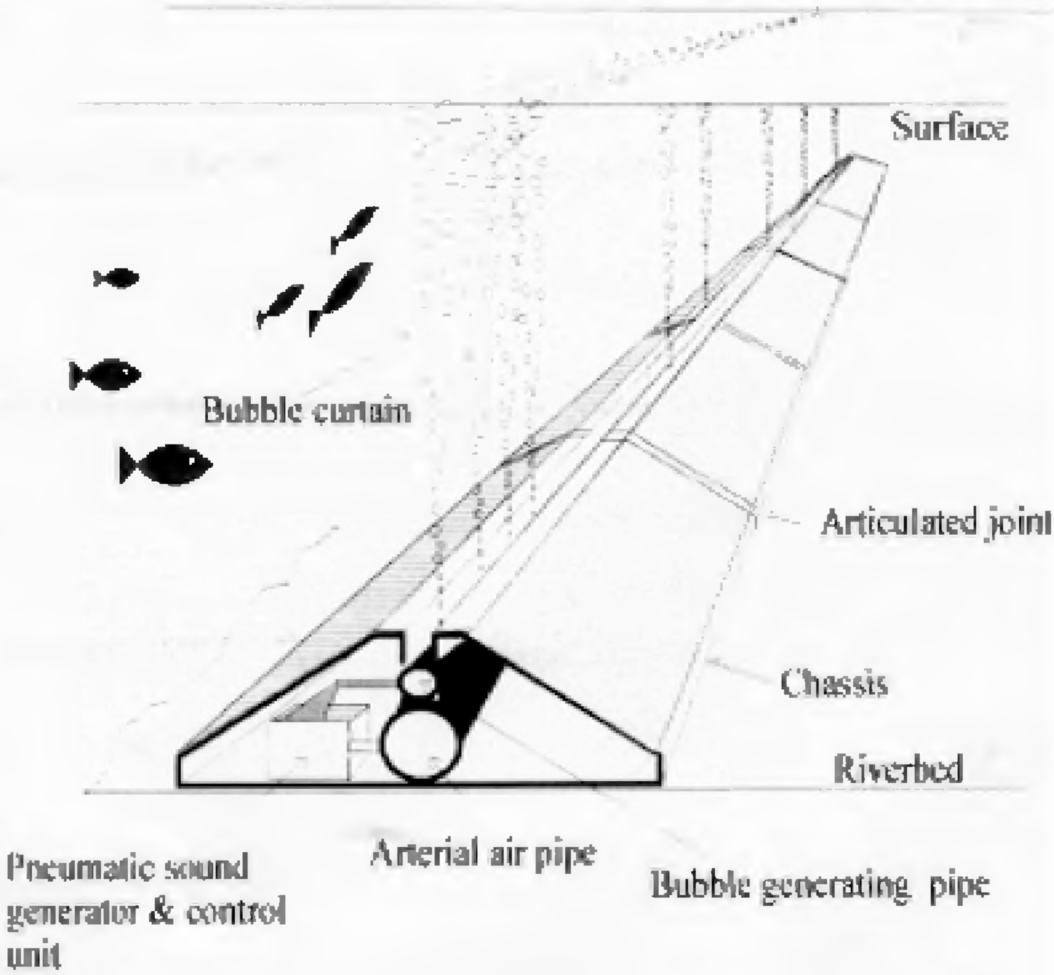


Figure B19

The Bio-Acoustic Fish Fence (BAFF)

gaps when in daylight but not in the dark. New bubble tube materials have now reduced the biofouling risk, which should eliminate this problem.

Running costs for the BAFF are higher than for an equivalent SPA system, as they require an air blower or compressor. However, the air demand is less than that for an equivalent stand-alone bubble curtain, as a smaller the amount of air is required.

'BIO-ACOUSTIC FISH FENCE'	
Recommended uses	Alternative to angled flat-panel screen, louvre screen or bubble curtain for fish deflection into bypasses. Suitable for cooling water and low- and high-head hydro canals, fish farms.
Range of flows	All. Suited to flows > 5 cumecs
Capital cost per cumec	£1.25k (based on 20-60 cumecs)
Maintenance cost per cumec	£0.15k (as above)
Maintenance requirements	Minimal if kept running; de-silting may be required after long period of inactivity; annual overhaul of submerged equipment.
Optimum diversion efficiency	~90%
Causes of losses of efficiency	As for bubble curtains.
Problems in use	As for bubble curtains. Some airborne noise.
Benefits	High-efficiency fish-guidance without hydraulic loss.
Reported Examples	River Frome smolt census, Dorset (Welton *et al.*, 1995); Blantyre hydroelectric plant (Anon., 1996a).

