Evidence

Protection of biota from cooling water intakes at nuclear power stations: scoping study

Project SC160009/R1

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

Since the publication in 2010 of the Environment Agency's Evidence document *Cooling water options for the new generation of nuclear power stations in the UK* there have been a number of developments both in technology and research aimed at protecting aquatic organisms from high-volume water intakes. In addition, the industry has made progress in putting into practice the advice and developments, while environmental regulators (the Environment Agency, Natural Resources Wales and the Marine Management Organisation) and statutory conservation bodies (Natural England) have acquired direct experience of dealing with the issues. The Environment Agency therefore considers it is time to review these developments and experience with a view to updating the available information on the environmental effects of cooling water use in nuclear and other large thermal power stations.

The purpose of the present document is to identify key developments and experience and to highlight where further clarification is needed. This is an initial scoping document with the intention to produce a full review of these technologies in due course. Information on biota protection measures from cooling water intakes at exiting nuclear and conventional power stations and other large volume water intakes has been included where relevant. The information summarised in this report could have relevance to other large scale water intakes e.g. existing nuclear and conventional power stations, tidal hydropower.

This report is divided into sections on technologies and practices and it is hoped that information highlighted and identified in this report can be used to inform a full review of the subject areas identified as important. This, in turn, will provide information and data on current available technologies to inform the decision-making processes on large-scale cooling water intakes.

It was stated in the Environment Agency 2010 document that direct (once-through) cooling can be the best available technique (BAT) for estuarine and coastal sites, provided that best practice in planning, design, mitigation and compensation is followed. However, a number of topics have been identified as meriting further attention, and these are summarised below.

Optimising cooling water (CW) intake structure siting: New nuclear build designs site CW intake structures further offshore (up to 4–5km) than at existing coastal stations (typically 600m or less). While baseline surveys carried out by developers serve to identify differences in 'available' biota assemblages at such locations, any direct experience of consequent biota impingement and entrainment risk will not be forthcoming until such sites are commissioned. In the meantime, studies have concluded that the available predictive tool (PISCES Expert System) should only be used as an initial scoping tool and not relied upon for quantitative assessment purposes. However, rapid advances in individual-based modelling techniques using a Eulerian–Lagrangian platform to predict biota movements suggest that this could enhance future assessments and allow impacts on migratory and other species to be minimised. An innovative concept of siting intake heads, along with fine screening plant (drum- or band-screens), on an offshore island is also considered, this having the advantage of minimising or even eliminating biota return pathways.

Intake head designs: engineering practice: Proposed innovative designs for offshore CW intake structures allow intake velocities to be controlled in a varying tidal stream velocity. Key requirements are to maintain nuclear safety, achieve buildability, maintainability and good hydraulic design, and meet intake water approach velocity criteria that are protective to biota. Developers should be encouraged to share their experiences.

Intake approach/escape velocity: A default nominal CW intake approach water velocity of $0.3ms^{-1}$ is recommended in the Environment Agency 2010 report, although earlier (2005) Environment Agency best practice guidance allowed that this may be varied to suit the fish assemblage present, subject to a risk assessment. Recent experience of developers indicates that while this value can be realistically achieved as an average across the intake openings, local values may fluctuate and deviate from this. Further scientific guidance on acceptable deviation would be helpful.

Fish behavioural deterrents: The use of behavioural fish-repellent devices, notably underwater acoustic fish deterrents and strobe light systems, is identified in the Environment Agency's 2005 report as part of a best practice fish protection solution for large water intakes and is further supported by the Environment Agency's 2010 report. Installation of such systems is creating new challenges when planning intakes which may be located up to 4–5km offshore in potentially hostile sea conditions. New technical developments are emerging to meet these potential issues, as well as the development of practicable ultrasound devices which have specific application for clupeid deterrence.

CW system tunnels pressure change effects: Fish injuries caused by barotrauma (pressure-related effects) may arise from passage through long, deeply buried tunnels associated with offshore CW intakes. The urgent need for further research to assess the significance of these effects is indicated.

Forebay, screen and fish recovery and return (FRR) system design, including hydraulic conditions: Further clarification is needed on acceptable hydraulic conditions within plant forebay and drum- and band-screenwells. The use of hydraulic strain or shear-stress criteria appear to be more appropriate than criteria used in fish pass design. More information is required on the boundaries of where particular hydraulic conditions are required to be met within FRR systems.

Fish lift pumps and ensuring fish-friendliness for appropriate FRR-dependent species: Discussions with developers have identified the need for further information on the criteria for selection of fish lift pumps that may be required to overcome a lack of available hydraulic head in FRR systems.

Biofouling control, implications for FRR and fish risk assessment protocols: The 2010 Environment Agency report advises that biofouling control agents such as chlorine products should not be used within the sections of the CW system upstream of the fish removal screens, or within the FRR launders and pipework. If there is an operational need for using such products, it should be supported by an ecotoxicological risk assessment. Recent experience indicates that such an operational need may arise and that there is currently no consensus on how the risk assessment should be conducted. It is recommended that any further review of information should also consider the viability of returned fish following exposure to control chemicals.

Passage survival of CW systems downstream of fine screens: The survival of entrained biota that has passed through the CW system and back to sea is known from existing entrainment mimic unit trials to vary considerably according to species and life stage. Published data are limited to a few cases. Many new trials have been carried out by Cefas as part of the BEEMS programme but these are not publicly available. There could be further efforts to encourage data availability in order to review this work.

Monitoring and assessment protocols: The Environment Agency 2010 report did not address monitoring requirements for fish deterrent systems and FRR performance in any detail. As Nuclear New Build plans progress, further information and consensus on monitoring and assessment protocols will be needed.

Updated methods for fisheries impact assessment: Two key methods are presented in the 2010 Environment Agency report: equivalent adult value (EAV) and equivalent area of lost production (EALP). Further information and guidance is now available on these methods, including a streamlined method for calculating EAV, and additional examples of fish production values suitable for UK waters.

Contents

1	**Introduction**	**1**
2	**Optimising CW intake siting for minimising impacts on aquatic biota**	**3**
3	**Intake head designs: engineering practice**	**6**
4	**Approach/escape velocity**	**8**
5	**Fish behavioural deterrents**	**9**
6	**CWS tunnels: pressure change effects**	**11**
7	**Forebay and screenwell design, including hydraulic conditions**	**12**
8	**Onshore screening including fish recovery facilities**	**14**
9	**Fish return launders and discharge head design**	**16**
10	**Fish lift pumps: ensuring fish-friendliness for appropriate FRR-dependent species**	**18**
11	**Biofouling control, implications for FRR and fish risk assessment protocols**	**19**
12	**CW systems downstream of fine screens**	**20**
13	**Monitoring and assessment protocols for fish recovery and return facilities**	**21**
14	**Monitoring and assessment protocols for fish deterrent effectiveness**	**22**
15	**Updated methods for fisheries impact assessment**	**24**
15.1	Equivalent adult value	24
15.2	Equivalent area of lost production	24
16	**Conclusions**	**26**
References		**27**
List of abbreviations		**34**
Appendix		**35**

1 Introduction

Alongside renewable generation, nuclear power is a key component of the UK government's low-carbon energy mix. The seven stations that currently comprise the UK's nuclear fleet generate approximately 20% of the country's electricity. All these stations are however due to retire between 2023 and 2035. In preparation for this, the industry has set out plans for a programme of new nuclear builds at five sites by 2030 to provide a generating capacity of approximately 16GW.

Nuclear power stations will have a large demand for waste heat removal, which is commonly and most efficiently achieved with direct cooling. Within the UK, the sea or transitional waters are the only sources that can reliably support a direct cooling water system (CWS) for a large power station; however, abstraction of cooling water (CW) on this large scale has the potential to kill or damage large numbers of fish and other aquatic organisms through entrapment. Habitats and species adjacent to nuclear sites often have high levels of designation and require protection.

A review by the European Commission in 2001 of the application of best available techniques (BAT) to industrial cooling systems (BAT Reference (BREF)) recognised that 'BAT for cooling a process is a complex matter balancing the cooling requirements of the process, the site-specific factors and the environmental requirements, which allows implementation under economically and technically viable conditions'. The report identified the use of once-through direct CWSs to be BAT for large cooling capacities (>10MWth). In the case of estuaries, once-through CW could also be acceptable if:

- extension of the heat plume in the surface water does not impede fish migration
- the CW intake is designed to reduced fish entrainment
- heat load does not interfere with other users of the receiving surface water

Since publication of the European Commission's (2001) BREF industrial cooling systems report, a review published by the Environment Agency in 2010 on *Cooling water options for the new generation of nuclear power stations in the UK* (Environment Agency 2010a) has considered new developments in technology and research and concluded that 'direct cooling may be the best environmental option for large power stations sited on the coast or estuaries, subject to current best planning, design and operational practice and mitigation methods being put in place, and meeting conservation objectives of the site in question'.

The aim of this scoping report is to outline the relevant developments (in technologies, research or experience) in the protection of aquatic organisms from high-volume water intakes since the Environment Agency (2010a) report, which with increased experience on new build design have come to be considered as more important. This scoping report compiles information sources on advances in CW technologies as a precursor to a further in-depth report on the protection of biota from CW entrainment and impingement at nuclear power stations.

The report provides a comprehensive list of source material to provide a scoping document which may inform a full review of available information in biota protection at marine/estuarine industrial CWSs which would be compatible with UK nuclear power plant safety. Information on biota protection measures from cooling water intakes at existing nuclear and conventional power stations and other large volume water intakes has been included where relevant. The information summarised in this report could have relevance to other large scale water intakes e.g. existing nuclear and conventional power stations, tidal hydropower.

A literature search for information on the mitigation measures for biota entrainment and impingement at large intakes of water in marine, estuarine and large-volume fresh water environments within the UK, Europe and similar temperate areas was conducted by the Environment Agency (February 2017) and has been included as an Appendix.

The report is structured in a logical sequence such that the CW components and the associated fish protection measures are described in the order that biota may encounter them at a generic station, as follows:

- CW intake head
- behavioural deterrents
- CW tunnels
- forebay and screenwell design
- onshore screening
- fish return launders
- fish lift pumps
- biofouling
- entrainment – downstream of fine screens
- monitoring and assessment
- fisheries impact assessment

2 Optimising CW intake siting for minimising impacts on aquatic biota

Current Environment Agency published information provides generic guiding principles for the location of CW intakes applicable to both nuclear and conventional thermal power stations that primarily include avoidance of construction within areas of notable ecological value such as ‘important fish spawning (or the drift path from the spawning grounds), nursery grounds, ecologically sensitive habitats, economically important shell fisheries and fish migration routes’.

Optimal ecological location for CW intakes in both estuarine and coastal waters will be subject to a number of site-specific constraints such as geographic planning, hydrology (the need to avoid recirculation) and design (both economic and technical viability). Given the site-specific nature of each of these issues, this scoping document does not seek to provide information towards guidance on this matter. Instead it considers the biological factors that should inform the planning stage to reduce impacts upon fish and other biota.

Current design best practice recognises the ethos that ‘prevention is better than cure’, and while modern screening and recovery and return techniques greatly reduce the losses resulting from entrapment, it is greatly preferable to exclude fish and biota from the point of entry.

The Environment Agency (2010a) report describes typical configurations for both onshore- and offshore-located intakes. Prior to the current Nuclear New Build (NNB) programme, offshore intakes for nuclear power stations have typically been relatively close inshore, with tunnel lengths of up to 500–600m. Current NNB designs in some cases envisage intake locations further offshore, potentially requiring tunnel lengths of up to 4–5km. This relates to topography and the need to ensure sufficient intake submergence to avoid drawing air at the lowest tide levels and under extreme wave action. Consideration will need to be given to separation of new intakes/outfall from any existing ones in order to avoid thermal or water quality and biota recirculation.

The potential significance of fish zonation to siting of CW intakes has been recognised, and the available evidence from existing nuclear power stations such as Sizewell A (intake 300m offshore) versus Sizewell B stations (intake 600m offshore) has demonstrated the expected differences in juvenile catches (Fleming et al. 1994, Turnpenny and Taylor 2000, Environment Agency 2010b).

The tendency of demersal fish species to segregate themselves according to depth and age is well known, with younger age-classes favouring shallow coastal nursery areas and older fish occupying deeper areas (Riley et al. 1981). Also, habitation of different depth bands can vary seasonally according to thermal preferences, with juvenile fish of species such as sea bass (*Dicentrarchus labrax*) and flatfish species such as Dover sole (*Solea solea*) occupying shallow marginal areas in the summer months to take advantage of solar warming and abundant food supply, but retreating into deeper waters of more stable temperature regime to overwinter (Wither et al. 2012).

It remains to be seen how different the findings would be for intakes located several kilometres offshore when the NNB stations are commissioned. Nonetheless, some years of trawling and plankton surveys have now been carried out for NNB sites with proposed offshore CW intakes, such as Hinkley C, Moorside and Sizewell C (unpublished data – circulation restricted), from which the 'available' fish for entrapment can now be better ascertained. It is recommended that a review and summary of this data would allow better optioneering of how intake location might be expected to influence the demographic of impingement and entrainment.

