Environment Agency

Nuclear power station cooling waters: protecting biota

Chief Scientist's Group report

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Professor Doug Wilson
Chief Scientist

Executive summary

New nuclear power stations planned at coastal or estuarine sites in the UK can have a large demand for waste heat removal.

Cooling water discharges are controlled in accordance with permits that are issued by the Environment Agency. As specified in the National Policy Statement for Nuclear Power Generation EN-6 (DECC 2011), applicants for those permits are expected to demonstrate the use of best available techniques to minimise the impact of cooling water discharges. The Environment Agency may permit the discharge of cooling waters following a satisfactory compliance assessment for water discharge activities under the Water Framework Directive, the Environmental Protection Regulations 2010 and the Habitats Directive.

Abstraction of high volumes of cooling waters from the sea or estuaries for this purpose has an impact on fish and other aquatic organisms through entrapment and entrainment in the process.

In 2010, the Environment Agency published a review 'Cooling Water Options for the New Generation of Nuclear Power Stations in the UK' (Environment Agency 2010) in preparation for the government's production of the National Policy Statement for Nuclear Power Generation (DECC 2011). The development in biota protection technologies for cooling waters since the Environment Agency (2010a) review meant that there was a need to revisit some aspects of that report, particularly considering:

- biota protection methodologies
- emerging technologies
- experience in the installation, operation and maintenance of these technologies.

The progression of plans for new build nuclear power stations in the UK has continued and it is, therefore, prudent to update the 2010 report. Following a scoping study outlining areas of interest (Protection of biota from cooling water intakes at nuclear power stations: scoping study, Environment Agency 2018), and a detailed review of 3 important aspects of cooling water systems (Nuclear power station cooling waters: evidence on 3 aspects, Environment Agency 2019), a review of all the areas of interest is reported here. It covers 12 topics and also summarises the 3 topics reviewed in the earlier report.

The topics covered were:

- fish behavioural deterrent systems
- decisions on cooling waters taken by other environmental regulators
- updated methods for fisheries impact assessment:
    - equivalent adult value
    - equivalent area of lost production
- optimising cooling water intake siting for minimising impacts on aquatic biota
- intake head designs: engineering practice
- approach/escape velocity

- cooling water system tunnels: pressure change effects
- forebay and screenwell design, including hydraulic conditions
- entrainment - cooling water systems downstream of fine screens
- onshore screening, including fish recovery facilities
- fish return launders and discharge head design
- fish lift pumps: fish friendliness for fish recovery and return
- biofouling control, implications for fish return
- monitoring and assessment protocols for fish recovery and return facilities
- monitoring and assessment protocols for fish deterrent effectiveness

Fish behavioural deterrents and updated methods for fisheries impact assessment are reviewed in the previous report (Nuclear power station cooling waters: evidence on 3 aspects, Environment Agency 2019), as are the decisions on cooling waters taken by other environmental regulators internationally. Brief summaries of those review findings are presented here.

The findings of the evidence review are summarised for each subject area below. Some subject areas reviewed have very little direct evidence available. In these cases, evidence from sources that give an insight into the process are reviewed.

Intakes - design and location

1. **Optimising cooling water intake siting to minimise impacts on aquatic biota**
   - Regulators can have **Medium** confidence in the evidence that siting an intake offshore will reduce the impacts on aquatic biota if suitable site surveys are undertaken.
   - Regulators can have **Low** confidence in the evidence that individual-based models (IBMs) can be used to predict impingement and entrainment at a site, particularly for the entire community.
2. **Intake head designs**
   - Regulators can have **Medium** confidence in the evidence that Low Velocity Side Entry intakes will reduce impingement. No entrainment reductions are expected. Low intake velocities could reduce impingement rate per cubic metre of water abstracted.
   - Regulators can have **High** confidence in the evidence that capped intakes will reduce impingement, with a greater reduction in pelagic species than non-pelagic species.
3. **Approach/escape velocity**
   - Regulators can have **Medium** confidence in the evidence that reducing the intake velocity reduces the number of fish captured. Using swimming speed as an estimate of capture vulnerability at an intake is simplistic, and other factors such as the fish being able to sense the intake, might be important at some sites.

- Regulators can have **Medium** confidence in the evidence that reducing the volume abstracted by an intake reduces the number of fish captured per cubic metre of water abstracted.

Passage through the station – excluding screening

4. Cooling water system tunnels: pressure change effects

- Regulators can have **High** confidence in the evidence that barotrauma is a significant cause of injury to some fish species captured at offshore intakes.

5. Forebay and screenwell design, including hydraulic conditions

- Regulators can have **Low** confidence in the evidence that shear stress will not cause injury at 1,600Nm^{-2} for UK marine species.

6. Cooling water systems downstream of fine screens

- Regulators can have **Low** confidence in the evidence that there will be a high survival of entrained organisms that pass through a power station. Multiple stressors impact entrained animals, and longer transit times through the station could increase mortality rates.

Screening and survival

7. Onshore screening, including fish recovery facilities

- Regulators can have **Low** confidence that a bypass system within the forebay of a station will reduce impingement on angled rake screens. It is an untried technology in the UK.
- Regulators can have **Low** confidence that a fish-friendly rake system will result in low mortality. No trials on UK marine species have been found.
- Regulators can have **High** confidence in the evidence that some species of fish will survive impingement on travelling screens. The mortality rate is highly species-specific.