B5.3.5.2 Ultrasound Transducer Arrays

Fish are not, in general, sensitive to ultrasound. At present, the clupeid fish (herrings and shads) alone are known to possess this capability, a fact that has emerged incidentally from various studies involving the use of high frequency (>100 kHz) sonar, and has recently been tested in laboratory experiments (Mann *et al.*, 1997). It is thought that ultrasound hearing may be associated with detection and evasion of marine mammal predators.

The phenomenon has been exploited with some success in the USA, 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 this is unlikely at hydroelectric installations. Also, similar results can be obtained from audible-frequency systems, to which clupeids are more sensitive than ultrasound (Mann *et al.*, 1997), probably at lower cost. The latter have the advantage of also repelling non-clupeid species.

B5.3.5.3 Infrasound

An infrasound (<20 Hz) detection capability in fish was shown by Sand and Karlsen (1986) and a flight response from infrasound has since been demonstrated in Atlantic and Pacific (*Oncorhynchus* spp.) salmon juveniles (Knudsen *et al.*,1992; 1994; 1997). Good results have been achieved in both laboratory and small-scale field conditions using a 10 Hz pure tone signal. The signal was generated using a motor-driven piston (4 cm peak-to-peak displacement) operated within a 25 cm diameter aluminium cylinder.

Infrasound shows promise for future development but the technology for generating the necessary levels has not yet reached a practical commercial form. The authors also comment that larger-scale field studies are needed to test the true effectiveness of infrasound under natural conditions.

Their studies also compared reactions of fish to the 10 Hz signal with those for a 150 Hz pure tone signal, the latter being the optimum hearing frequency for salmonids (Hawkins and Johnstone, 1978). As in the study reported by Turnpenny *et al.* (1993), no behavioural reaction was shown to a pure tone at this frequency.

At present, infrasound systems are under research and not widely available on a commercial basis but results look promising.

B5.3.5.4 Biological Aspects of Acoustic Barriers

Fish Species

Fish vary in their sensitivity to underwater sound, and this fact will clearly influence the potential efficiency of an acoustic barrier.

When considering audible-range frequencies, hearing sensitivity is determined by the presence (higher sensitivity) or absence (lower sensitivity) of a swimbladder, and by any anatomical specialisations that improve the conduction of sound from the swimbladder to the inner ear (Hawkins, 1986). Thus, flatfish, which have no functional swimbladder, are relatively difficult to deflect by acoustic means compared with most swimbladder species. Fish with hearing specialisations include the clupeids (herrings and shads) and cyprinids, making these species most sensitive to acoustic signals. Some species of intermediate sensitivity, including the Atlantic salmon, have poor connectivity between the swimbladder and the inner ear, and avoidance reactions in these fish are believed to be due to detection of vibration rather than sound pressure. The fish then need to be close to the sound source, in the acoustic ‘near-field’, to respond (Hawkins, 1986).

Detection of infrasound is by vibration, not sound pressure, and does not rely on the presence of a swimbladder or other specialisations. Infrasound may therefore be more appropriate for species not sensitive to sound pressure.

Ultrasound is at present only known to be effective against certain clupeid species.

Fish Size

Fish size is also a factor to be considered in relation to acoustic deterrence. At the Foss installation described above, acoustic deterrence was found to be effective over a wide range of fish sizes and stages, including 0-group fish. However, where a preponderance of small fish is expected, recent (unpublished) research at Fawley Aquatic Research Laboratories has indicated that signals incorporating a higher frequency element (up to 3 kHz) can be advantageous. Higher frequencies are not incorporated in deterrence signals as a matter of course, since this reduces the power available at the lower frequencies, which are effective against larger fish

Habituation

Habituation to sound is not a problem with migratory fish, which are rarely in contact with the sound for a long period. Nevertheless, it is an aspect that must be considered with 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 it is recommended that the deterrent signal should be altered at intervals (e.g. once per day). Signal generators with multi-signal capability are available for this purpose.