The Environment Agency report (2010a, p. 90) refers to PISCES (Prediction of Inshore Saline Communities Expert System), a computer programme designed to provide indicative levels of fish and crustacean impingement that might be expected to occur for intakes at different locations around the British coastline, and flagged the forthcoming arrival of a new version (PISCES 2009). The original purpose of the PISCES software was to compare relative impingement risk at alternative intake locations. Following the release of PISCES 2009, Metcalfe (2011) undertook a review of its performance under the BEEMS (British Energy Estuarine and Marine Studies) programme. The main conclusion was as follows:

> *PISCES 2009 is not capable of accurately predicting impingement rates at specific locations that might then be used formally as scientific reasoning for the decision to locate a new power station at a particular site. It should therefore be used as only one of a suite of tools in the preliminary stages of exploring the positioning of new power stations, and cannot be considered as a replacement for scientific investigation into, and reporting on, specific sites. It is our view that direct observations and surveys at candidate sites remain the best way to obtain robust scientific information.*

This conclusion should be taken into account in any future use of PISCES 2009, or indeed earlier versions.

A further possible development is the introduction of CW intake offshore islands, now being considered for some UK NNB and Combined Cycle Gas Turbine (CCGT) sites. These differ from conventional submerged offshore intake heads in that there would be an engineered island on which the drum- or band-screens would be located rather than having them onshore at the CW pump house. This has the potential benefit of being able to return fish removed by fish recovery and return (FRR) facilities to sea via a very short route. However, the FRR return point would have to be located to ensure no recirculation of fish back into the intakes

The Central Electricity Generating Board (CEGB) planning department and Generation Design & Construction Division (Barnwood) considered options for offshore intake islands during the 1960s. At the time, these options were not progressed due to concerns relating to access for maintenance in all weathers, security and navigation (J. Coughlan, personal communication) There is no precedent for the use of CW intake offshore islands in the USA (Doug Dixon, 316(b) Program Manager Electric Power Research Institute, USA, personal communication: email dated 2 February 2017). No evidence from elsewhere has been identified in this review.

The use of individual-based models (IBMs) using a Eulerian–Lagrangian platform in which biota are treated as agents within an underlying hydrodynamic model, has become a powerful predictive tool for fish migration pathways and interactive behaviours that may be used to inform expert opinion on the siting of intakes in order to reduce the impact on migratory species. IBMs have been used to model fish larval advection and to predict probability of entrainment at CW intakes since the early 1990s (Bartsch et al. 1989, Ahsan et al. 2003). For NNB design, passive particle ('drogue') tracking models have previously been used (e.g. on Horizon's Wylfa project), whereby fish were treated as passive objects without taking account of their swimming behaviour and reactions to depth changes or habitat structures. In recent years, modelling capability has developed rapidly enabling rule sets to be developed that can parameterise IBMs for species and life stages whose transition through estuaries and coastal waters are not influenced by hydrodynamics alone. Virtual fish can be given attributes of behaviour according to species and life stage, and therefore the model can seek to predict the most likely reactions to habitat structure and currents (e.g. in breakwaters). For example, IBMs can predict the relative numbers of fish that are likely to encounter the intake under various design scenarios using behavioural data such as volitional swimming speed and track tortuosity recorded in representative environments (Willis 2011).

Due to the challenges of successfully monitoring the migratory pathways of fish in transitional and coastal waters, few studies have previously collected the data required to inform IBMs. Technological advances, increased investment in coastal and offshore projects such as wind farms, tidal lagoons, tidal turbines and power stations, combined with an emphasis on understanding the complex migratory pathways and life histories of diadromous species (e.g. sea trout (*Salmo trutta*): Turnpenny et al. 2017) has led to a number of more recent projects. Specifically, research into the estuarine and coastal migration of Atlantic salmon (*Salmo salar*) (Kocik et al. 2009, Dever et al. 2016, Lothian et al. 2017) and sea trout (*Salmo trutta*) smolts (Davidsen et al. 2014, Eldøy et al. 2015, Flaten et al. 2016) and kelts (Aarestrup et al. 2015, Aldvén et al. 2015) and adult European eel (*Anguilla anguilla*) (Walker et al. 2014 Bultel et al. 2014, Barry et al. 2016 Verhelst et al. 2016) in some environments has increased. Movements of other diadromous species and life stages, such as pre-spawning adult salmonids, sea (*Petromyzon marinus*) and river (*Lampetra fluviatilis*) lamprey and allis (*Alosa alosa*) and twaite (*Alosa fallax*) shad remain less well documented. In the UK, research is currently focused in Scotland (Guerin et al. 2014, Lothian et al. 2017) and Ireland (Barry et al. 2016; however, a number of studies are planned around England. Willis (2011) and Guerin et al. (2014) provide good reviews of modelling fish behaviour in hydrodynamic models.

3 Intake head designs: engineering practice

The Environment Agency (2005) best practice guide proposed that offshore CW intake head designs with 360-degree abstraction, operating in a tidal stream and typical of older UK nuclear stations, should be superseded by intakes with lateral openings so that intake velocities would not be unduly influenced by tidal currents. The document presented the design of a low-velocity side-entry intake developed by the Central Electricity Research Laboratories which had been model-tested but never previously built.

Putting this into practice has presented a number of challenges to developers. The key ones have been:

- developing a hydraulic design which provides a reasonably uniform approach velocity across the intake openings (see section 4)
- developing a constructible engineering design that can be built off site (e.g. in a shipyard) and towed into place
- achieving compliance with nuclear safety imperatives (principally resistance to seismic shock, minimising chances of accidental blockage of flow openings by flotsam, jetsam and collapsing components of the intake itself or in the event of ship or aircraft collision)
- ensuring maintainability
- design and maintainability of any added fish protection device (e.g. behavioural fish deterrents: section 5)

Presently, the only fully developed design has been for the Hinkley Point C (HPC) project and therefore this design merits close scrutiny. Jacobs (2010) presents a design study undertaken for HPC. This document followed a Phase 1 study (not seen by the authors), in which five intake options were considered, and the Phase 2 report focused on the preferred option only. The selected design was considered to have better hydraulic performance and greater resistance to seismic deformation which is required to meet nuclear safety requirements. Further design developments may have taken place since the Phase 2 report and should be included in the review if they can be made available.

The use of shoreline intakes has been optioneered at more than one NNB site and may also be of interest in any new CCGT developments. Little was discussed in relation to shoreline intakes in a review of CW options (Environment Agency 2010a), but some aspects have come to light in discussion with developers and merit further advice. These particularly concern the use of breakwaters:

- The potential for tidal concentration of fish into dredged intake channels as the tide falls was highlighted by the Environment Agency (2010a), with the remedy of sheet-piling the channel margins to divert fish away from the channel. Other forms of breakwater have been considered by developers for this purpose (e.g. NuGen for Moorside). Innovative methods for breakwater construction are being developed within the tidal energy sector (Tidal Lagoon Swansea Bay Project) and may have useful application within the NNB field.

- Where onshore intakes open onto exposed coastal waters, developers have indicated the need to install breakwaters to protect the intake from destructive wave action. The default is to consider the design and placement of breakwaters purely from a coastal defence perspective, whereas it is apparent to fisheries specialists that the shelter created by these structures may unwittingly provide refuges for fish and their predators, which may endanger fish by encouraging them to remain in the vicinity of the intakes.

4 Approach/escape velocity

Approach velocity for a CW intake can be considered to be the main channel flow or tidal stream velocity, whereas the escape velocity is the speed a fish needs to be able to swim in order to escape, which may be different if the escape direction is not aligned with the flow. For onshore intake applications with an approach channel this calculation is straightforward (see Environment Agency 2005) but for a side-entry intake it can vary along the length of the side openings. This is partly because the momentum of the water in the direction of flow can bias the distribution along the intake face. Secondly, the distribution of riser pipes connecting the intake head to the culvert below can affect the internal hydraulics of the head. Finally, the flow distribution along the intake face can be affected by the porosity of the coarse screening fitted and by any internal baffles installed to regulate the distribution of flow. Furthermore, the velocity distribution can be expected to vary depending on tidal velocity and CW abstraction rate. Local velocity hot-spots may also result should screens become heavily fouled.

Environment Agency (2010a, p. 112) proposes: ‘For most power plant intake purposes a design fish-escape velocity of $0.3ms^{-1}$ will be suitable and meet best practice requirements. Where a different value might be preferable, the guide should be consulted.’ It is unclear what exactly the term ‘design velocity’ means here. Conventionally, the design velocity starting point is taken as $U = Q/A$, where Q is the CW flow and A the screen open area and developers have generally taken the $0.3ms^{-1}$ in this context. This represents an average velocity across the screens. Environment Agency (2005) best practice guidance promotes the use of hydraulic modelling to examine how actual velocities might deviate from the nominal design value under various operating and tidal conditions. The Jacobs (2010) Phase 2 CW intake design report for HPC included an extensive computational hydraulic modelling study carried out by HR Wallingford which investigated the variation of escape velocity along the lateral intake openings under different tidal stream states. It showed that hot-spots of up to 50% higher than the design value can occur in extreme cases, although the higher velocity areas are balanced by lower velocities on other parts of the opening. The subject was further investigated in a biological context by Turnpenny (2010) who examined the implications for fish at the Hinkley Point sites according to predicted swimming abilities.

Subject to release of the documents by EDF, it will be helpful to critically review the findings of the HPC studies to provide regulators with a better understanding of what can realistically be achieved in intake design. This could also provide information on fish risk assessment procedures and the effects of variation from an average design approach/escape velocity value of $0.3ms^{-1}$.

5 Fish behavioural deterrents

The Environment Agency (2010a) report indicated that, despite environmental challenges, direct seawater cooling can still be considered BAT as per the Integrated Pollution Prevention and Control Directive (Environment Agency 2003), ‘provided that best practice in planning, design, mitigation and compensation are followed’, which would include the use of behavioural fish deterrents as described in Environment Agency (2005) to minimise the risk of impingement of hearing-sensitive species that are not amenable to the FRR process. Such species notably include fragile pelagic species such as herring, sprat and shad, but many other less fragile species such as gadoids and bass can also benefit from deflection at the CWS intake point.

This is an emerging topic, as NNB sites have only within the last few years moved on to considering the practicalities of deploying fish deterrents at a remote offshore CW intake. To date, almost all the fish deterrent systems used have been fitted to onshore intakes (e.g. Pembroke CCGT: Lambert 2014) where electrical supply and control gear are readily accessible and where there is pedestrian and vehicle access for maintenance. The only exceptions have been Hinkley Point B (trial system in 1991–92) where there was pedestrian access to the offshore intake via a 500m sub-sea tunnel and an existing electrical power supply at the intake head, and Doel Nuclear Station in Belgium (Maes et al. 2004) where the offshore intake was located within a hundred metres or so of a jetty which housed the electronic control gear.

Acoustic propagation models such as PrISM™ can be used to determine optimum configuration of sound projectors for acoustic fish deterrent (AFD) (Lambert 2014). Recent discussions with designers and manufacturers have however identified additional considerations that are required to be taken into account so as to ensure nuclear safety imperatives are not contravened including:

- AFD hardware should not disturb the hydraulic performance of the CW intake head.
- Orientation of the AFD sound projectors should be arranged in such a way as to minimise effects of water currents on AFD performance and to minimise silt ingress.
- There should be a sufficient number of sound projectors to provide redundancy for reasonably expected unit failures between service intervals. Advice on how this is to be estimated should be provided.
- There should be a proven means of accessing and, if necessary, retrieving AFD equipment from offshore. This may be by raising units to the water surface by some means, or possibly by use of remotely operated vehicles as is being considered for HPC.
- There must be no risk of installations or units coming loose and entering/ blocking the intake ports.

A number of fish species are known to be able to detect and respond to ultrasound at frequencies greater than 20kHz (Ross et al. 1993, Popper et al. 2004, Teague and Clough 2014) and specialist AFD manufacturers are currently developing ultrasound deterrent devices which have a potential application for the deflection or exclusion of clupeid fish including shad. A particular innovation in the UK is the development of a wide dispersion transducer (Fish Guidance Systems), the benefit of which is to provide a more uniform acoustic gradient than existing devices which typically form ‘pencil’ beams.

Mortenson Companies (Minnesota, USA) report having successfully installed ultrasonic fish deterrents at three power plants to date: Haripo (Bangladesh), Samchenpo and Seochen (South Korea). However, the authors have yet to see independent verification of the effectiveness of these schemes.

In a literature review of the effectiveness of non-physical, behavioural barriers, Noatch and Suski (2012) noted that the effectiveness of strobe systems varied, dependent upon target species and life stage, design and brightness of the lights, turbidity and ambient light level. The Environment Agency (2010a) report noted that strobes appeared to be one of the few effective means of deterring eels, an important consideration under the Eels (England and Wales) Regulations 2009. Strobe lamp technology has continued to develop rapidly since the time of the 2010 report and a full and up-to-date account of both the technology and eel response to strobes has recently been published by EPRI (2017). The EPRI report, undertaken by THA Aquatic, comprised a review of the world's primary and grey literature (2007 to 2015) to evaluate the effectiveness of light stimulus to deflect downstream migrating eels. Additional independent studies undertaken recently by THA Aquatic have included flume trials on the response of fish species to strobe lighting. This recent unpublished work includes silver/yellow eel, elver, sand smelt (*Atherina presbyter*) and juvenile herring (*Clupea harengus*).