8. Fish return launders and discharge head design

- Regulators can have **Low** confidence in the evidence that debris in the fish launder will not affect fish survival. No trials on debris loading as fish survival were identified in the UK.
- Regulators can have **Low** confidence in the evidence that drop heights in fish launders will not affect fish survival. No trials on the impact of drop heights were identified on British marine fish.

9. Fish lift pumps: fish-friendliness for fish recovery and return

- Regulators can have **Low** confidence in fish lift pumps being friendly in fish return systems. No trials were identified on British marine fish. Technologies like Archimedes screws have been shown to be fish-friendly in different environments. In the situation with debris as well as marine fish, the survival rate is uncertain.

10. Biofouling control in fish return systems

- Regulators can have **Medium** confidence in the evidence on the effect of biocides on fish in a fish return system. No trials were identified on the impact of biocides on British marine fish in a fish return system. Biocide toxicity is well understood, but the synergetic effects with a fish return system are not.

11. Monitoring and assessment protocols for fish recovery and return system

- Regulators can have **Medium** confidence in the evidence for this subject area. Monitoring protocols are assessed for fish recovery and return facilities, and fish deterrent effectiveness. No survival studies were found on British marine species on intakes similar to those for a NNB power station. Some new monitoring technologies show promise in assessing conditions for fish in the CWS.

12. Monitoring and assessment protocols for fish deterrent effectiveness

- Regulators can have **Medium** confidence in the evidence for this subject area. Monitoring protocols for fish deterrent effectiveness are assessed and have much in common with those for monitoring of the fish return system. Some additional considerations for this monitoring are discussed.

Fish population considerations are reviewed briefly, however there is a limited amount of reported information on which to base an assessment and no conclusions can be made here regarding the confidence in the evidence for this subject.

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1 Introduction

New nuclear power stations planned at coastal or estuarine sites in the UK can have a large demand for waste heat removal via cooling waters. Abstraction of high volumes of cooling waters from the sea or estuaries for this purpose has an impact on fish and other aquatic organisms through entrapment and entrainment in the process. Habitats and species found adjacent to the planned sites normally have high levels of designation and require protection.

Under the Environmental Permitting Regulations (England and Wales) 2010, specified industrial processes with the potential to cause pollution or environmental harm are required to operate under permits that are designed to protect the environment and reduce any pollution they may cause. Cooling water discharges for new nuclear power stations are controlled in accordance with permits that are issued by the Environment Agency. As specified in the National Policy Statement for Nuclear Power Generation EN-6 (DECC 2011), applicants for those permits are expected to demonstrate they have used best available techniques (BAT) to minimise the impact of cooling water designs. The Environment Agency may permit the discharge of cooling waters following a satisfactory compliance assessment for water discharge activities under the Water Framework Directive, the Environmental Protection Regulations 2010 and the Habitats Directive.

For the Environment Agency to be effective in this permitting role, it is necessary for it to:

- continually review and evaluate the latest scientific evidence
- consider how advances in technology and the decisions of other international regulators may help inform the thinking in permitting decisions

The European Commission's review of best available techniques for industrial cooling systems culminated in the 'Reference Document on the Application of Best Available Techniques to Industrial Cooling Systems' (European Commission 2001). This BAT reference document (BREF) includes a discussion on the environmental aspects of industrial cooling systems and applied prevention and reduction techniques. The document also examines the risk of fish entrapment (entrainment and impingement) and sets out the BAT approach to reducing the entrapment of organisms.

In preparation for the government's production of a 'National Policy Statement for Nuclear Power Generation' (EN-6) (DECC 2011), the Environment Agency published the review, 'Cooling Water Options for the new Generation of Nuclear Power Stations in the UK' (Environment Agency 2010a). This report considered current knowledge on the engineering, siting and environmental issues likely to be of importance for a new generation of nuclear power stations with a large requirement for cooling. A specific aim of the review was to assess the evidence for the validity of the BREF's statement that direct cooling was BAT following challenges in the UK with regards to the Pembroke combined cycle gas turbine (CCGT) power station, and in the US by Riverkeeper Inc, under their Clean Water Act. The Environment Agency (2010a) review 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' (Environment Agency 2010a, p. 184).

The development in biota protection technologies for cooling waters since the Environment Agency (2010a) review meant that there was a need to revisit some aspects of that report, particularly considering:

- biota protection methodologies
- emerging technologies
- experience in the installation, operation and maintenance of these technologies

Given their size, the majority of intakes for nuclear power stations in the UK are likely to be required to be sited in deeper water offshore locations. In 2017, the Environment Agency initiated a project to conduct a review of:

- the available biota protection methodologies for large-scale cooling waters in use or development in the UK and around the world
- any changes since the 2010 Environment Agency cooling water options report (Environment Agency 2010a)

As some information is held commercially and some new information may be unpublished, a scoping study was conducted to identify available information. The scoping report provided a comprehensive list of literature available in the public domain on mitigation measures for biota entrainment at large cooling intakes (Environment Agency 2018).