Risk of Fish Injury

Exposure to exceptionally high sound levels, for example associated with seismic surveying or military sonar equipment, can cause hearing damage in fish, or more severe conditions such as swimbladder rupture (Turnpenny and Nedwell, 1994). The lowest level at which auditory injury has been observed is 180 dB re 1µPa for continuous pure tones in the 50-500 Hz range; exposure was over periods of hours. Other injury effects typically occur only at levels in excess of 200 dB re 1µPa. Acoustic deterrents use sound levels well below the 180 dB threshold, and exposures to the higher levels would normally be fleeting, not sustained. There has been no indication of any harmful effect on fish to date.

B6. CHOICE OF SCREENING SYSTEM

B6.1 Choice of Screening Location

As with other aspects of screening design, all alternatives should be considered.

Within the UK, only Northern Ireland is specific about screen location, *s*.59 of the Fisheries Act (NI) 1966 requiring screens to be placed “at the point of diversion” of water from a river, although exemptions from this stipulation may be granted. Legislation in England, Wales and Scotland makes specific provision for screens to be placed either at the offtake entrance or within the channel. It is worthwhile considering the merits of locating screens at the channel entrance against within-channel positions.

The entrance to an offtake from a river would normally be the first option considered. Excluding fish at this point represents the closest to the natural situation, allowing downstream migrants to continue their journey without leaving the natural course of the river. It should be remembered that once diverted into an offtake channel, the chances of delay and predation become significantly increased. Unfortunately, channel entrance screening often suffers from a number of disadvantages, *viz.*:

- Remoteness from the main operational site makes monitoring, cleaning and maintenance more difficult.
- In spate rivers, the natural flow regime may be very variable and screening systems may be at risk of flood damage.
- Electrical power supplies, if required, may be difficult and costly to provide.