It is perhaps surprising that, despite the installation of AFDs on a number of English (Shoreham, Marchwood, Staythorpe) and Welsh (Pembroke) CCGT power station sites over the past decade or so, there have been no formal biota deflection efficiency trials of the type described by Maes et al. (2004) at Doel Nuclear Station, Belgium. Under such circumstances, there appears to have been a reluctance to approve switching off the deterrents for the periods that would be necessary to achieve a statistically robust trial. It is recommended that conditions are considered during preparation of the relevant environmental permit such that would require the deterrent to be operated at all times unless otherwise permitted by the permitting authorities.

In other applications, such as protection of down-migrating salmonids at irrigation intakes on large rivers in the USA (Bowen et al. 2009, California Department of Water Resources 2014) and control of the spread of invasive fish species (Ruebush et al. 2012) there has been more recent positive evaluation of the performance of light- and sound-based fish barriers using similar hardware to that installed on UK power stations.

6 CWS tunnels: pressure change effects

Current evidence (Environment Agency 2010a) makes reference to potential pressure-related effects (barotrauma) associated with fish passage through deep CWS tunnels. The basic premise is that when fish are subject to rapid depressurisation, gas-filled organs (principally the swim bladder, but also pro-optic bullae in clupeids) tend to expand according to Boyle's Law, risking rupture. Those most at risk are physoclists (e.g. gadoids, bass), which can only adapt over periods of hours by vascular gas exchange, whereas physostomes (e.g. salmonids, eels, clupeids) can vent excess gas to the exterior. Gadoids such as cod (*Gadus morhua*), bib (*Trisopterus luscus*) and whiting (*Merlangius merlangus*) have been found to be most affected in previous studies (Turnpenny 1992, Seaby 1994). This has since been supported by unpublished studies at Thameside and Medway stations, including Tilbury and Isle of Grain. There is also evidence of gas embolisms in eyes of clupeid fish, although this is less critical in the power station context since their protection depends on deterrent systems fitted at the CWS intakes rather than FRR (for which 100% mortality is generally assumed).

Interest in this topic has increased with the likelihood of building deep tunnels of up to 70–80m below bed level at some proposed NNB sites. This is often a necessity to reach the stable geology through which the tunnels can be successfully bored. Each 10m descent below the seabed increases the hydrostatic pressure by 1 bar, so fish drawn into the tunnel may be exposed to pressure increases of several bar, this being maintained for the duration of passage to the pumphouse/forebay. Approaching the forebay with its free water surface, the ascending section of the tunnel brings the pressure back towards atmospheric levels.

Further consideration of this topic is required to clarify the important aspects of this process. The risk of pressure-related injury is most likely related to differences between the original acclimation pressure of the fish (based on the depth from which they were drawn into the intake) and atmospheric pressure as fish are lifted from the water by the fine screens. As an example, if the fish's acclimation depth was 10m (1 bar pressure due to water + 1 bar atmospheric = 2 bar absolute), bringing the fish to atmospheric pressure (1 bar absolute) would halve the pressure and double the swim bladder gas volume, potentially rupturing the swim bladder in a physoclist. Hence the depth of the tunnel per se should not affect barotrauma risk. Also of relevance are the rates of acclimation of varying species, and the limited information on whether the pressurisation phase is benign.

Information on barotrauma effects in fish has come primarily from work relating to fish passage of hydroelectric turbines. Of most relevance to NNB applications are data from laboratory studies on pressure change effects in UK marine and anadromous species reported by Turnpenny (1988) and Turnpenny et al*.* (1992) in relation to tidal energy barrages.

Since there is no direct evidence from deep tunnel passage monitoring for sites with tunnels that are likely to be several kilometres in length for NNB, there is an urgent need to commission laboratory studies which simulate NNB tunnel passage more specifically, using engineering data on tunnel design and water speed. In this case, methodologies similar to those described in Turnpenny (1988) and Turnpenny et al*.* (1992) would be appropriate.

7 Forebay and screenwell design, including hydraulic conditions

A key area for update of existing information relates to the potential impact on survival of turbulence and stress due to forebay and screenwell design. The possibility that turbulence in the forebay and screenwells may affect fish survival rates, and that prolonged swimming may lead to exhaustion, are mentioned within the 2010 report (Environment Agency 2010a, p. 91) but not discussed further. However, this topic has attracted some discussion during the NNB programme and is worthy of further consideration.

Particular issues that have emerged include:

- turbulence and energy dissipation in forebays and screenwells
- promontories and ‘sharp’ corners extending into the forebay
- optimum band- or drum-screen surface approach velocities
- the possibility of attracting and pumping out larger fish that are excluded by forebay bar screens and directing them into the FRR system, rather than allowing them to be removed by the bar-rack raking system before being transferred to FRR launders

The matter of turbulence and energy dissipation appears to have been confused by a recommendation given in Environment Agency (2010a, p. 122), which states in relation to FRR system design:

> *Turbulence should be minimised to reduce the risks of fish exhaustion and injury. It is recommended that energy dissipation throughout the system should be kept at or below 100Wm^{-3}. This particularly applies to any fish sampling or holding facility that may be incorporated for fish impingement monitoring purposes.*

The confusion arises over where this criterion should apply. In the original development of the document, the phrase ‘throughout the system’ made references to the FRR system, this being defined as starting from the surface of the drum- or band-screens and ending at the release point. It was not meant to include the forebay and screenwell, where it is entirely impractical owing to the physics of the situation to achieve energy dissipation levels below 100Wm^{-3} around the tidal cycle. This is because of the high kinetic energy of up to a hundred or more tonnes per second of seawater entering the forebay at tunnel velocities of typically 2–3ms^{-1}.

The 100Wm^{-3} criterion was taken from the Environment Agency *Fish Pass Manual* (Environment Agency 2010b, where it was presented for use in fish pass resting pools. It therefore applies in a situation where fish are being retained in a volume of water for long periods, for example in this case in fish sampling or holding facilities within the FRR. The calculation of how this applies to launders within the FRR system has also caused confusion and we would suggest that this criterion in future guidance should apply only to fish sampling or holding facilities within the FRR. Conditions within the launders, where the intention is to pass fish quickly through, are best met by specifying other criteria (see section 9).

Alternative advice based on hydraulic shear stress is proposed rather than use of the energy dissipation criterion within the forebay and screenwells (THA 2015a). Shear stress occurs in fluids across a velocity gradient. A fish that enters such an area is exposed to shearing forces across its body, which can lead to various forms of trauma, including scale and mucus loss from the body surface, and injuries to exposed delicate organs, principally the eyes and gills (Turnpenny 1998, Turnpenny et al*.* 1992, Čada et al*.* 2007). Since turbulence results in the formation of vortices across which there may be strong velocity gradients, shear stress and turbulence are closely linked. Torsion injuries can include spinal fracture or decapitation. The more extreme injuries only occur in much more energetic conditions, however, such as within a hydraulic turbine (Turnpenny 1998).

Shear stress, like pressure, is a force per unit area, and has the same units, Newtons per square metre (Nm^{-2}) or Pascals (Pa: 1Pa = $1Nm^{-2}$); but whereas a pressure is directed perpendicular to a surface, shear stress acts parallel to the surface.

Threshold values for injury of fish exposed to shear stress are derived from laboratory studies. In the USA, Čada et al*.* (2007) defined a threshold shear stress value for fish injury of $1{,}600Nm^{-2}$ but the work on which this is based appears to have focused mainly on salmonid fish. Of greater relevance to fish species in UK coastal waters is the laboratory work carried out by Turnpenny et al*.* (1992) as part of earlier Severn Tidal Power investigations, which leads to a similar estimate of injury threshold. We recommend that future guidance for allowable forebay and screenwell turbulence requires estimation of shear stress, therefore, rather than energy dissipation. Further consideration of the available information in this area is recommended.

Where biota are required to be recovered onto a fine screen to enable recovery to a return system, current recommended screen approach velocities (Environment Agency 2005, 2010a, 2011) may not be appropriate as these values fall below the calculated sustained swimming speed (90th percentile) of the principal species encountered around the UK coastline. Where fish are to be returned to the source water by a FRR facility, screen escape (approach) velocities may need to be higher than those previously recommended. Velocities should be optimised to minimise the retention of the target species within the forebay/screenwell while ensuring that once impinged fish/biota are not damaged. As for hydraulic turbulence and shear stress, this issue is worthy of further consideration.

8 Onshore screening including fish recovery facilities

Onshore fish screening for NNB plant usually comprises an initial tier of bar-rack screens of ~50–100mm spacings, followed by an array of band- or drum-screens. Fish handling in relation to forebay raked screens is discussed in Environment Agency (2010a, p. 66). At that time, no standard commercial designs for fish-handling screen rakes were known and therefore advice was limited to the statement: ‘Regulators should be satisfied that the design and performance of any forebay raking system is compatible with FRR requirements’.

Since that time, screen manufacturers including Beaudray (France) and Ovivo (UK) have developed fish-friendly raking systems. The ‘Bio-flush’ raking system developed by Beaudray has been installed on trash screens at Wilhelmshaven power plant, Germany, and further evaluation of this system is warranted. Ovivo has incorporated fish-friendly components to its fixed head cable hauled raking machine, incorporating a trough/skip onto the rake head to retain fish away from the screen face during the cleaning process and prior to their being transferred to a return launder. The system, although proposed for HPC, has yet to be installed and it is therefore not possible to judge the efficacy of the designs. With respect to providing further advice, this may have to be limited to advising developers that they would need to demonstrate fish-friendliness of designs in a prototype system prior to plant construction.

Bilfinger GmbH do not currently market a ‘fish-friendly’ bar screen raking system. They have however developed a ‘soft-start’ arrangement whereby once the rake is lowered and engaged into the screen, the procedure pauses to enable fish to swim away from the path of the rake. While this would not overcome the problem of larger fish becoming trapped in the forebay it would be worth evaluating alongside the offering from both Beaudray and Ovivo.

An alternative concept to a fish-friendly rake is a fish guidance and return system. Such a system is used in the San Onofre Nuclear Generating Station (SONGS) in southern California, where a unique ‘Fish Chase’ procedure has been developed. This procedure slowly reintroduces heated water back into the forebay via crossover gates to herd and dislodge fish that have aggregated in areas of low flow in front of behavioural screens towards a fish return system. The fish return system consists of an elevator that periodically raises fish herded into the elevator chamber to the surface and releases them via a sluiceway back to the source water.

Light-based systems offer an alternative to thermal guidance and have been demonstrated to effectively attract or repel a variety of fish species (Environment Agency 2005) where water conditions are appropriate. Light guidance devices could be used to encourage fish entrapped within a forebay towards a fish return system (e.g. a fish-friendly pump or fish lift). Studies undertaken in the USA by ATET-TECH (Ford et al. 2017) and by Fish Guidance Systems in the UK (commercial in confidence) have shown various spectral and flash frequency to be effective at either attracting or repelling a wide variety of fish species and this approach warrants further research.

The use of band-screens on NNB within the UK is generally restricted to screening of auxiliary/essential seawater supplies, with the larger capacity drum-screens providing the main CW screening duty. A factor in choice of design of either type is any nuclear safety qualification. This would typically require resistance to seismic shock and aircraft impact but only applies to non-closed-circuit-cooled reactor designs.

Seismic qualification is related to stability and mass of moving parts and is easy to achieve with little or no qualification on drum-screens. For band-screens, the addition of fish recovery buckets filled with water considerably increases the mass of the moving elements of the screens and requires more careful design and use of low-mass components. For this reason, some developers have sought clarification on whether band-screens need to be FRR compliant, arguing that they are infrequently operated and of low flow capacity compared with main CW screens (typically around 5%). New information should be sought which may give clarification on this.

Recent development of travelling water screens (TWS) has been undertaken by both Hydrolox and Bilfinger Water Technologies GmbH.

Hydrolox band-screens, designed with a cantilevered head to aid delivery of fish from the fish bucket to the return launder and fitted with modified Ristroph-style fish collection buckets, have been shown to minimise impingement mortality (EPRI 2015a) and suggest the design is best technology available (BTA) enabling compliance with Section 316(b) of the Environmental Protection Agency (EPA) Clean Water Act (USA). Modified Ristroph TWS have also been evaluated at Alabama Power Company's Gorgas Generating Station and a study incorporating fish impingement rates and 24- and 48-hour latent impingement mortality rates has been published by EPRI (2006, 2014). Further studies undertaken by Black and Perry (2014) evaluated the performance of the screen to prevent impingement losses over three approach velocities: 0.3, 0.6 and 0.9ms^{-1}.

Bilfinger Water Technologies GmbH have also developed the Geiger MultiDisc® screen incorporating a fish return system (Rehnig 2014). The MultiDisc screen has been evaluated in laboratory trials (EPRI 2013c) that assessed the survival, injury and scale loss of fish exposed to, and recovered by, the screen to assess the potential for these screens to meet requirements of Section 316(b) of the EPA Clean Water Act (USA). The MultiDisc screens have been installed at a number of nuclear power stations throughout the USA.