The 2018 scoping report considered 14 different topic areas and briefly discussed the publicly available information, current issues and applicability to the UK new build nuclear power stations. The topic areas were:

- optimising cooling water intake siting for minimising impacts on aquatic biota
- intake head designs: engineering practice
- approach/escape velocity
- fish behavioural deterrents
- cooling water system tunnels: pressure change effects
- forebay and screenwell design, including hydraulic conditions
- onshore screening, including fish recovery facilities
- fish return launders and discharge head design
- fish lift pumps: ensuring fish friendliness for appropriate fish recovery and return dependent species
- biofouling control: implications for fish return and recovery and fish risk assessment protocols
- cooling water systems downstream of fine screens
- monitoring and assessment protocols for fish recovery and return facilities
- monitoring and assessment protocols for fish deterrent effectiveness
    - equivalent adult value (EAV)

    - equivalent area of lost production (EALP)

Two aspects from the scoping review were considered to be of high current interest. In addition, the recent approaches of the United States Environmental Protection Agency (USEPA) and other international regulators to biota protection methods for large-scale cooling water systems was of interest. Consequently, 3 subject areas were reviewed in full in an Environment Agency report (Environment Agency 2019) using and building on the literature sources identified in the scoping review (Environment Agency 2018) and covering the following topics:

- fish behavioural deterrent systems
- decisions on cooling waters taken by other environmental regulators
- fisheries and other aquatic biota impact assessment methodologies

This current report reviews in full the remaining 12 of the 14 topics outlined in the scoping report (Environment Agency 2018), and summarises the findings of the review of 3 subjects listed above and reported in Environment Agency (2019). This full review brings together all the updated information on biota protection methodologies in large-scale cooling water systems applicable to nuclear power stations in the UK. This report aims to build on the findings of the Environment Agency (2010a) Cooling Water Options report and to provide a comprehensive update on the available evidence on biota protection in cooling water systems that is relevant to the regulation of new nuclear power stations in the UK.

2 Methodology

In this review, we set out the evidence and data to inform our position on a wide range of issues relating to large-scale intakes at new nuclear power stations. Various relevant aspects of biota protection systems and methods were identified in the Environment Agency report ‘Protection of biota from cooling water intakes at nuclear power stations: scoping study - SC160009/R1’ (Environment Agency 2018). This was followed by an Environment Agency report into 3 aspects of particular relevance to new build nuclear power station cooing waters ‘Nuclear power station cooling waters: evidence on 3 aspects – SC170021/R1’ (Environment Agency 2019).

The current report follows on from these 2 previous reports and reviews in full the aspects identified in the scoping report (Environment Agency 2018). It also summarises the findings of the review of the 3 aspects of particular relevance (Environment Agency 2019). The overall aim of the series of reports was to update and expand the review of suitable biota protection methods that might be used in nuclear power station cooling water systems since the 2010 Environment Agency report ‘Cooling water options for the new generation of nuclear power stations in the UK – SC070015/SR3’ (Environment Agency 2010a).

For policy and permitting decisions to be made, it is important that the evidence and data used in those decisions is open and transparent, and that judgements made on the issues are based on the strength of the information provided. It is also important to highlight weaknesses and omissions in the data, both to inform the regulator where knowledge is required to make better decisions, and to show where uncertainty exists, and therefore caution must be used in interpreting the data.

This current review examines 12 topics relating to 4 general areas of cooling water systems, and assesses the confidence that can be placed in the existing evidence on each of the aspects considered. The 12 topics are:

Intakes - design and location:

1. optimising cooling water intake siting to minimise impacts on aquatic biota
2. intake head designs
3. approach/escape velocity

Passage through the station – excluding screening:

4. cooling water system tunnels: pressure change effects
5. forebay and screenwell design, including hydraulic conditions
6. cooling water systems downstream of fine screens

Screening and survival:

7. onshore screening, including fish recovery facilities
8. fish return launders and discharge head design
9. fish lift pumps: ensuring fish-friendliness for appropriate fish recovery and returning dependent species

10. biofouling control

Monitoring protocols:

11. monitoring and assessment protocols for fish recovery and return facilities
12. monitoring and assessment protocols for fish deterrent effectiveness

For each of the areas outlined, the current opinion on each subject (where it exists) is outlined, based on the current Environment Agency position. Some of the areas above have very little direct evidence available. In these cases, evidence from sources that give an insight into the process are reviewed.

In addition to reviewing the aspects listed above, the results from a review report 'Nuclear power station cooling waters: evidence on 3 aspects - SC170021/R1' (Environment Agency 2019) into 3 additional areas are briefly summarised. The areas covered are:

1. fish behavioural deterrents
2. decisions on cooling waters taken by other environmental regulators
3. updated methods for fisheries impact assessment

For each section, the review will:

- state the current position and present a brief review of the supporting data
- review other data sources and papers that are relevant to the evidence base for the position
- produce a synthesis of the state of knowledge for this section

Where appropriate data or information have been identified, the method outlined in the Government Chief Scientific Adviser's Guidelines for the use of scientific and engineering advice in policy making (Government Office for Science, 2010), is used. This method is as follows:

- a general summary of the reviewed document is presented
- important pieces of evidence within the reviewed document have been identified and described
- a confidence assessment has been carried out for each document as a whole, using the criteria set out below
- where appropriate, if differing important pieces of evidence are covered within the document, confidence has been assessed for each piece of evidence
- the potential implications of uncertainty (or a wide range of expert opinion) within the evidence base for policy decisions have been indicated
- emerging findings on this subject since the previous Environment Agency (2010a) review have been identified
- any mechanisms for managing the uncertainty within the evidence base have been recommended as appropriate/where possible

The method for identifying high-quality and robust evidence to inform decision-making will follow the method outlined in the Environment Agency (2019) report, ‘Nuclear power station cooling waters: evidence on 3 aspects - SC170021/R1’ (Environment Agency 2019).