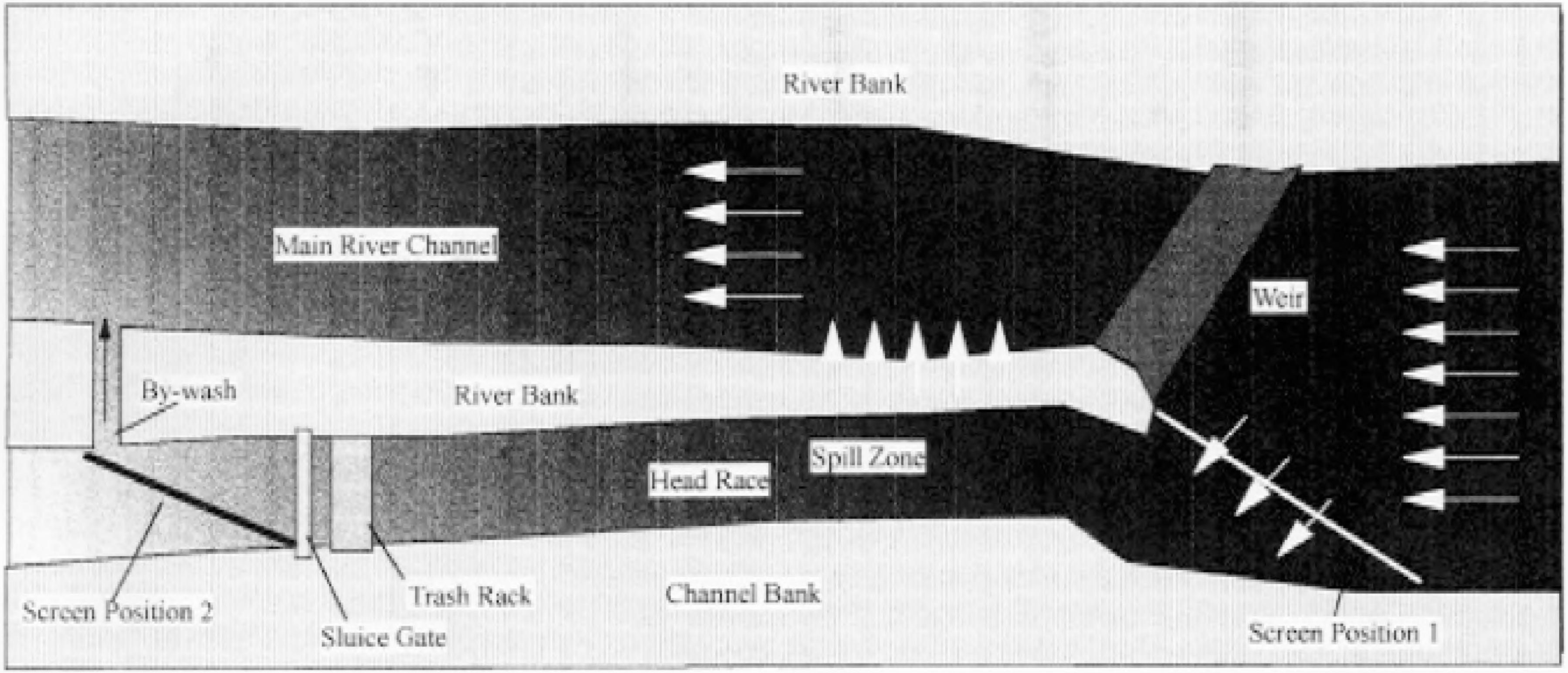


Figure B20 Alternative positions for screen location: at the channel entrance (Position 1) or within the head race (Position 2)

Locating screens within the channel has the disadvantage of diverting fish away from the natural path of the river with possible consequent delays and predation and also relies on an effective bypass arrangement, but it has a number of significant advantages:

- The flow regime is controlled: maximum flow is limited by the channel capacity, reducing risk of overloading the screening system.
- The screening system may be brought within the main operational site boundary, making regular cleaning and maintenance easier to carry out, and detection of problems more likely.
- Electrical power, if required, is likely to be more accessible.

A case study shown in Figure B20 illustrates some of the factors in choice of screening location. The site was a small hydroelectric plant, which abstracts water via a short (200m) headrace from a weir pond. The initial proposal was to place a screen at the channel entrance, in Position 1. There were concerns about the stability of the riverbed at the entrance, following excavation to create a rectangular-section channel, and the risk of silt banks building up against the screens. Also, there was a significant overtopping of the headrace banks at the high river flows near to the entrance. Position 2 was therefore selected at the downstream end of the headrace. At this point, flow was stable, excess floodwater having been lost in the overspill section of the headrace. The channel dimension limited maximum flow. This meant that the screens could be designed to ensure that the fish escape velocity could not be exceeded (provided that the screens were kept clean). Added benefits of this position were that an upstream trash rack prevented larger debris from accumulating on the screen and an electrically operated sluice gate immediately above the screen position enabled the channel section to be drained as required for screen inspection and maintenance.

B6.2 Behavioural versus Mechanical Screens

From the operator's point of view, behavioural screens may offer significant advantages over physical screens, in that they have little impact on scheme hydraulics and require minimal maintenance and are therefore highly cost-effective. However, owing to their generally lower fish deflection efficiency, behavioural systems will not always provide a solution that is acceptable to fisheries bodies nor that will be legally compliant. Most fishery authorities will, in the first instance, lean towards the more certain fish protection provided by mechanical screens. Screening measures should always be discussed in advance with the regulating body and other interested parties.

There are various circumstances in which behavioural barriers offer significant advantages over mechanical screens to the fishery regulator as well as to the operator. For example:

- In England and Wales, SFFA *s.*14 prohibits the use of screens that might impede navigation. Behavioural barriers might provide a solution where a mechanical screen would fall foul of this regulation.
- In England and Wales, SFFA *s.*15 allows the Environment Agency to place and maintain screens at its own cost. This is seldom done in practice, owing to the maintenance level required and the liability that falls upon the Agency *vis a vis* any loss of water supply to the operator. Behavioural barriers would reduce the

maintenance requirement and eliminate any risk of loss of water supply due to blockage.

- Where the regulator's policy is governed by the BATNEEC principle, or otherwise takes into account cost versus benefit, behavioural screens may be the preferred choice.
- Where the policing of screening regulations is difficult, and there is considered to be a significant risk that the operator will not operate screens correctly (e.g. ensuring that screens are always in place, fully seated and properly cleaned), behavioural screens may in practice offer a higher degree of fish protection and be the more pragmatic solution.

Other circumstances may also favour behavioural barriers, e.g. on rivers that are not frequented by salmon and sea trout, where formal screening regulations do not apply, or where operators have a license-of-right that pre-dates formal regulations, but where they may be prepared to install fish protection for goodwill. Some existing intakes may simply not be amenable to mechanical screening solutions, whereas most forms of behavioural barrier are easy to retrofit to a wide variety of intake configurations.