Sinuous species such as the European eel are vulnerable to physical and stress-related injuries and delay to migration resulting from inadequate or unsuitable recovery mechanisms associated with physical exclusion screens. The design of the fish-retaining buckets on existing band- and drum-screens may not be suitable for the retention of larger specimens of eel and lamprey during the period of elevation from the screenwell to the collection hopper (THA 2012). This may result in fish falling back into the screenwell and being subjected to repeated handling. The design of 'fish buckets' has attracted considerable discussion in regulatory negotiations with NNB developers and is worthy of further consideration.

KLAWA has developed an eel bypass system to intercept eels at water undertakings prior to impingement that has been installed at hydroelectric schemes within Germany (e.g. north Hesse). The system consists of a perforated zig-zag collection-pipe located on the bed and placed in front of and parallel to the toe of a physical exclusion or trash screen. The placement of bristle brush laid perpendicular to the flow immediately upstream of the pipe is designed to optimise habitat and flow conditions and encourage eel entry into the pipe. Eels entering the pipe are pumped to a bypass/return channel. The design has potential to remove large eels from the forebay and screenwells of power stations and further evaluation of this system is warranted.

9 Fish return launders and discharge head design

There is currently no recommended guidance within best practice for the height of drops within a fish recover and return system or the depth of the receiving water body into which fish fall to ensure optimum fish welfare. Similarly, once fish have been recovered into a return launder there is little guidance on the optimal depth or velocity of water required to convey fish through the system. Onus is with the designer/operator to provide a system that avoids injury to fish and this is subject to professional opinion.

The acceptable fall height for both fish and biota discharged from fish buckets to collection hoppers (drum-screens) and from fish buckets to the head of a fish return launder (travelling band-screens) has been a point of discussion in regulatory negotiations with NNB developers and is worthy of further consideration.

Studies undertaken by EPRI (2013a) for a limited range of North American freshwater species indicated that the survival rates of fish discharged from heights ranging from 0.61m to 1.22m were significantly lower than fish released at the same velocity via an underwater discharge. There are no data for the survival of fish common to UK coastal waters and this may be a potential area for future research. Some studies of UK fish trawling discard survival by Cefas may have relevant information worth reviewing.

Studies within the UK (Turnpenny 2010) suggest that turbulence throughout the FRR system should be minimised to reduce the risks of fish exhaustion and injury. It is recommended that energy dissipation should be kept at or below $100Wm^{-3}$. This value has been derived from the power density value recommended for resting facilities in fish passes as cited in the *Fish Pass Manual* (Environment Agency 2010b) The value was recommended in the Environment Agency 2010a document following observations of fish holding facilities installed within the FRR launders in some coastal stations, introduced to facilitate monitoring of survival rates within the CWSs. It was considered that holding fish for prolonged periods (in excess of 24 hours) in turbulent environments may in itself adversely affect survival rates. Power dissipation values are not pertinent within launders or gutters, where a low-energy environment may result in silt or debris settlement and fish may be encouraged to loiter thereby increasing the delay to fish passing through the FRR. Turbulence within the launders and channels where fish should not be encouraged to dwell may be better evaluated against shear stress (measured in Nm^{-2}) and scale of turbulence.

Injuries recorded at various levels of shear stress generated within a laboratory flume for species commonly found around the UK coastline have been provided by Turnpenny et al. (1992). This shows that only at levels above $1{,}600Nm^{-2}$ were injuries or mortalities recorded, other than in juvenile herring, which are exceptionally fragile. There is however a paucity of data below shear stress levels of $1{,}920Nm^{-2}$ and again this is recommended as an area for future study.

Handling fish and significant volumes of debris in the same gutters is not regarded as BAT as fish may be smothered and asphyxiated when compressed among other debris and may suffer osmotic stress caused by damage to the epithelial tissue or resulting from significant scale loss. While physiological stress may not result in immediate death, it may lead to subsequent mortality of the organism due to a lowered resistance to predation and disease or an inability to actively compete for food (Mesa 1994, cited in Čada et al. 1997). A review of the survival and injury of juvenile fish resulting from debris exposure with an FRR has been undertaken by EPRI (2010, 2012, 2013b).

A review of fish conveyance systems in FRR at existing facilities within the USA has been undertaken within EPRI (2015b). The report reviews inter alia the developments in the current state-of-knowledge of stressors that can influence the safe transport of fish within a fish return conveyance system. A review of the effects of distance on the survival and injury of juvenile fish within FRR has been undertaken by EPRI (2013b).

10 Fish lift pumps: ensuring fish-friendliness for appropriate FRR-dependent species

Where the fish return launders or pipes are not sufficiently elevated to discharge under gravity, additional lift can be provided using fish-friendly pumps. Types include Archimedean, helical and axial screw pumps.

An evaluation of Archimedean screw pumps for the safe passage of eel was carried out within a review on behalf of the Environment Agency by Solomon (2010). The factors considered to influence fish-friendliness of Archimedean screws were considered to be as follows:

- the design of the leading edge of the first winding at the entrance to the pump
- the number of flights (blades), with a greater number of flights giving an increased risk of fish colliding with the leading edge
- screw diameter and rotational speed
- clearance between the edges of the windings and the trough
- pitch of the screw

Shrouding the screw eliminates gaps between the blades and the trough in which it rotates and is considered to improve the fish-friendly credentials of the screw by reducing leakage through this gap, which can result in fish becoming pinched and damaged. FishFlow Innovations (Netherlands) provides an evaluation of its fully shrouded screw installed at Kortenhoef pumping through its website (FishFlow Innovations 2017. Landustrie Sneek BV (Netherlands) has developed a partially shrouded screw with the lower inlet shrouded where the blade and trough interface meet with the remainder of the screw above this point rotating within an open channel. Blade modifications which increase gradually in diameter from the hub towards the outside diameter of the screw pump where they merge with the enclosing shrouded provide additional protection to fish entering the pump. Both ANDRITZ Atro GmbH and Spaans Babcock make similar fish-friendly claims for unshrouded screw pumps used for power generation (Kibel et al. 2009, Kibel and Coe 2011).

The Environment Agency has provided guidance for the design of screw generators (which work in the reverse direction to pumps) based on good design practice adopted by pump manufacturers within its hydropower good practice guidelines (Environment Agency 2011). To date this has formed de facto best practice for screw pumps.

Alternatives to the screw pump include spiral vane pumps (Hidrostal Ltd), helical screw centrifugal fish pumps and axial pumps (Bedford Pumps Ltd, UK; FishFlow Innovations, Netherlands) all of which claim fish-friendly credentials. A review of fish- and eel-friendly pumps has been provided by Solomon (2010), EPRI (2013a) and Jackson (2014).

There is scope to improve our current understanding of fish welfare and best practice with regards to the passage of fish through 'fish-friendly' pumps and this may be achieved through a review of primary literature or further independent research.

11 Biofouling control, implications for FRR and fish risk assessment protocols

The key need for biofouling control within elements of the FRR system occurs where an offshore intake supplies seawater to the forebay and drum-screen area via a long tunnel which may become partially blocked by mussel growth and other biofouling. Environment Agency (2010a) assumed that where FRR systems were incorporated, fish would not be exposed to chlorination or other toxic biocidal treatments during passage through the plant unless it could be demonstrated through a suitable ecotoxicological risk assessment that no harm would result to the fish. The risk and consequence of marine fouling was considered by Eley and Fyfield (2009) and the toxicity of chlorine by-products was reported in BEEMS (2011b).

It is understood of course that nuclear safety considerations may override the need to protect fish in some circumstances. The Environment Agency (2010a) report also did not envisage that it would be necessary to chlorinate the FRR system itself downstream of the drum-screens to prevent biofouling within the launders or return tunnel (using manual or ‘pig’ cleaning instead), but developers are now proposing that this may be necessary. This makes the requirement for an ecotoxicological assessment more important but presently there is no agreed protocol for undertaking such an assessment. In any new assessment, consideration should be given to both acutely lethal and sub-lethal effects, including any additional loss of equilibrium caused by chlorination, or other biocide, that might put fish at a disadvantage to predators at the release point.

Where lethal test data are put forward as part of the risk assessment, the protocol needs to address exposure times and biocide concentrations relevant to FRR applications, species, life stages and numbers of test fish and replicates, water temperatures and other standard ecotoxicological requirements. Available published data should be used wherever possible in order to comply with Home Office licensing requirements to minimise unnecessary lethal testing; however, published data on relevant UK species are limited and need to pass a compliance test based on the conditions that will be set out in ecotoxicological protocols.

A rotary flow technique pioneered by Lindahl and Schanbom (1971) presents a method for assessing sub-lethal effects following exposure to biocidal treatments. In this method, fish are placed in a water tunnel with rotating flow (‘swirl’). As fish experience physiological trauma, they lose equilibrium and cannot maintain orientation in a flow. This seems to be a particularly relevant test in relation to a fish’s ability to behave naturally and avoid predation as it emerges from an FRR outfall.

Further understanding regarding when there is an essential operational need to apply biocides at FFRs and components that should contribute to an ecotoxicological risk assessment would be beneficial.

12 CW systems downstream of fine screens

The laboratory simulator known as ‘EMU’ (entrainment mimic unit) was designed to simulate conditions in CWS as a means of assessing likely mortalities of entrained organisms such as fish eggs and larvae (Bamber et al. 1994). The facility allowed the assessment of the effects of the four principal stressors of entrainment: temperature, pressure, biocide and mechanical effects, alone and in combination. Reviewing the science on power plant entrainment survival studies in relation to US EPA policy, EPRI (2009) commented favourably upon the UK work using EMU as an effective means of estimating passage survival. Its concluding comments on the use of laboratory simulators are stated as follows:

> *Overall these various studies show that entrainment simulators provide a viable approach for examining the effects of the various entrainment stresses, as well as the potential for interaction among stresses. They also eliminate most, if not all, of the hypothetical concerns about sampling bias that must be addressed for in-plant survival studies.*

Hence simulator studies can be considered state-of-the-art for entrainment survival assessment purposes, and are the only practical means of predicting effects for the CWSs of yet-to-be-built plants.

While the EMU approach is considered best practice for evaluation of entrainment survival, the specialised equipment and expertise required to develop new information extending the range of test conditions, species and life stages, and the length of study programme required to generate new information has prevented developers other than EDF Energy from taking this further. The EDF Energy BEEMS programme has carried out further extensive EMU testing but data are not currently publicly available.

A review of laboratory entrainment studies (Turnpenny 2000) details the most up-to-date entrainment simulator survival studies that have been published.

There is also some literature on the effects of shear stress on planktonic life forms, and shear stress and pressure changes on larval fish in relation to transit over weirs and under sluice gates, which may be worth reviewing in a further report.

13 Monitoring and assessment protocols for fish recovery and return facilities

A brief mention of monitoring impingement rates within FRR systems is made in Environment Agency (2010a, p. 91, pp. 179–180) but specification of monitoring requirements is not mentioned in detail.

Important issues that require further definition relate to FRR fish survival after passing through the FRR launders and include:

- choice of sampling point and collection method
- types of fish to be included (i.e. there is no point in testing fragile species such as clupeids where close to 100% mortality can already be assumed)
- sample sizes and number of replicates (noting that impingement rates may not support large sample sizes of some species)
- exposure conditions (e.g. tank set-up, volume, energy dissipation)
- biological monitoring criteria (e.g. survival, scale loss, injury types)

Now that the physical configurations of FRR lines are becoming better understood it should be possible to offer further practical advice on sampling points and set-ups.

As the NNB programme progresses it will be helpful to set out regulatory expectations on impingement quantity and survival monitoring. The BEEMS Expert Panel (BEEMS 2011a) set out best practice on estimating annual impingement rates as seen at the time of writing and it would be expected that any new advice would not deviate significantly from this. However, as the report is not widely available it would be helpful to reiterate the key points in a new Environment Agency publication. In particular, it considers the use of statistical power analysis to establish the optimum sampling regime. Another useful source of advice on statistical aspects is Murarka and Bodeau (1977).

Recent interest in this subject in the USA also provides examples for consideration, for example a presentation at the 2015 American Fisheries Symposium by Olken et al. (2015). Much of the US work on this subject is commissioned by EPRI, although its findings are not usually made available to non-EPRI members for 3 years or so. However, information may be available directly from the authors on request.

Further information may be available on sub-lethal effects that may affect fish behaviour and possibly compromise their ability to evade predators. The rotary flow technique (Lindahl and Schanbom 1971) is one possible method. Other potential testing options are considered in the publications authored by Čada and Odeh (Čada and Odeh 2001, Čada et al. 2006, 2007), in which fish reactions to simulated predators are observed following exposure to hydroelectric turbine passage.

Further information on FRR systems may be found in Turnpenny (2014).