Each piece of literature identified for review, and evidence within the literature, has been critically evaluated. A simple qualitative scoring method has been developed to assess the confidence in each piece of evidence identified, based on 3 aspects as listed below:

- **quality of information sources** – whether the evidence is based on peer-reviewed papers, grey literature or expert judgement, and whether the evidence is presenting primary, secondary or synthesised data
- **applicability of evidence** – whether the evidence is based on similar activities, scales of abstraction, environments, fish species or requirements of regulatory systems
- **strength of conclusion** – considering whether the evidence draws clear conclusions on the direction and magnitude of impact, efficacy, international opinion/practice

Each of these aspects is scored using High, Medium or Low confidence criteria. The wider evidence base for each of the 3 subjects is also assessed as part of the project, using the same confidence criteria, to give an overall assessment of the confidence for each subject. High confidence is where a permitting decision could be taken with a high level of confidence that the available evidence is sufficient on which to base the assessment, or that decisions made by other international organisations are applicable and transferrable to the UK regulatory situation. Medium or Low confidence requires varying levels of uncertainty management and/or additional mitigation to make a permitting decision.

2.1 Literature sources

The majority of the literature reviewed for this report comes from peer-reviewed papers and books. However, much of the research into power station cooling water intakes is released as reports from institutions or companies. These are not generally peer-reviewed but are often from experts in the field and have therefore been included in this review. Where possible, the papers and reports included in this report are available in the public domain.

Other documents relating to specific developments or case studies were not available for this review as they have not yet been released by developers. Further information relevant to this review will therefore become available over time.

References are given for the documents reviewed. Papers or reports where only summaries or shortened forms of the report have been seen are noted.

3 Summary of Environment Agency report SC170021/R1 - Nuclear power station cooling waters: evidence on 3 aspects

This section is a summary of the above document that reviewed 3 subjects of high relevance to regulatory decision making for cooling waters of nuclear power plants:

- fish behavioural deterrent systems
- decisions on cooling waters taken by other environmental regulators
- fisheries and other aquatic biota impact assessment

No assessment of these issues was made by the author of this current report.

3.1 Fish behavioural deterrent systems

Since the Environment Agency review of cooling water options in 2010 (Environment Agency 2010a) there have been few additional studies. Those that were identified did not provide any significant new information that would indicate that a change to best available techniques (BAT) from the Environment Agency (2010a) report should be recommended.

The review looked at data from over 20 relevant power stations with biota deterrent technologies in the cooling water systems. These included intakes in a range of environments, including lakes, rivers, estuaries and the sea. Relevant investigations were generally carried out on-site at the water intake facility, the majority in the US. However, there were also a number of laboratory-based studies reported. The studies indicated that the effectiveness of the deterrent systems was highly site- and species-specific. The review found that laboratory studies on deterrent systems should be treated with caution, as they are likely to be restricted to the specific case they were designed to investigate. Using the laboratory data outside the test parameters is possible, but care is needed.

Most studies reviewed looked at each technology in isolation rather than in combination with the other fish protection technologies. To implement BAT for a turbine condenser cooling water discharge system, it is likely that a site would need to operate a combination of different technologies, including physical and behavioural solutions. The review found that the operation of behavioural deterrent solutions and physical technologies, such as fish return systems, were closely inter-linked, and it was difficult to separate the 2 protection technologies in the literature.

Efficiency of deterrent systems was variable, with some species appearing to be more responsive than others. Clupeids were identified as a group of species with greater hearing sensitivity, and some systems have been demonstrated to be more effective for this group than others. Site-specific variations, in terms of layout of the system, the intake design and local conditions, made predicting the efficiency at any particular site difficult. The review found that flow was often cited as the limiting factor to the effectiveness of acoustic deterrents, and turbidity was often cited as the limiting factor to the effectiveness of light deterrents.

The review noted that no fish behavioural deterrent systems are effective at reducing the entrainment of eggs, larvae or very young fish, and reduction of impingement was generally only demonstrated to be effective for specific species rather than wider assemblages. To protect a range of fish species, a combination of different technologies may therefore need to operate.

The recommendations for the application of deterrent systems were that:

- deterrent systems need to be designed to be effective under operational and environmental extremes
- deterrent systems should be designed and constructed so that they can be adapted and improved to optimise the effectiveness of the intake. The systems should be capable of being upgraded as and when improvements are available over the lifetime of the project

Further site-specific evidence is needed to determine that behavioural deterrent systems are effective in reducing entrapment of aquatic biota at cooling water intake systems of nuclear power stations. All intakes have site-specific features that make them unique. Each intake is therefore likely to require a bespoke deterrent system. With the unique nature of each intake and the uncertainty of the efficiency of deterrent systems, there are inherent uncertainties within the operational and deterrence efficiencies proposed. The actual efficiency of the deterrent systems will only be known after in situ testing. This should be considered when assessing the effectiveness of a behavioural deterrent as a mitigation measure to reduce entrapment of aquatic biota.