The possibility of improving overall screening system performance by using combinations of devices should not be overlooked. For example, where mechanical screening systems exist but lack any fish guidance capability (e.g. where screens are orthogonal to the flow), behavioural systems such as bubble barriers, louvres or BAFF acoustic barriers might be used to enhance guidance into bypasses, reducing delays and impingement risk. Combined physical/behavioural barriers are increasingly being used in the USA (Brown, 1987b). Also, where a physical screen would be impractical, it may be possible to increase the effectiveness of behavioural screens by using more than one level of defence, e.g. a bubble screen followed by an acoustic screen, etc.

B6.3 Selection of a Screening System

A summary of characteristics and requirements of different fish screens and behavioural barriers is given in Table B4. These are the main factors that will influence the choice of a screen. For example, if it is not feasible or economic to bring power to the preferred screen location, certain methods will immediately be excluded, including all of the behavioural methods other than louvre screens. Certain methods, primarily those that use low porosity screens, made for example of wedge-wire, are suited only to flows of 5 $m^3.s^{-1}$ or less, and therefore, within the hydropower context, are likely to be suited only to either micro-hydro schemes or small, high-head schemes.

Having decided what options must be excluded on the above grounds, the next criterion to consider is the required fish diversion efficiency. As described in Part A, agreement on this question should be reached with the relevant fishery agencies, preferably based on the outcome some sort of agreed risk assessment procedure. It is important that the concept of the overall Scheme Passage Rate (see Section A9) should be evaluated, rather than looking only at the screen or barrier efficiencies as given in Table B4. This takes into account the proportion of water passed through the turbine and the likely injury rate in the turbine(s). This process further narrows down the options available.

The final choice of system can be made on grounds of cost and other features, such as maintenance requirements.

Hence, the process is initially one of progressive elimination:

Identify technically non-feasible options

↓

Establish required fish diversion efficiency and eliminate unsuitable options. Remember that combinations of equipment may be used to enhance overall efficiency

↓

Make final choice on grounds of cost, maintenance requirements and other criteria

B6.4 Design of the Screening System

Having selected a suitable fish screen, the overall design process is illustrated in the flowchart below. Details of each step are to be found in the earlier sections of Part B of the Guide.

Select type of screen

↓

Investigate alternative screen positions with suitable escape routes for fish

↓

Assess intake flows by measurement or hydraulic modelling

↓

Develop model of how the fish are expected to escape (route, velocities, streamlines etc.)

↓

Design screening system

↓

Install and commission

↓

Test or monitor performance of screen, by-wash, etc., with fish

Table B4 Summary of Characteristics and Requirements of Different Screening Technologies

Type of Screen or Barrier	Typical Flow Range $m^3.s^{-1}$	Capital + 10-year Running Cost per $m^3.s^{-1}$ (£k)	Mainten-ance Frequency	Impact on Flow	Power Required ?	Fish Diversion Efficiency
PHYSICAL SCREENS						
Flat Panel	All	9	Daily	Medium	Varies	~100%
Wedge-Wire Cylinder	≤5	31	Annual	High	Yes	100%
Eicher Pressure Screen	All	120	?	Medium	Yes	~90%
Under-Gravel Filter	≤1	160	Annual	High	Yes	100%
Raked Bar Screen	All	28	Annual	Medium	Yes	~
Coanda-Effect	≤5	20	Monthly	High	No	100%
Smolt-Safe™ Screen	≤5	17	Monthly	Medium	No	~100%
Rotary Disk Screen	≤5	186	Weekly	Medium	Yes	~100%
Econoscreen™	≤1	14	Monthly	High	No	~100%
BEHAVIOURAL BARRIERS						
Bubble Curtain	All	3.7	Monthly	Nil	Yes	~40%
Louvre Screen	All	3.0	Monthly	Low	No	~90%
Continuous Light	All	7.1	Monthly	Nil	Yes	~70%: eels
Strobe Light	All	7.1	Monthly	Nil	Yes	~60%
SPA Acoustic Barrier	All	2.8	Quarterly	Nil	Yes	~80%
BAFF™ Acoustic Barrier	All	2.8	Monthly	Nil	Yes	~90%

B7. COMMON FAULTS IN SCREEN DESIGN AND OPERATION AND POSSIBLE IMPROVEMENTS

The previous sections have given advice on the correct design of screening systems but little has been mentioned about operational faults. The following lists some of the common faults that have been observed during inspections of screening systems. Sadly, most are the result of neglect, wilful interference or poor operator training. It must be emphasised that these are not typical of the more responsible operators, although some examples are from larger concerns. The fact that these faults are found may in some cases be as much a reflection of inadequate design as poor operational practice. In most cases they are due to reducing manpower levels on operational sites. When designing or assessing fish screening systems, it is essential that such realities be taken into account. The question should be asked, "Are sufficient operational staff going to be made available to operate this screening system, or should a less labour-intensive method be used?"