14 Monitoring and assessment protocols for fish deterrent effectiveness

Fish deterrents, which may include use of acoustic, strobe light or other behavioural stimuli, vary in effectiveness according to the sensitivity of the species/life stages to the stimuli, the characteristics of the stimulus field that the installed system is able to generate, the velocity field around the intake and other physiological and environmental factors (Environment Agency 2005). To test their effectiveness in a power plant application, the simplest method is to compare band- or drum-screen impingement rates for alternating periods with the system turned on and off. The sampling methods in this case are as for impingement sampling (section 13) but a number of additional considerations apply:

- It is unlikely to be necessary to conduct testing year-round but periods should be chosen when valued ecological receptor or other 'target' species are likely to be present.
- Periods with the deterrent system off should be kept to a minimum so as not to unnecessarily compromise fish protection.
- There should be sufficient intervals between 'on' and 'off' periods to allow the forebay/screenwells to be cleared of fish from the previous test period. This requires residence time to be estimated (e.g. by tagging and monitoring fish return).
- Statistical power analysis should be used to assess the number of samples required (e.g. based on previous monitoring experience at the same or a similar site).

Evaluation of previous power station deterrent system trials could inform the design of future monitoring programmes, for example from trials at Hinkley Point, Hartlepool), Doel, Belgium (Maes et al. 2004) and Plant Barry, USA (EPRI 2008).

Consideration should be given to the use of power analysis in the design of tests to achieve the required regulatory objectives on detectable levels of reduction in impingement. The aim of these studies should be to validate assumptions on deterrent system efficiency presented in the project Environmental Statement and agreed as part of the Development Consent Order or Marine Licence. In the event of significant underperformance the operator would be required to liaise with the regulator on a site-specific basis.

Protocols for determining fish residence time within the forebay and screenwells should also be evaluated.

Part of the performance assessment process should also to be to validate by field measurement, any stimulus field modelling presented to regulators. This would normally be carried out during the project commissioning phase. Experience to date only relates to validation of acoustic emissions using the PrISM™ acoustic model. There are two parts to this: firstly, ensuring that the specified sound output levels are met and, secondly, making sure that the sound field will not extend beyond the required range with potential harmful effects on activities of fish and marine mammals in the wider sea area. Presently there are no formal protocols on this, but a number of investigations have taken place to assess the AFD sound field at RWE nPower's Pembroke CCGT power station (Ben Williams, RWE Pembroke Power Station, personal communication) which the operators may be prepared to share for this purpose.

An evaluation of previous field trials/studies of the stimulus field of behavioural deterrents supported by a review of standard operating protocols for underwater noise monitoring may inform the development of formal protocols to be adopted in post-commissioning trials of these alternative measures.

15 Updated methods for fisheries impact assessment

15.1 Equivalent adult value

The equivalent adult value (EAV) method has been used in UK power station fish impingement assessments since its introduction by Turnpenny (1988, 1989). The Environment Agency (2010a) report (pp. 102–104) refers to its use in NNB impact assessments and it has accordingly been adopted by NNB developers for this purpose. The EAV procedure is a valuable tool which allows catches of juvenile fish (which comprise the majority of fish impinged at power stations) to be converted to the equivalent numbers or weight of adults that would have survived to enter the fishery had they not been removed as a result of CW abstraction. They can then be compared in quantity with reported commercial landings, providing a context for assessment.

EAV calculations by the method of Turnpenny (1988, 1989) requires the compilation of life tables, which detail life history parameters including age-specific mortality, fecundity, sex ratio, age at first maturity and weight-at-age. Ideally the life tables are compiled using data for individual regional stocks and for recent periods (e.g. from the most recent 5–10 years). In practice, these require years of study that are beyond the realistic scope of developers and EAV application has therefore relied upon whatever available published data are most relevant and up to date. Turnpenny (1988, 1989) contains EAV data for a number of common commercially exploited species and the range of species and localities has been extended in other project-related applications (e.g. Turnpenny and Watkins 2006), but scope for inclusion of other species, stocks and timeframes remains limited by the available data.

Recently, Cefas (Metcalfe et al. 2016: BEEMS Technical Report TR383 (classified as UK Protect & Commercial Contracts)) has reviewed EAV methodology and has developed an alternative approach which estimates mortality data using length-at-age data via a von Bertalanffy Growth model. The method avoids the need for reproductive data and is based upon established general relationships between fish growth rate and maximum size and natural mortality rates set out by Charnov et al. (2013) and Kenchington (2013). It has the advantage of using more readily available or easily collected data on fish length-at-age for individual stocks and therefore increases the potential number of species to which EAV methodology can be applied using local and recent data. A full explanation of the method and worked examples should be provided in any future review.

15.2 Equivalent area of lost production

The equivalent area of lost production (EALP) method was developed in the USA to allow quantities of fish removed by power stations to be equated to the equivalent area of marine habitat being taken out of production for that species (California Energy Commission 2005, in Environment Agency 2010a, pp. 105–106). This is particularly suited to considering ecological requirements in compensation for residual impacts once other mitigation measures have been applied. California Energy Commission (2005) gives a brief mention of the EALP method but is not explicit. A limitation of the method has been the paucity of published data on fish production rates for UK estuarine and coastal waters which form the basis of EALP estimates. However, further advice can be provided on how to estimate production from biomass data using established relationships between production and biomass for estuarine and coastal waters. This will make the method easier for developers to apply and provide a practical basis for estimating compensatory habitat requirements.

In the EALP method the impact on fisheries productivity is expressed in terms of loss of fish production, *P*, which is defined by loss of biomass, *B* (kg km^{-2}: sometimes termed 'biomass density') per year (kg km^{-2} y^{-1}) (Bradford et al. 2014). This refers to the net biomass production of fish populations over time, taking into account weight gains through growth (kg km^{-2}) and losses through death (Randall and Minns 2000). The ratio of production to biomass, or *P/B*, gives an index of growth or decline in biomass and it has been shown that *P/B* ratios tend to be similar when similar types of marine or estuarine habitat are considered (Adams 1976, Thorman and Fladvad 1981, Elliott and Taylor 1989, Elliott et al. 1990). Fish biomass (kg km^{-2}) is estimated from routine survey techniques such as trawling or seine-netting, where the sampled area is clearly defined and taking into account gear efficiencies. Gear efficiency data for different sampling techniques can be obtained from published literature, provided that the same methods have been followed.

As a simple example, fish production (total biological production) for the North Sea has been estimated at 2,500kg km^{-2} y^{-1}, while estuarine production estimated for the Forth Estuary was 4,300kg km^{-2} y^{-1} (Elliott and Taylor 1989). These figures can be applied directly to power station fish catch estimates. For example, 43 tonnes of mixed fish per year impinged at Sizewell Power Station (Turnpenny and Taylor 2000) equates to an equivalent area of lost North Sea production of 17.2km^2 on this basis when the North Sea is taken as a whole. It is also preferable to relate to more specific habitat types where such information is available, in particular distinguishing between production in intertidal versus subtidal areas rather than using whole-water-body figures.

A review and evaluation of both primary and grey literature pertaining to fish biomass and production data may improve the applicability of EALP methodology in UK waters.

16 Conclusions

This preliminary study has outlined areas where there have been recent advances in technologies to protect biota from entrainment and impingement at large-scale water undertakings, and also in applicable assessment methods, since publication of the Environment Agency's Evidence document *Cooling water options for the new generation of nuclear power stations in the UK* (2010a).

The report has scoped the available information on existing and emerging technologies suitable for using in very large-scale CWSs, and outlined areas where a fuller review of material would be warranted.

The emphasis of the report is on fish protection, but these measures will also protect larval forms and other biota within the CWS.

The experience acquired by both regulators and industry in techniques for reducing biota entrainment and impingement gained since the Environment Agency (2010a) report has also been discussed and highlights where further clarity is required. Many of the technologies outlined in this document are emerging and developing technologies and information on their effectiveness and approaches for their implementation may change in the future.

Further information is available on many of the subjects covered in this document. A full review of the information sourced and identified in this report is recommended in order to provide an updated compilation of information and data on biota protection for large cooling water intakes such as required for new nuclear power stations.

References

AARESTRUP, K., BAKTOFT, H., THORSTAD, E.B., SVENDSEN, J.C., HÖJESJÖ, J. AND KOED, A. (2015) Survival and progression rates of anadromous brown trout kelts *Salmo trutta* during downstream migration in freshwater and at sea. *Marine Ecology Progress Series*, 535, 185–195.

ADAMS, S.M. (1976) Feeding ecology of Eelgrass fish communities. *Transactions of the American Fisheries Society, 105:4, 514-519.*

AHSAN, Q., BLUMBERG, A.F., DUNNING, D., LI, H., ALUARACHCHI, I.D., HEIMBUCH, D. AND LOGAN, D. (2003) Predicting entrainment of ichthyoplankton at a power plant intake on the East River, N.Y. *Proceedings of the World Water and Environmental Resources Congress 2003*; Philadelphia, PA 2003, pp. 2949–2958.

ALDVÉN, D., HEDGER, R., ØKLAND, F., RIVINOJA, P. AND HÖJESJÖ, J. (2015) Migration speed, routes, and mortality rates of anadromous brown trout *Salmo trutta* during outward migration through a complex coastal habitat. *Marine Ecology Progress Series*, 541, 151–163.

BAMBER, R.N., SEABY, R.M.H., FLEMING, J.M. AND TAYLOR, C.J.L. (1994) The effects of entrainment passage on embryonic development of the Pacific oyster *Crassostrea gigas*. *Nuclear Energy*, 33, 353–357.

BARRY, J., NEWTON, M., DODD, J.A., LUCAS, M.C., BOYLAN, P. AND ADAMS, C.E. (2016) Freshwater and coastal migration patterns in the silver-stage eel *Anguilla anguilla*. *Journal of Fish Biology*, 88(2), 676–689.

BARTSCH, J., BRANDER, K., HEATH, M., MUNK, P., RICHARDSON, K. AND SVENDSEN, E. (1989) Modelling the advection of herring larvae in the North Sea. *Nature*, 340, 632–636.

BEEMS (2011a) *Methodology for the measurement of impingement*. BEEMS Science Advisory Report Series No. 006 Ed. 2. BEEMS Expert Panel, EDF Energy.

BEEMS (2011b) *Chlorination by-products in power station cooling waters*. BEEMS Science Advisory Report Series No. 009 Ed. 1. BEEMS Expert Panel, EDF Energy.

BLACK, J.L. AND PERRY, E.S. (2014) Laboratory evaluation of the survival of fish impinged on modified traveling water screens. *North American Journal of Fisheries Management*, 34(2), 359–372.

BOWEN, M., TURNPENNY, A.W.H. AND JOHNSON, S. (2009) Testing of a non-physical barrier to improve escapement of Chinook smolts on the San Joaquin River in California's Sacramento-San Joaquin Delta. *Proceedings of the Institute of Fisheries Management 40th Annual Conference*, Stratford-upon-Avon, England.

BRADFORD, M.J., RANDALL, R.G., SMOKOROWSKI, K.S., KEATLEY, B.E. AND CLARKE, K.D. (2014) *A framework for assessing fisheries productivity for the Fisheries Protection Program*. DFO Canadian Science Advisory Secretariat Research Document 2013/067. v + 25 pp.

BULTEL, E., LASNE, E., ACOU, A., GUILLAUDEAU, J., BERTIER, C. AND FEUNTEUN, E. (2014) Migration behaviour of silver eels (*Anguilla anguilla*) in a large estuary of Western Europe inferred from acoustic telemetry. *Estuarine, Coastal and Shelf Science*, 137, 23–31.

ČADA, G.F. AND ODEH, M. (2001) *Turbulence at hydroelectric power plants and its potential effects on fish.* DOE/BP-26531-1 Report to Bonneville Power Administration, Contract No. 2000AI26531, Project No. 200005700, 37 pp. (BPA Report DOE/BP-26531–1).

ČADA, G.F., COUTANT, C.C. AND WHITNEY, R.R. (1997) *Development of biological criteria for the design of advanced hydropower turbines*. Publication No. 4639 for US Department of Energy, Idaho.

ČADA, G.F., RYON, M.G. AND SMITH, J. (2006) *The effects of turbine passage on C-start behavior of salmon at the Wanapum Dam, Washington*. US Department of Energy Report ORNL/TM – 2006/88.

ČADA, G.F., LOAR, J., GARRISON, L. AND FISHER, R. (2007) Determining the effect of shear stress on fish mortality during turbine passage. *Hydro Review*, November 2007.

CALIFORNIA DEPARTMENT OF WATER RESOURCES (2014) *2012 Georgiana Slough non-physical barrier performance evaluation project report, final*. California Department of Water Resources, 416 9th Street, Sacramento, CA 94236-001, Contact: Ryan Reeves.

CALIFORNIA ENERGY COMMISSION (2005) *Issues and environmental impacts associated with once-through cooling at California's coastal power plants*. Report No. CEC-700-2005-013.

CHARNOV, E.L., GISLASON, H. AND POPE, J.G. (2013) Evolutionary assembly rules for fish life histories. *Fish and Fisheries*, 14, 213–224.

DAVIDSEN, J.G., DAVERDIN, M., ARNEKLEIV, J.V., RØNNING, L., SJURSEN, A.D. AND KOKSVIK, J.I. (2014) Riverine and near coastal migration performance of hatchery brown trout *Salmo trutta*. *Journal of Fish Biology*, 85(3), 586–596.