It is important to assess the cooling water system as a whole rather than its constituent parts. Reducing aquatic biota entrapment into an intake requires several protection measures to be implemented, which might include both behavioural and physical screening technologies. Understanding the implications of any linkages between the protection measures is important, as their joint performance can depend on one another.

This section sets out 3 criteria and assesses the confidence in the above findings.

Table 3.1.1: Summary of subject area scoring for fish behavioural deterrent systems (Environment Agency 2019)

Confidence criteria	Overall confidence
Evidence on the ability to site and install available and suitable systems in onshore and offshore environments with consideration of nuclear safety requirements.	Medium
Evidence on effective operation, safe maintenance and reliability of a system in onshore and offshore environments and at the	Medium

scale required for a new nuclear power station in the UK and over the lifetime of the station.	
Evidence that systems are effective for fish protection in onshore and offshore environments under different environmental conditions.	Medium

3.2 Decisions on cooling waters taken by other environmental regulators

The review examined changes to the international policy and legislative context for cooling water intake systems of coastal and estuarine new nuclear power stations since publication of the Environment Agency (2010a) report. It reviewed what is considered to be 'best available' for use outside of the UK, to inform the approach to defining BAT for turbine condenser cooling water discharge systems for new nuclear power stations in the UK.

The USEPA Final Rule (USEPA 2014) sets a limit on the level of impingement and entrainment at a new-build site. The standard requires that entrainment and impingement mortality rates match those of a closed-cycle recirculating system. The review considered that the USEPA had not identified evidence that unequivocally demonstrates significant effects on fish species, populations or ecosystems as a result of entrainment and impingement through cooling water intake systems. The USEPA had also not been able to demonstrate that entrapment through cooling water intake systems does not cause a significant effect on fish populations. Therefore, the USEPA had taken a precautionary approach in its regulatory mechanisms by requiring mitigation for the effects of entrapment regardless of the predicted impacts upon aquatic biota. Even with the reduction in impingement and entrainment, it is still possible for captures to pose potentially significant effects on species if they are particularly exploited or vulnerable to additional anthropogenic pressures.

The review stated that there was no systematic demonstration of detrimental effects on fish and shellfish populations from power stations. Data from the last 60 years of operation indicated that it is not possible to apply a 'one-size fits all' approach to regulating these operations for their effects on fish and shellfish.

Since the justification for the Final Rule set out by the USEPA was not entirely applicable to the UK situation, such application may result in the loss of some of the resolution and understanding in decision-making offered by the current UK approach. The review therefore considered it appropriate to continue to utilise project-specific assessments for consenting purposes. Within this, the wider effects of multiple pressures upon aquatic biota populations (from, for example, multiple power stations or other anthropogenic developments or activities) must be understood to manage species populations safely.

Studies that assessed the cumulative effects of a number of marine/coastal power stations upon marine or diadromous fish species populations were not found. Such studies would be possible in the UK where multiple power stations are operating and entraining and impinging fish in the same stock.

The review recommended that “Each project should be considered on its own merits and regard given to the nature of the site and fish and shellfish populations present, using the best available evidence. This should result in design of an appropriate intake system that will not result in a significant adverse effect on fish and shellfish populations due to entrainment and impingement in the cooling water intake system.”

The regulatory system currently adopted in the UK, and the focus within UK legislation under the Environmental Impact Assessment (EIA) Directive and the Habitats Directive, of identifying whether there are ‘significant’ effects upon species, makes site by site assessment necessary. It was considered that the evidence provided by the USEPA was potentially useful on a site- and species-specific basis for project-level assessments. However, the UK regulatory system does not provide the same prescriptive rule based guidance as the USEPA, but can evaluate on a project-specific, technology-specific, site-specific and location-specific basis.

There is little other evidence of limits to entrainment and impingement legislated for by countries other than the USA and Canada, with countries in Europe such as the Netherlands following a similar, bespoke, project-specific approach as the UK.

Table 3.2.1: Summary of subject area scoring for decisions on cooling waters taken by other environmental regulators (Environment Agency 2019)

Confidence criteria	Overall confidence
Are cooling water developments in other countries sufficiently comparable to the UK new nuclear industry for their regulatory decisions to be considered a relevant evidence base?	High
What are the rationales for decisions made in other countries (for example, compliance with environmental regulation, protection of specific fish species, non-fish related drivers) and are they comparable to the UK permitting framework?	Medium
Is there any evidence available on the implications of decisions made by other environmental regulators (for example, a reduction in new development applications, or objections from developers)?	Low

3.3 Fisheries and other aquatic biota impact assessment

The initial task for any assessment of entrainment and impingement due to a cooling water intake system is to define, calculate or estimate the numbers of fish and shellfish that may be entrained or impinged in the system. This is done either by monitoring data at the site in question or nearby sites or, where historic site-specific or comparable impingement and entrainment monitoring data do not exist, this can be estimated from fisheries survey data. The analysis can be further refined by using individual-based models (IBMs) or predictive software.

Impact assessments generally focus on the contextualisation of fish losses upon stocks or populations. Relatively few studies consider other aquatic biota or wider ecosystem effects.