Observed faults:

- Screens not kept clear of debris;
- Screens not put in place at the required time(s) of year;
- Screens not properly seated, owing to debris accumulation;
- Screens not properly seated, owing to deliberate obstruction, e.g. welding legs to the bottom of the screens to maintain an open gap;
- Shear-pins not replaced on pressure-relief plates, allowing unscreened water to enter;
- Screening material damaged;
- Screens distorted owing to past blockage, allowing fish to enter.

The risk to fish caused by partial blockage of screens, and consequent development of high velocity areas, can be reduced by the provision of a suitable early-warning system. Levels sensors are fitted upstream and downstream of the screens. Once a certain head-loss has been exceeded, an indication is sent to the plant control centre, allowing action to be taken.

An enforcement problem found with some kinds of flat panel screen is that it may not be quite clear to the observer whether or not a screen is fully seated to the bottom of its travel. It is good practice to ensure that a benchmark is provided to identify the correct position, e.g. a pair of corresponding lines on the frame and screen that become aligned when the screen is fully seated.

A similar issue exists with certain kinds of behavioural screen (e.g. electrical or acoustic), with which correct function may not be obvious just from appearance, especially when the systems operate some distance away from the river bank. Some sort of visible indicator to confirm correct performance is then required.

B8. CONCLUSIONS

1. A wide variety of fish screening systems is available to suit different needs, environmental conditions and budgets. New types of screens are continually under development. The full range of options should be considered when planning new fish protection measures.

2. Physical screens still offer the highest guaranteed fish diversion efficiencies and may be the most cost-efficient for very small intakes (<1 cumec). A number of self-cleaning physical screens are available, which reduce manpower requirements, but these are mainly cost-effective on smaller intakes, and are therefore best suited to high-head schemes. Physical screens are only efficient if they are correctly operated, cleaned and maintained, however.
3. Behavioural fish barriers offer advantages in terms of low cost, particularly on large intakes, low maintenance, little or no obstruction to flow and therefore low hydraulic resistance, and ease of retrofitting. Fish diversion efficiencies are generally lower than for physical screens, ranging from ~40% for bubble curtains to >90% for louvre and certain acoustic barriers. Higher efficiencies may possibly be obtained by operating two systems in tandem. Behavioural systems may also be used to improve the performance of poorly designed physical screening systems.
4. Behavioural barriers also have a role in certain situations where physical screens are impractical, e.g. where physical screens might obstruct a navigable channel, and where an operator is not obliged by law to fit fish screens but is willing to use a 'no-trouble' behavioural barrier (e.g. on cyprinid waters).
5. The design of bypass (by-wash) facilities is critical to the good performance of any fish screen that is placed within a channel. This is particularly true of behavioural screens, where failure of fish to locate an exit quickly will increase its chances of entrainment. With physical screens, delays may also lead to increased risks of predation or impingement. Improved design criteria now available should reduce these risks.
6. No fish screening system will work if the water velocities from which the fish are required to escape are too high. Existing criteria appear to ensure adequate fish safety but are stringent and require large screening areas to be used, leading to high screening costs. There is evidence that the currently accepted 25-30 $cm.s^{-1}$ escape velocity criterion for salmonid smolts underestimates their true swimming capability and may lead to excessive costs in providing screening structures. It is important that these are kept under review to ensure that costs to operators are not unnecessarily burdensome.
7. For newer screening methods to be fully accepted by fishery authorities, it will be necessary to ensure that test results from varied applications are generated and made available. Failures in screening systems of all types occur mainly due to lack of maintenance or to failure to operate them correctly. This is often due to inadequate manning or operational staff not being aware of how , when and why screening systems should be operated. Occasionally, it is through wilful neglect, owing to the gain in flow and reduced maintenance effort when screen are not in place or not fully seated. It is important that operational staff are trained in the required operation of screens and are made aware of the legal obligation of the owners.

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