DEVER, M., KOCIK, J., ZYDLEWSKI, J., HEBERT, D. AND STICH, D. (2016) Linkage between coastal conditions and migratory patterns and behavior of Atlantic salmon smolts along the Halifax Line. *American Geophysical Union, Ocean Sciences Meeting 2016.*

ELDØY, S.H, DAVIDSEN, J.G., THORSTAD, E.B., WHORISKEY, F., AARESTRUP, K., NÆSJE, T.F., RØNNING, L., SJURSEN, A.D., RIKARDSEN, A.H. AND ARNEKLEIV, J.V. (2015) Marine migration and habitat use of anadromous brown trout (*Salmo trutta*). *Canadian Journal of Fisheries and Aquatic Sciences*, 72(9), 1366–1378.

ELEY, C.D. AND FYFIELD, R. (2009) *The control of marine fouling. Report to British Energy.* Report Ref. BEG/SPEC/ENG/BEOM/006.

ELLIOTT, M. AND TAYLOR, C.J.L. (1989) The structure and function of an estuarine/marine fish community in the Forth estuary, Scotland. *Proceedings of the 21st European Marine Biological Symposium (Gdansk).* Polish Academy of Sciences, Institute of Oceanography, Warsaw, Poland, pp. 227–240.

ELLIOTT, M., O'REILLY, M.G. AND TAYLOR, C.J.L. (1990) The Forth estuary: a nursery and overwintering area for North Sea fishes. In: *North Sea – Estuaries Interactions*. Netherlands: Springer, pp. 89–103.

ENVIRONMENT AGENCY, ENVIRONMENT AND HERITAGE SERVICE, SCOTTISH ENVIRONMENT PROTECTION AGENCY, 2003. Horizontal Guidance Note IPPC H1. Integrated Pollution Prevention and Control. Environmental Assessment and Appraisal of BAT.

ENVIRONMENT AGENCY (2005) *Best practice guide for intake and outfall fish screening.* Environment Agency Science Report SC030231. Bristol: Environment Agency.

ENVIRONMENT AGENCY (2010a) *Cooling water options for the new generation of nuclear power stations in the UK*. Environment Agency Science Report SC070015/SR3. Bristol: Environment Agency.

ENVIRONMENT AGENCY (2010b) *Fish pass manual ver. 2.2 document* – GEHO 0910 BTBP-E-E. Bristol: Environment Agency (publication withdrawn from the Government website, now hosted by the Institute of Fisheries Management).

ENVIRONMENT AGENCY (2011) *Hydropower good practice guide v 1*. Appendix 1. Interim guidance on the permitting of Archimedes 3, 4 and 5 blade screws (publication withdrawn).

EPRI (2006) *Laboratory evaluation of modified Ristroph traveling screens for protecting fish at cooling water intakes.* EPRI, Palo Alto, CA, 1013238 (restricted access).

EPRI (2008) *Evaluation of strobe light and acoustic deterrent system: Plant Barry*. EPRI, Palo Alto, CA, 1014022 (restricted access).

EPRI (2009) *Entrainment survival: status of technical issues and role in best technology available (BTA) selection*. Final Report. EPRI, Palo Alto, CA, 1019025.

EPRI (2010) *Evaluation of factors affecting juvenile and larval fish survival in fish return systems at cooling water intakes*. EPRI, Palo Alto, CA, 1021372 (restricted access).

EPRI (2012) *Effects of fouling and debris on larval fish within a fish return system.* EPRI, Palo Alto, CA, 1024999 (restricted access).

EPRI (2013a) *Fish protection at cooling water intake structures: a technical reference manual – 2012 update*. EPRI, Palo Alto, CA, 3002000231 (restricted access).

EPRI (2013b) *Effects of distance and debris exposure on survival and injury of juvenile fish within a fish return system.* EPRI, Palo Alto, CA, 3002001467 (restricted access).

EPRI (2013c) *Post-impingement survival of juvenile and adult fish with a Geiger multi-disc screen: laboratory evaluations*. EPRI, Palo Alto, CA, 3002000180 (restricted access).

EPRI (2014) *Ristroph-modified traveling water screen fish impingement and survival case study at Plant Gorgas Generating Station*. EPRI, Palo Alto, CA, 3002003380 (restricted access).

EPRI (2015a) *Hydrolox traveling water screen fish impingement and survival case study: Plant Barry Generating Station.* EPRI, Palo Alto, CA, 3002005832 (restricted access).

EPRI (2015b) *Design of fish return systems and operations/maintenance guidelines.* Product ID:3002001422. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002001422 (restricted access).

EPRI (2017) *Recent research on the effect of light on out migrating eels and recent advancements in lighting technology*. Product ID:3002009407. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002009407 (restricted access).

EUROPEAN COMMISSION (2001) Integrated Pollution Prevention and Control (IPPC) – reference document on the application of best available techniques to industrial cooling systems. Available at: http://eippcb.jrc.ec.europa.eu/reference/BREF/cvs_bref_1201.pdf [Accessed 11 September 2017]

FISHFLOW INNOVATIONS (2017) *Monitoring report pumping station Kortenhoef*. Available at: http://fishflowinnovations.nl/wp-content/uploads/2016/12/Monitoring-Report-Pumping-Station-Kortenhoef-Autumn-2014-5.pdf [Accessed 13 March 2017].

FLATEN, A.C., DAVIDSEN, J.G., THORSTAD, E.B., WHORISKEY, F., RØNNING, L., SJURSEN, A.D., RIKARDSEN, A.H. AND ARNEKLEIV, J.V. (2016) The first months at sea: marine migration and habitat use of sea trout *Salmo trutta* post-smolts. *Journal of Fish Biology*, 89(3), 1624–1640.

FLEMING, J.M., SEABY, R.M.H. AND TURNPENNY, A.W.H. (1994) *A comparison of fish impingement rates at Sizewell A & B power stations*. Fawley Aquatic Research Laboratories Consultancy Report to Nuclear Electric plc, No. FRR 104/94, July 1994.

FORD, M.I., ELVIDGE, C.K., BAKER, D., PRATT, T.C., SMOKOROWSKI, K.E., PATRICK, P., SILLS, M. AND COOKE, S.J. (2017) Evaluating a light-louver system for behavioural guidance of age-0 white sturgeon. *River Research and Applications*, 33(8), 1286-1294.

GUERIN, A.J., JACKSON, A.C., BOWYER, P.A. AND YOUNGSON, A.F. (2014) *Hydrodynamic models to understand salmon migration in Scotland*. The Crown Estate, 116 pp. ISBN: 978-1-906410-52-0.

JACKSON, D. (2014) Implications of the Eel Regulations on the design of a pumping plant. In: Turnpenny, A.W.H and Horsfield, R.A. (eds). *International Fish Screening Techniques*, WIT Press, Southampton, UK, pp. 111–126.

JACOBS (2010) *Hinkley UK EPR – concept design for intake and outfall head structures*. Phase 2 Report, No. B1365500/R/002. Reading: Jacobs Engineering.

KENCHINGTON, T.J. (2013) Natural mortality estimators for information-limited fisheries. *Fish and Fisheries,* DOI: 10.1111/faf.12027.

KIBEL, P. AND COE, T. (2011) *Archimedean screw risk assessment: strike and delay probabilities.* Fishtek Consulting, report to Ham Hydro CIC, Spaans Babcock, Ritz Atro, B.SpokeeWaterpower.

KIBEL, P., PIKE, R. AND COE, T. (2009) *The Archimedes screw turbine; assessment of three leading edge profiles.* Fishtek Consulting, report to Mann Power Consulting.

KOCIK, J.F., HAWKES, J.P., SHEEHAN, T.F., MUSIC, P.A. AND BELAND, K.F. (2009) Assessing estuarine and coastal migration and survival of wild Atlantic salmon smolts from the Narraguagus River, Maine using ultrasonic telemetry. In: *American Fisheries Society Symposium*, 69, pp. 293–310.

LAMBERT, D. (2014) Planning and design of the UK's largest acoustic and light-based fish deterrent system. In: Turnpenny, A.W.H. and Horsfield, R.A. (eds). *International Fish Screening Techniques*. WIT Press, Southampton, UK, pp. 127–140.

LINDAHL, P.E. AND SCHANBOM, E. (1971) Rotatory flow technique as a means of detecting sublethal poisoning in fish populations. *Oikos,* 22, 354–357.

LOTHIAN, A.J., NEWTON, M., BARRY, J., WALTERS, M., MILLER, R.C. AND ADAMS, C.E. (2017) Migration pathways, speed and mortality of Atlantic salmon (*Salmo salar*) smolts in a Scottish river and the near-shore coastal marine environment. *Ecology of Freshwater Fish*, DOI:10.1111/eff.12369.

MAES, J., TURNPENNY, A.W.H., LAMBERT, D., NEDWELL, J.R., PARMENTIER, A. AND OLLEVIER, F. (2004) Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet (Doel, Belgium). *Journal of Fish Biology,* 64(4), 938–946.

METCALFE, J. (2011) *PISCES 2009: final report and Cefas evaluation*. BEEMS Technical Report TR112. Lowestoft: Cefas (not protectively marked).

METCALFE, J., WALMSLEY, S. AND WALKER, N. (2016) *Sizewell Site: a new approach for calculating Equivalent Adult Value (EAV) metrics*. BEEMS Technical Report TR383. Lowestoft: Cefas (classified UK Protect).

MURARKA, I.P. AND BODEAU, D.J. (1977) *Sampling designs and methods for estimating fish impingement losses at cooling-water intakes*. Argonne, Ill.: Argonne National Laboratory.

NOATCH, M.R. AND SUSKI, C.D. (2012) Non-physical barriers to deter fish movements. *Environmental Reviews*, 2012, 20(1), 71-82.

OLKEN, N., GIZA, D., TUTTLE, R. AND DIXON, D.A. (2015) Practical application of fish return design guidelines. Presentation at *145th Annual Meeting of the American Fisheries Symposium*, ‘Protecting fish at cooling water intakes: recent advances in 316(b) science’, Portland, Oregon, USA, 16–20 August 2015.

POPPER, A.N., PLACHTA, D.T.T., MANN, D.A. AND HIGGS, D. (2004) Response of clupeid fish to ultrasound: a review. *ICES Journal of Marine Science*, 61(7), 1057–1061.

RANDALL, R.G. AND MINNS, C.K. (2000) Use of fish production per unit biomass ratios for measuring the productive capacity of fish habitats. *Canadian Journal of Fisheries and Aquatic Sciences*, 57(8), 1657–1667.

REHNIG, F. (2014) Power plant cooling. *Fish protection for water intake structures Nuclear Engineering Internationa*l http://www.neimagazine.com May 2014 pp. 38–40. Available at: http://www.water.bilfinger.com/fileadmin/water-technologies/applications/water_intake/Downloads_EN/FishProtectionForWaterIntakeStructures.pdf. [Accessed 20 March 2017].

RILEY, J.D., SYMONDS, D.J. AND WOOLNER, L.E. (1981) On the factors influencing the distribution of 0-group demersal fish in coastal waters. *Rapports et Proces-verbaux des Réunions. Conseil International pour l'Éxploration de la Mer*, 178, 223–228.

ROSS, Q.E., DUNNING, D.J., THORNE, R., MENEZES, J.K., TILLER, G.W. AND WATSON, J.K. (1993) Response of alewives to high-frequency sound at a power plant intake on Lake Ontario. *North American Journal of Fisheries Management*, 13(2), 291–303.

RUEBUSH, B.C., SASS, G.G., CHICK, J.H. AND STAFFORD, J.D. (2012) In-situ tests of sound-bubble-strobe light barrier technologies to prevent range expansions of Asian carp. *Aquatic Invasions,* 7(1), 37–48.

SEABY, R.H.S. (1994) *Survivorship trial of the fish-return system at Sizewell ‘B’ Power Station.* Report to Nuclear Electric plc, Report Ref: FCR 102/94.

SOLOMON, D.J. (2010) *Eel passage at tidal structures and pumping stations*. Report to Environment Agency, Thames Region.

TEAGUE, N. AND CLOUGH, S.C. (2014) Investigations into the response of 0+ twaite shad (*Alosa fallax*) to ultrasound and its potential as an entrainment deterrent. In: *International fish screening techniques*, Turnpenny, A.W.H. and Horsfield, R.A. (eds), WIT Press, Southampton, UK, pp. 111–123.

THA (2012) *Effectiveness of band- and drum-screen fish recovery and return systems for silver eel and adult river lamprey: stage 1. Report to E.ON*. New Build & Technology Ltd, Environment Agency, RWE Npower. Turnpenny Horsfield Associates, Report No. 544R0105.

THA (2015a) *Hinkley C Forebay fish-hydraulic modelling assessment.* Internal Technical Note to EDF, Document No: 546N0302.

THORMAN, S. AND FLADVAD, B. (1981). Growth and production of fish in River Broalven estuary in the Swedish west coast. *Rep. Natn. Swedish Environm. Prot. P.M. 1416.*

TURNPENNY, A.W.H. (1988) Fish impingement at estuarine power stations and its significance to commercial fishing. *Journal of Fish Biology*, 33 (suppl. A), 103–110.

TURNPENNY, A.W.H. (1989) *The equivalent adult approach for assessing the value of juvenile fish kills, with reference to commercial species in British Water*. CERL Report No. RD/L/3454/R89.