The review identified some methods suitable for assessing the impingement and entrainment effects of cooling water intake systems of nuclear power stations on fish and biota populations. These include collecting data locally from suitable sources, and developing IBMs to build bespoke encounter models.

The equivalent adult value (EAV) and habitat production foregone (HPF) approaches (otherwise termed equivalent area of lost production (EALP)) were also discussed as methods of contextualising entrainment and impingement numbers.

EAV and EALP methods were established for power stations to use in relating annual entrainment and impingement numbers to a standard comparable metric. Established methods of reporting impingement and entrainment predictions (annual rates), and contextualising using EAV and EALP methods, do not consider the wider population implications of entrainment and impingement over a number of years, or changes across the ecosystem and trophic levels.

There is a range of methods available to use, but there is no guidance on which techniques should be used for a project in a given scenario. Consistency of approach is unlikely between assessments, because different projects will adopt different approaches.

The review noted that although appropriate modelling tools were available, there were critical gaps within the data for the parameters required for models, especially if considering a wide range of species across the entire ecosystem under consideration. The models may create outputs of variable quality and with varying levels of confidence. The review suggested that creating a centralised database might ensure consistency across assessments, but noted that this could limit innovation in the modelling techniques as they develop.

The importance of how parameters are chosen and applied was discussed. Once developed, the models must be calibrated to ensure they have the predictive ability needed for decision-making.

It has not been possible to date to unequivocally determine, through monitoring programmes, whether entrainment and impingement cause significant adverse effects on aquatic biota populations. This is likely to be mainly due to the statistical power of experimental designs, variability within datasets, and practical difficulties in collecting data. The review stated that using advanced modelling techniques may be able to identify more subtle effects within the ecosystems.

With the current state of knowledge, the review stated that to determine the effects of entrapment of aquatic biota systematic documentation and treatment of the variability and uncertainty in each step of the assessment process will be needed. This will allow an understanding of the possible range of predicted outputs.

Table 3.3.1 Summary of subject area scoring for fisheries and other aquatic biota impact assessment (Environment Agency 2019)

Confidence criteria	**Overall confidence**
Are models available to satisfactorily assess impacts from cooling water on fish stocks, including considering new intake and screen technologies, and long-term stock/ecosystem level implications?	Medium
Are sufficient model input data and their associated uncertainties available for use?	Medium
Are the available models validated with empirical monitoring data?	Low

4 Intakes – design and location

The Environment Agency provides generic guiding principles for the location of cooling water (CW) intakes for thermal power stations. These include avoiding placing intakes 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' (Environment Agency 2010a).

Animals that come close to any intake are at risk of entrapment. Large-scale industrial intakes can abstract, catch and kill considerable numbers of animals. The animals entrapped in the system may have 2 possible fates; impingement or entrainment.

Impingement is used here to describe the capture of fish and other organisms that are retained on the filter screens of a water intake system. These organisms are washed off the screens, and either collected in a trash basket for subsequent disposal or sluiced along a channel and returned to the environment. The rate of impingement in all habitats increases with the volume of water extracted and the speed at which the water is travelling as it enters the intake system. Furthermore, for a variety of reasons linked in part to fish behaviour, larger intakes catch considerably more fish than would be predicted by using the catch per unit volume observed at smaller intakes (Henderson 2018).

Entrainment is a term used here to describe the fate of organisms that are drawn into the system via the water intake structure but pass through the filter screens. The maximum size of the animals entrained depends on the mesh size of the screens used to filter the water and the shape of the animal. The organisms pass through filter screens, travel through the power plant's pipe-work, and are discharged back to the environment with the effluent water. Of the wide range of planktonic organisms and early life stages that are entrained, the animals that are usually studied are small crustaceans and fish eggs, larvae and young. Of particular concern is the entrainment of fish eggs and larvae, which may be killed in very large numbers when passing through a plant. Studies show that mortality rates of entrained organisms are highly variable and may be as high as 97%, but that mortality rates are very dependent upon the species and life stage entrained (USEPA 2007, Jacobs 2008). It is often assumed that 100% mortality occurs as this is conservative and evidence of survival is difficult to obtain.

The passage of biota through the plant with water can be damaging as organisms undergo a range of stresses that often lead to injury or death. The main causes of harm can be classified into (1) mechanical (abrasion, pressure changes, shear stress), (2) thermal (elevated water temperature and rapid changes in temperature) and (3) chemical (addition of biocides, low oxygen).

Factors that affect entrainment rates include:

- intake location in relation to spawning grounds
- life history of species
- habitat preferences of species
- swimming ability

- growth rates and morphology

There are several methods of reducing capture rates, such as:

- using less water – not only are the numbers of animals drawn in lower, but more protective technologies become feasible
- placing the intake where the animal density is low
- reducing the attractiveness of the intake so animals do not gather at it
- reducing the velocity of water entering the station so more animals can escape
- designing the intake to increase the likelihood of escape

All of these methods can reduce the scale of the potential impact from the intake on some of the organisms. Behavioural-based systems generally cannot protect planktonic life forms (Allen et al. 2012, Henderson 2018), and they will be entrapped in relation to their density in the environment and the amount of water abstracted.