TURNPENNY, A.W.H. (1992) *Fish return at cooling water intakes*. Report to Nuclear Electric plc, Fawley Aquatic Research Laboratories Ltd, Report No. FCR 023/92.

TURNPENNY, A.W.H. (1998) Mechanisms of fish damage in low-head turbines: An experimental appraisal. In: *Fish migration and fish bypasses*, Jungwirth, M., Schmutz, S. and Weiss, S. (eds), Oxford: Blackwell Publishing, pp. 300–314.

TURNPENNY, A.W.H. (2000) *Shoreham Power Station: survival of elvers (Anguilla anguilla) during simulated cooling system passage.* Fawley Aquatic Research Laboratories Ltd, Report No. FCR 332/00.

TURNPENNY, A.W.H. (2010) *Assessment of effects of CW intake velocity on fish entrapment risk at Hinkley Point*. Turnpenny Horsfield Associates, Report to EDF Energy No. 502R0109.

TURNPENNY, A.W.H. (2014) Trials and tribulations of fish recovery and return. In: *International Fish Screening Techniques*, Turnpenny, A.W.H. and Horsfield, R.A. (eds), WIT Press, Southampton, UK, pp. 111–123.

TURNPENNY, A.W.H. AND TAYLOR, C.J.L. (2000) An assessment of the effect of the Sizewell power stations on fish populations. *Hydroecologie appliquee*, 12(1–2), 87–134.

TURNPENNY, A.W.H. AND WATKINS, A. (2006) *Equivalent adult analysis of fry entrainment at the Thames Gateway Water Treatment Plant*. Jacobs Babtie Report No. 12405.

TURNPENNY, A.W.H., DAVIS, M.H., FLEMING, J.M. AND DAVIES, J.K. (1992) *Experimental studies relating to the passage of fish and shrimps through tidal power turbines*. Technical Report for AEA Technology, Harwell National Power PLC.

TURNPENNY, A., HORSFIELD, R. AND WILLIS, J. (2017) Sea trout and tidal power: challenges and approaches. In: Harris, G. (ed.) *Sea Trout Science & Management*, Proceedings of the 2nd International Sea Trout Conference, Dundalk, Ireland, 2015. Leicester: Matador.

VERHELST, P., REUBENS, J., MOENS, T., GOETHALS, P., BUYSSE, D., COECK, J. AND MOUTON, A. (2016) Estuarine behaviour of European silver eel (*Anguilla anguilla*) in the Scheldt Estuary. In: *International Symposium on Ecohydraulics*. University of Ghent publication.

WALKER, A.M., GODARD, M.J. AND DAVISON, P. (2014) The home range and behaviour of yellow-stage European eel *Anguilla anguilla* in an estuarine environment. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 24(2), 155–165.

WITHER, A., BAMBER, R., COLCLOUGH, S., DYER, K., ELLIOTT, M., HOLMES, P., JENNER, H., TAYLOR, C. AND TURNPENNY, A. (2012) Setting new thermal standards for transitional and coastal (TraC) waters. *Marine Pollution Bulletin,* 64, 1564–1579.

WILLIS, J. (2011) Modelling swimming aquatic animals in hydrodynamic models. *Ecological Modelling*, 222, 3869–3887.

List of abbreviations

AFD	acoustic fish deflector
BAT	best available techniques
BTA	best technology available
BEEMS	British Energy Estuarine and Marine Studies
CCGT	combined cycle gas turbine
CEGB	Central Electricity Generating Board
CW	cooling water
CWS	cooling water system
EALP	equivalent area of lost production
EAV	equivalent adult value
EMU	entrainment mimic unit
EPRI	Electric Power Research Institute
FRR	fish recovery and return
HPC	Hinkley Point C
IBM	individual-based model
NNB	Nuclear New Build (Programme)
PISCES	Prediction of Inshore Saline Communities Expert System
TWS	travelling water screens

Appendix

Biota entrainment mitigation measures for cooling water intakes

February 2017

Compiled by Gerard Lenagan for Louise Paul

1. Background

This document contains the results of a search for information on the mitigation measures for cooling water intakes (or other large intakes of water such as hydropower) on biota entrainment and impingement, including fish, fry, invertebrates, larval forms, and plants.

The search focussed on UK, Europe and similar temperate areas; the scope of the search included estuarine waters, marine and large volume fresh water environments.

2. Results

Mitigation:

Bethlehem Energy Center. 2006. *Power,* 150(6), pp. 17–17.
http://search.ebscohost.com/login.aspx?direct=true&db=eih&AN=22513575&site=ehost-live

Innovative intake screen protects fish at Newington energy. 2004. *Power Engineering (Barrington, Illinois),* 108(11), pp. 190–193
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0944262249&partnerID=40&md5=8484e92e394c2888f241e4ab5aab8847.

ALLEN, G., AMARAL, S. and BLACK, J., 2012. Fish protection technologies: The US experience. pp. 371–390
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84949176271&doi=10.1007%2f978-1-4614-1698-2_17&partnerID=40&md5=ac48ecf28665dcb92832562a5a3592ce.

BIGBEE, D.L., KING, R.G., DIXON, K.M., DIXON, D.A. and PERRY, E.S., 2010. **Survival of fish impinged on a rotary disk screen.** *North American Journal of Fisheries Management,* 30(6), pp. 1420–1433
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84862336986&doi=10.1577%2fM09-059.1&partnerID=40&md5=59a994d88dd6013f73dfaceb109a96fd.

BRUIJS, M.C.M. and TAYLOR, C.J.L., 2012. **Fish impingement and prevention seen in the light of population dynamics.** pp. 391–409
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84929289236&doi=10.1007%2f978-1-4614-1698-2_18&partnerID=40&md5=c28a7825b17aeb53c462c93133c0a5dd

HANSON, J.H. and MURPHY, J.T., 2005. **Evaluation of filter for surface water intakes to meet new CWA standards.** *Ultrapure Water,* 22(4), pp. 44–47 https://www.scopus.com/inward/record.uri?eid=2-s2.0-20444390628&partnerID=40&md5=fa882295c960b04134d009bcbf366493.

HORLACHER, H., HEYER, T., RAMOS, C.M. and DA SILVA, M.C., 2012. 6.03 http://www.sciencedirect.com/science/article/pii/B9780080878720006041.

JONES, J.M. and MAYER, B., 2005. **An integrated cooling water intake system enhancement strategy,** 2005, pp. 29–33 https://www.scopus.com/inward/record.uri?eid=2-s2.0-27744541579&partnerID=40&md5=813241288407bde12fe4f341e2ab276d.

JYRKAMA, M.I. and PANDEY, M.D., 2012. **Reliability analysis of a fish diversion structure at the cooling water intake of a power generating station,** 2012, pp. 5273–5277 https://www.scopus.com/inward/record.uri?eid=2-s2.0-84873131895&partnerID=40&md5=233424521573b058aefeaccd1b94d744.

MAES, J., TURNPENNY, A.W.H., LAMBERT, D.R., NEDWELL, J.R., PARMENTIER, A. and OLLEVIER, F., 2004. **Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet.** *Journal of Fish Biology,* 64(4), pp. 938–946 https://www.scopus.com/inward/record.uri?eid=2-s2.0-1942489668&doi=10.1111%2fj.1095-8649.2004.00360.x&partnerID=40&md5=85be1085df6e5e2fb05ce8fe9e532b04.

PEREDO-ALVAREZ, V.M., BELLAS, A.S., TRAINOR-GUITTON, W.J. and LANGE, I., 2016. **Mandate a Man to Fish?: Technological advance in cooling systems at U.S. thermal electric plants.** *Water Resources Research,* 52(2), pp. 1418–1426 http://dx.doi.org/10.1002/2015WR017676.

SCRUTON, D.A., MCKINLEY, R.S., KOUWEN, N., EDDY, W. and BOOTH, R.K., 2003. **Improvement and optimization of fish guidance efficiency (FGE) at a behavioural fish protection system for downstream migrating Atlantic salmon (Salmo salar) smolts.** *River Research and Applications,* 19(5–6), pp. 605–617 http://dx.doi.org/10.1002/rra.735.

SHEPHERD, M.A., LABAY, A., SHEA, P.J., RAUTIAINEN, R. and ACHUTAN, C., 2016. **Operational, water quality and temporal factors affecting impingement of fish and shellfish at a Texas coastal power plant.** *Global Ecology and Conservation,* 5, pp. 48–57 http://www.sciencedirect.com/science/article/pii/S2351989415001080.

SUPER, R.W. and GORDON, D.K., 2002. **Minimizing adverse environmental impact: how murky the waters.** *TheScientificWorldJournal [electronic resource],* 2 Suppl 2, pp. 219–237 https://www.scopus.com/inward/record.uri?eid=2-s2.0-2542452335&partnerID=40&md5=0d87d8e6e6946129c2d771127c8f0471.

WHEELER, B., 2010. **Retrofit options to comply with 316(b).** *Power Engineering (Barrington, Illinois),* 114(10), pp. 38–48 https://www.scopus.com/inward/record.uri?eid=2-s2.0-78649406122&partnerID=40&md5=2b59e2951f429d8f841c390754f1dbd0.

WHITNEY, R.R., COUTANT, C.C. and MUNDY, P.R., 2006. **Mitigation of Salmon Losses Due to Hydroelectric Development.** In: R.N. WILLIAMS, ed, *Return to the River.* Burlington: Academic Press, pp. 325–416
http://www.sciencedirect.com/science/article/pii/B9780120884148500102

Regulation:

Power Plants Seek Review Of EPA Cooling Water Rule. 2014. *BNA's Environmental*
http://search.ebscohost.com/login.aspx?direct=true&db=8gh&AN=98607591&site=ehost-live

White House Reviewing Proposed Rule On Permits, Notice on Fish Impingement Data. 2012.
http://search.ebscohost.com/login.aspx?direct=true&db=8gh&AN=72065421&site=ehost-live

EPA Proposes New Cooling Water Intake Structure Standards. 2011. *Venulex Legal Summaries,* pp. 1–3
http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=66189854&site=ehost-live

National Pollutant Discharge Elimination System-Cooling Water Intake Structures at Existing Facilities and Phase I Facilities: Proposed rule. 2011. *Federal register,* 76(76), pp. 22174–22288
https://www.scopus.com/inward/record.uri?eid=2-s2.0-79955143573&partnerID=40&md5=2e2f321641f951b16534269208fe559d.

Replacing Fish Destroyed by Power Plants Not Authorized by CWA: Riverkeeper, Inc., et al v. U.S. Environmental Protection Agency. 2004. *National Environmental Enforcement Journal,* 19(3), pp. 19–22
http://search.ebscohost.com/login.aspx?direct=true&db=eih&AN=13000834&site=ehost-live

AMARAL, S., SULLIVAN, T. and TUTTLE, R., 2005. **Developing CWA Section 316(b) fish protection technologies through laboratory and field evaluations.** *Power,* 149(4), pp. 42–50
https://www.scopus.com/inward/record.uri?eid=2-s2.0-20344380933&partnerID=40&md5=5ecada0dd00f74de96d1a60309f3ffa4.

BINGHAM, M.F. and KINNELL, J.C., 2014. **EPA's new 316(b) rule and the opportunity of social costs.** *Power,* 158(9).
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84907462397&partnerID=40&md5=5286fe6a3b835b5dcb47a8191e285f0b.

CHRISTMAN, J., BULLEIT, K. and HOGAN, T., 2007. **Legal spotlight: EPA's new rules for cooling water intake structures.** *EM: Air and Waste Management Association's Magazine for Environmental Managers,* (MAR.), pp. 14–17
https://www.scopus.com/inward/record.uri?eid=2-s2.0-42449083429&partnerID=40&md5=dd43a74110d3c94020a95e7468c1eb6f.

ENVIRONMENT AGENCY, 2013. **Hinkley Point C Appropriate Assessment for Environment Agency Permissions.**
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/291300/LIT_7887_b828d6.pdf.

FOTIS, S., CARBONNELL, T. and GREGG, K., 2011. **EPA impinges on intakes.** *Modern Power Systems,* 31(6), pp. 14–14
http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=64304478&site=ehost-live

IOVANNA, R. and GRIFFITHS, C., 2006. **Clean water, ecological benefits, and benefits transfer: A work in progress at the U.S. EPA.** *Ecological Economics,* 60(2), pp. 473–482
http://www.sciencedirect.com/science/article/pii/S0921800906003077.

KOPENHAVER, J., 2014. **EPA Publishes Final Cooling Water Intake Rule.** *Analyst (Association of Water Technologies),* 21(4), pp. 60–62
http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=66189854&site=ehost-live

SCHIMMOLLER, B.K., 2004. **Section 316(b) regulations: The Yin and Yang of fish survival and power plant operation.** *Power Engineering (Barrington, Illinois),* 108(7), pp. 28–35
https://www.scopus.com/inward/record.uri?eid=2-s2.0-3843066610&partnerID=40&md5=33a53d28155f05d924da02ae7796c902.

SEEGERT, G., 2013. **Assessment of what the new 316b rule will require AFPM members to do,** 2013, pp. 515–529
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84902440421&partnerID=40&md5=81c2d8763204aea0ef99be64ed18a1e5.

STONER, N.K., 2012. **National Pollutant Discharge Elimination System-Proposed Regulations to Establish Requirements for Cooling Water Intake Structures at Existing Facilities; Notice of Data Availability Related to Impingement Mortality Control Requirements.** *Federal Register (National Archives & Records Service, US Office of the Federal Register* https://www.scopus.com/inward/record.uri?eid=2-s2.0-79955143573&partnerID=40&md5=2e2f321641f951b16534269208fe559d

URBAN, D., GARETH, M. and GALYA, D., 2005. **CWA Section 316(b) regulations for cooling water intakes at refineries and offshore oil & gas extraction facilities,** 2005
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33646264083&partnerID=40&md5=9e29be6d2496950fc388bbd4ac201f89.

VAN WINKLE, W., DEY, W.P., JINKS, S.M., BEVLHIMER, M.S. and COUTANT, C.C., 2002. **A blueprint for the problem formulation phase of EPA-type ecological risk assessments for 316(b) determinations.** *TheScientificWorldJournal [electronic resource],* 2 Suppl 2, pp. 271–298
https://www.scopus.com/inward/record.uri?eid=2-s2.0-3042742638&partnerID=40&md5=e0d96f694bd7d5b9c5a360983f92352d.

VEIL, J.A., PUDER, M.G., LITTLETON, D.J. and JOHNSON, N., 2002. **A holistic look at minimizing adverse environmental impact under Section 316(b) of the Clean Water Act.** *TheScientificWorldJournal [electronic resource],* 2 Suppl 2, pp. 41–57
https://www.scopus.com/inward/record.uri?eid=2-s2.0-2142691725&partnerID=40&md5=20e5d688482da7d9550da4399b12ae62.

YOUNG, J.R. and DEY, W.P., 2002. **Uncertainty and conservatism in assessing environmental impact under paragraph 316(b): lessons from the Hudson River case.** *TheScientificWorldJournal [electronic resource],* 2 Suppl 2, pp. 30–40 https://www.scopus.com/inward/record.uri?eid=2-s2.0-3042745536&partnerID=40&md5=2c97c1761182db736075386c1c6bb5ba.

YOUNOS, T., 2005. **Permits and Regulatory Requirements.** *Journal of Contemporary Water Research & Education,* 132(1), pp. 19–26 http://dx.doi.org/10.1111/j.1936-704X.2005.mp132001004.x.

General:

EPA Analyzes Data On Fish Kills at Intakes. 2012. *BNA's Environmental Compliance Bulletin,* 19(13), pp. 204–204 http://search.ebscohost.com/login.aspx?direct=true&db=8gh&AN=77790730&site=ehost-live

AHSAN, Q., BLUMBERG, A.F., DUNNING, D., LI, H., KALUARACHCHI, I.D., HEIMBUCH, D. and LOGAN, D., 2003. **Predicting Entrainment of Ichthyoplankton at a Power Plant Intake on the East River, N.Y.** 2003, pp. 2949–2958 https://www.scopus.com/inward/record.uri?eid=2-s2.0-1642557267&partnerID=40&md5=0693e450d809ff1f2f46407384e32aa4.

AZILA, A. and CHONG, V.C., 2010. **Multispecies impingement in a tropical power plant, Straits of Malacca.** *Marine Environmental Research,* 70(1), pp. 13–25 https://www.scopus.com/inward/record.uri?eid=2-s2.0-77953535366&doi=10.1016%2fj.marenvres.2010.02.004&partnerID=40&md5=67cf595ceb6a0f3b029040c2e71f5309.

BALLETTO, J.H., HEIMBUCH, M.V. and MAHONEY, H.J., 2005. **Delaware Bay salt marsh restoration: Mitigation for a power plant cooling water system in New Jersey, USA.** *Ecological Engineering,* 25(3), pp. 204–213 http://www.sciencedirect.com/science/article/pii/S0925857405000960.

BARNTHOUSE, L.W., 2013. **Impacts of entrainment and impingement on fish populations: A review of the scientific evidence.** *Environmental Science and Policy,* 31, pp. 149–156 https://www.scopus.com/inward/record.uri?eid=2-s2.0-84878255564&doi=10.1016%2fj.envsci.2013.03.001&partnerID=40&md5=891cb98fc64ab2c6a127a1ddcc669068.

BARNTHOUSE, L.W., BINGHAM, M. and KINNELL, J., 2016. **Quantifying nonuse and indirect economic benefits of impingement & entrainment reductions at U.S. power plants.** *Environmental Science & Policy,* 60, pp. 53–62 http://www.sciencedirect.com/science/article/pii/S146290111630051X.

BLACK, J.L. and PERRY, E.S., 2014. **Laboratory Evaluation of the Survival of Fish Impinged on Modified Traveling Water Screens.** *North American Journal of Fisheries Management,* 34(2), pp. 359–372 https://www.scopus.com/inward/record.uri?eid=2-s2.0-84898980455&doi=10.1080%2f02755947.2013.862193&partnerID=40&md5=6b90023ec97ebf3ca3d143994ae1272f.

BRUIJS, M.C.M. and TAYLOR, C.J.L., 2012**. Fish impingement and prevention seen in the light of population dynamics.** pp. 391–409 https://www.scopus.com/inward/record.uri?eid=2-s2.0-84929289236&doi=10.1007%2f978-1-4614-1698-2_18&partnerID=40&md5=c28a7825b17aeb53c462c93133c0a5dd.

CALLAGHAN, T.P., 2004. **Entrainment and Impingement of Organisms in Power Plant Cooling**. In: C.J. CLEVELAND, ed, *Encyclopedia of Energy.* New York: Elsevier, pp. 447–457
http://www.sciencedirect.com/science/article/pii/B012176480X005544.

FOLEY, C.J., BRADLEY, D.L. and HÖÖK, T.O., 2016. **A review and assessment of the potential use of RNA:DNA ratios to assess the condition of entrained fish larvae.** *Ecological Indicators,* 60, pp. 346–357
http://www.sciencedirect.com/science/article/pii/S1470160X15003830.

GREENWOOD, M.F.D., 2008. **Fish mortality by impingement on the cooling-water intake screens of Britain's largest direct-cooled power station.** *Marine Pollution Bulletin,* 56(4), pp. 723–739
https://www.scopus.com/inward/record.uri?eid=2-s2.0-41149119819&doi=10.1016%2fj.marpolbul.2007.12.008&partnerID=40&md5=8bdb7ec117676e50d952aa28f0ff5918.

HADDERINGH, R.H. and JAGER, Z., 2002. **Comparison of fish impingement by a thermal power station with fish populations in the Ems Estuary.** *Journal of Fish Biology,* 61, pp. 105–124
http://dx.doi.org/10.1111/j.1095-8649.2002.tb01765.x.

HARRISON, P.M., GUTOWSKY, L.F.G., MARTINS, E.G., PATTERSON, D.A., COOKE, S.J. and POWER, M., 2016. **Burbot and large hydropower in North America: benefits, threats and research needs for mitigation.** *Fisheries Management and Ecology,* 23(5), pp. 335–349
http://dx.doi.org/10.1111/fme.12178.

JOHNSON, G.E., HEDGEPETH, J.B., SKALSKI, J.R. and GIORGI, A.E., 2004. **A Markov chain analysis of fish movements to determine entrainment zones.** *Fisheries Research,* 69(3), pp. 349–358
https://www.scopus.com/inward/record.uri?eid=2-s2.0-4644319314&doi=10.1016%2fj.fishres.2004.06.007&partnerID=40&md5=444874021a495aa1d07b168c2649b211.

KEMP, P.S., 2015. **Impoundments, barriers and abstractions**. *Freshwater Fisheries Ecology.* John Wiley & Sons, Ltd, pp. 717–769
http://dx.doi.org/10.1002/9781118394380.ch52.

KHAMIS, I. and KAVVADIAS, K.C., 2012. **Trends and challenges toward efficient water management in nuclear power plants.** *Nuclear Engineering and Design,* 248, pp. 48–54
http://www.sciencedirect.com/science/article/pii/S0029549312001732.

MAYHEW, D.A., MUESSIG, P.H. and JENSEN, L.D., 2002. **Adverse environmental impact: 30-year search for a definition.** *TheScientificWorldJournal [electronic resource],* 2 Suppl 2, pp. 21–29
https://www.scopus.com/inward/record.uri?eid=2-s2.0-2142692178&partnerID=40&md5=9d9c4f6d5867e197a9eb5dd88084a4ac.

NEWBOLD, S.C. and IOVANNA, R., 2007. **Ecological effects of density-independent mortality: application to cooling-water withdrawals.** *Ecological Applications,* 17(2), pp. 390–406
http://dx.doi.org/10.1890/06-0070.

PERRY, E., SEEGERT, G., VONDRUSKA, J., LOHNER, T. and LEWIS, R., 2002. **Modeling possible cooling-water intake system impacts on Ohio River fish populations.** *TheScientificWorldJournal [electronic resource],* 2 Suppl 1, pp. 58–80
https://www.scopus.com/inward/record.uri?eid=2-s2.0-3042698747&partnerID=40&md5=df08f363c061ed93f41fb33a0cbf4ef2.

POORNIMA, E.H., RAJADURAI, M., RAO, V.N.R., NARASIMHAN, S.V. and VENUGOPALAN, V.P., 2006. **Use of coastal waters as condenser coolant in electric power plants: Impact on phytoplankton and primary productivity.** *Journal of Thermal Biology,* 31(7), pp. 556–564
http://www.sciencedirect.com/science/article/pii/S0306456506000696.

RAJAGOPAL, S., JENNER, H.A. and VENUGOPALAN, V.P., eds, 2012. **Operational and environmental consequences of large industrial cooling water systems.** Springer Science & Business Media. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84945651273&doi=10.1007%2f978-1-4614-1698-2&partnerID=40&md5=72218bab028665502872517bc2b638b4

SONNY, D., KNUDSEN, F.R., ENGER, P.S., KVERNSTUEN, T. and SAND, O., 2006. **Reactions of cyprinids to infrasound in a lake and at the cooling water inlet of a nuclear power plant.** *Journal of Fish Biology,* 69(3), pp. 735–748
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33747393368&doi=10.1111%2fj.1095-8649.2006.01146.x&partnerID=40&md5=a1cbbc5612f7b96fc73f9e347ea138a6.

SUMNER, K., 2016. **Screening for small eels at hydropower sites: A review of evidence and gaps.** Environment Agency.
This short paper reports findings of a literature review of the risks posed to small eels (<300mm in length) from hydropower installations. The review is intended to support discussion on how we currently regulate in this area, particularly around the recent introduction of 2mm exclusion screens in some locations.
http://cdm21005.contentdm.oclc.org/cdm/ref/collection/EA_Data/id/24741.

THIELEN, F., WEIBEL, U., HIRT, J., MÜNDERLE, M., MARTEN, M., TARASCHEWSKI, H. and SURES, B., 2008. **Ichthyofauna in the upper Rhine River close to the city of Karlsruhe as determined by the analysis of fish impingement by cooling-water intakes of a power plant.** *Limnologica,* 38(1), pp. 76–85
https://www.scopus.com/inward/record.uri?eid=2-s2.0-38349105590&doi=10.1016%2fj.limno.2007.06.004&partnerID=40&md5=b9fc935a1723a597043684c36136d613.

VASSLIDES, J.M., TOWNSEND, H., BELTON, T. and JENSEN, O.P., 2017. **Modeling the Effects of a Power Plant Decommissioning on an Estuarine Food Web.** *Estuaries and Coasts,* 40(2), pp. 604–616
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84983440503&doi=10.1007%2fs12237-016-0151-8&partnerID=40&md5=467c08c294c0d1051ac5e62c7bcb9ac6

WHITE, J.W., NICKOLS, K.J., CLARKE, L. and LARGIER, J.L., 2010. **Larval entrainment in cooling water intakes: spatially explicit models reveal effects on benthic metapopulations and shortcomings of traditional assessments.** *Canadian Journal of Fisheries & Aquatic Sciences,* 67(12), pp. 2014–2031 http://search.ebscohost.com/login.aspx?direct=true&db=eih&AN=57773765&site=ehost-live

WILSON, J.W., NICKOLS, K.J., CLARKE, L. and LARGIER, J.L., 2010. **Larval entrainment in cooling water intakes: Spatially explicit models reveal effects on benthic metapopulations and shortcomings of traditional assessments.** *Canadian Journal of Fisheries and Aquatic Sciences,* 67(12), pp. 2014–2031

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3. Search Strategy

The search has been carried out using the following search strategies:

(“cooling water” OR “cooling water intake” OR “water extraction” OR “water abstraction” OR “water withdrawal” OR hydropower OR hydroelectric* OR “power plant” OR “electricity plant” OR “nuclear power plant”) AND (biota OR fish OR eels OR plankton OR plant OR macrophyte OR invertebrates) AND (entrainment OR impingement)

4. Search Sources

We have searched the following sources for relevant articles.

Databases of academic peer reviewed literature: Scopus, EBSCO Host, Science Direct, Wiley, Google Scholar.

Search engine: Environmental Agency Digital Library, Google.

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