4.1 Optimising cooling water intake siting for minimising impacts on aquatic biota

4.1.1 Introduction

The position of a CW intake for a station is determined by several factors. The most important is the type of cooling used at the power station. Direct-cooled stations need many times the volume of water that closed-cycle cooling designs require. Since the most important factors in choosing a site are availability of suitable volume and depth of water for the intake to function, the large volumes required for a direct-cooled station limit the siting options for the intake. Other important non-biological factors in the siting of an intake include avoiding recirculation of the outfall water, the geology of the site, maintenance, cost and design issues and avoiding shipping. In addition to these non-biological factors, the previous Environment Agency review (Environment Agency 2010a) indicated that it could be beneficial to avoid constructing intakes within areas of notable ecological value such as 'important fish spawning and nursery grounds, ecologically sensitive habitats, economically important shell fisheries and fish migration routes'.

All of these are site-specific and no one solution will suit all station sites and designs. Previous coastal power stations had a mix of onshore (for example, Heysham, Hartlepool) and offshore intakes (for example, Sizewell, Hinkley). The onshore intakes were typically built either with a canal leading to the station, or with the intakes built into a dock. The offshore intakes were generally as close to the station as possible while allowing for site-specific factors such as bathymetry, tidal height, thermal regimes and possible wave action. These intakes were generally 500 to 600 m offshore (Environment Agency 2010a).

Once a site has been decided for the station, the options for the positioning of the intake are limited. Some current UK nuclear new build (NNB) designs propose intake locations 4 to 5 km offshore.

The productivity of the sea generally declines from shallow to deep water, especially below the photic zone. This suggests that moving an intake further offshore would reduce the environmental impact, as the concentration of organisms present would be lower. In a review of intakes for desalination plants (Missimer and Maliva 2018) suggest that 'deep' in this context means at least deeper than 20 m and possibly over 100 m.

In coastal waters, there is only weak evidence to support the assertion that moving the outfall further from shore will reduce the impact on aquatic biota. The main evidence is based on (1) the habitat preference of 0-group flatfish (that is, flatfish in the first year of life), which tend to be found in shallow water (Riley et al. 1981), and (2) the study of Sizewell A and B capture rates (Turnpenny and Taylor 2000). The comparison of capture rates is complicated because the 2 intakes are not truly comparable, and we do not know which of the several factors that changed between the 2 intakes is important.

Turnpenny and Taylor (2000) outlined the major differences between the intakes. The intakes at A and B stations at Sizewell are 300 m and 600 m offshore, respectively. The older A station intake is a simple vertical shaft protected by a horizontal grill, which therefore draws water vertically down. The B station has a pair of intakes which are capped. This results in lower entrance velocities with a more horizontal inflow pattern, which fish are more able to avoid.

So, in the case of case Sizewell A/B comparison, we do not know if it is the position, the volume, the intake velocity or the velocity cap which might be important.

Individual-based models (IBMs)

Looking at individual fish as data points, and modelling their likelihood of being impinged or entrained has been used in several studies. Treating eggs and larvae as passive objects in the water body and looking at the chance of entrainment at a power station has been used to try to predict the impact (Ahsan et al. 2003). As with all modelling, the models are very vulnerable to the assumptions made and the parameters estimated (Blumberg et al. 2004).

For NNB design, passive particle (‘drogue’) tracking models have previously been used (for example, 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 (Environment Agency 2018).

In recent years, modelling capability has developed rapidly, enabling rule sets to be developed that can parameterise IBMs for species and life stages which migrate through estuaries (for example, Blumberg et al. 2004, and Guerin et al. 2014).

If proven reliable, these models could be used to inform opinion on the sighting of intakes in order to reduce the impact on species.

Offshore islands

In the Environment Agency scoping document (Environment Agency 2018), the possible use of artificial offshore islands as locations for cooling water intakes was discussed. CW intake offshore islands have been considered for some UK NNB and combined cycle gas turbine (CCGT) sites. These intakes would be on an engineered island and would have the screening for the station on the island rather than at an onshore CW pump house. Screening systems could either remove impinged fish from the water by using horizontal rotating screens, or lift the fish clear of the water before returning them via a fish recovery system. This layout would allow any fish return system to potentially have a very short route back to sea. This would minimise the handling time for the fish, and potentially reduce the stress and damage done to the animals. An artificial island structure may become a habitat itself (reef effect), which would have to be considered for protecting biota. No current examples of CW intake offshore islands have been found for this review.

4.1.2 Documents reviewed

Fish density inshore/offshore

Distribution of juvenile Atlantic cod (Gadus morhua) relative to available habitat in Placentia Bay, Newfoundland (Gregory et al. 1997)

In a study of the distribution of young (one to 4 years old) cod, Gregory et al. (1997) found that cod were found in greater numbers at depth, with most found below 60 m. They contrast this depth preference with other nearshore studies of 0-group cod, which found the highest abundances in less than 10 m of water. The authors suggest that the cod move deeper as they grow, and that habitat preference is as important as depth in the distribution of young cod.

Settlement length and temporal settlement patterns of juvenile cod (Gadus morhua), haddock (Melanogrammus aeglefinus), and whiting (Merlangius merlangus) in a northern North Sea coastal nursery area (Bastrikin et al. 2014)

Bastrikin et al. (2014) examined the patterns of settlement of 3 gadoid species off the east coast of Scotland. In this study, they sampled at 3 similar sites at 800, 1,600 and 2,400 m from the shore, with average depths of 22, 32 and 42 m, respectively. They found that different species had different depth preferences. Young whiting started to settle at site 1 early than at site 2 or 3, but by the end of settlement the density at site 2 and 3 was significantly higher than at site 1. For cod, the fish settled in greater numbers at site 1 and 2 than at site 3. Haddock had the most complex relationship with depth, with most also favouring the deeper sites, with site 1 having significantly fewer fish than site 2 and 3. Of the deeper 2 sites, site 2 had the highest abundance. They also found that for haddock, the size of the fish at the 3 sites started similar, but as time passed, the 2 deeper sites held larger fish than the shallow site.

Sampling of fish and crustaceans at the cooling water intake of an estuarine power plant: a comparison with stow net fishery (Maes et al. 2001)

Maes et al. (2001) studied the captures at Doel Power Station in the Zeeschelde Estuary, Belgium. They paired samples from the station with stow net samples (2 large nets deployed from a stationary boat in the running tide). They found that the station caught more small fish, but had a similar diversity. The samples from the stow nets were dominated by sprat and herring (77% of total catch), whereas in the station sprat and herring accounted for 43%, with gobies making up another 20% of the catch. The combined species total for both sampling systems was 39, with the station catching 33 and the stow nets 32 species, with 26 species common to both sampling methods.

Over the period of regular sampling from 1995 to 2001, 63 fish species and 6 crustacean species were recorded at the intake, whereas year-round fyke netting on a neighbouring intertidal mud flat between 1994 and 1998 yielded only 47 fish species, and monthly beam trawling for one year in an adjacent part of the estuary resulted in only 28 species.

The authors state that the cooling water intake therefore samples the fish community more efficiently than the stow nets, with the abundance of fish at the intake 5 times higher on average than in the stow nets. There were substantial differences between species. The authors suggest this was due to differences in the size selectivity of the 2 methods.

This study highlights the difficulty of using other sampling methods to estimate the capture of an intake.

Essential fish habitat source document: Atlantic herring, Clupea harengus, life history and habitat characteristics (2nd edition) (Stevenson et al. 2005)

This document reviews the biology of the Atlantic herring on the east coast of the USA. It is interesting because here the depth preferences of juvenile (sub 250 mm) and adult herring are given separately (Figure *1* and Figure *2*). It is notable that the depth distribution of adults and juveniles are wide, with both groups being found from the surface to over 75 ft (around 23 m).

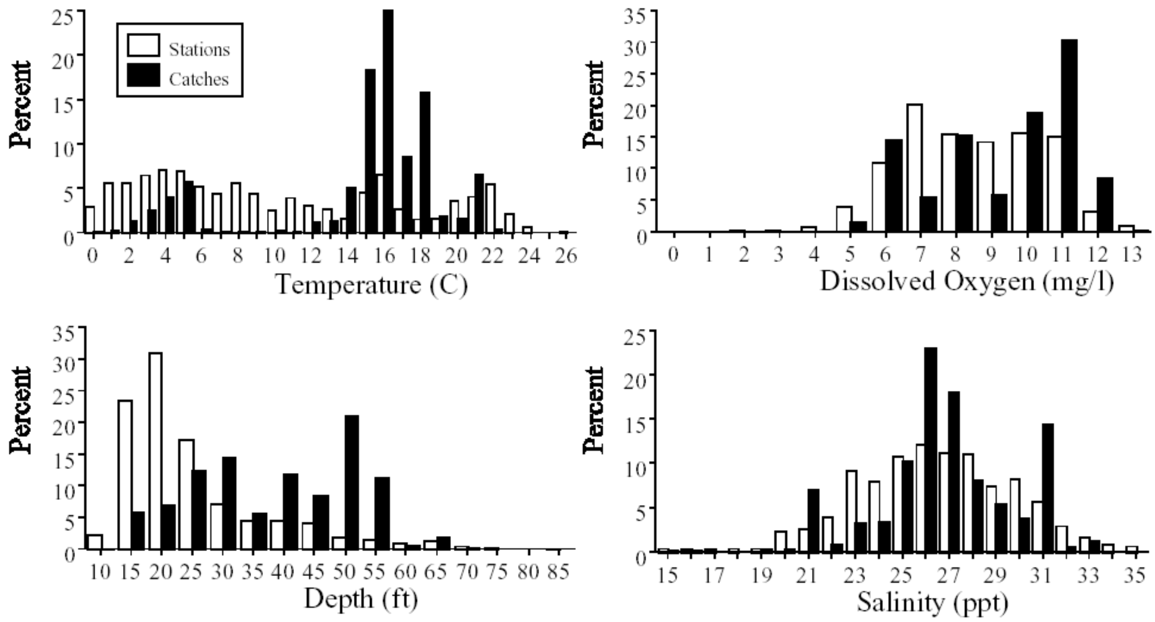


Figure 1: Distributions of juvenile Atlantic herring in the Hudson-Raritan Estuary relative to mean water temperature, depth, dissolved oxygen, and salinity. Based on the Hudson-Raritan trawl surveys, 1992 to 1997. Open bars represent stations surveyed and closed bars represent fish collected. (Reproduced from Gregory et al. 1997)

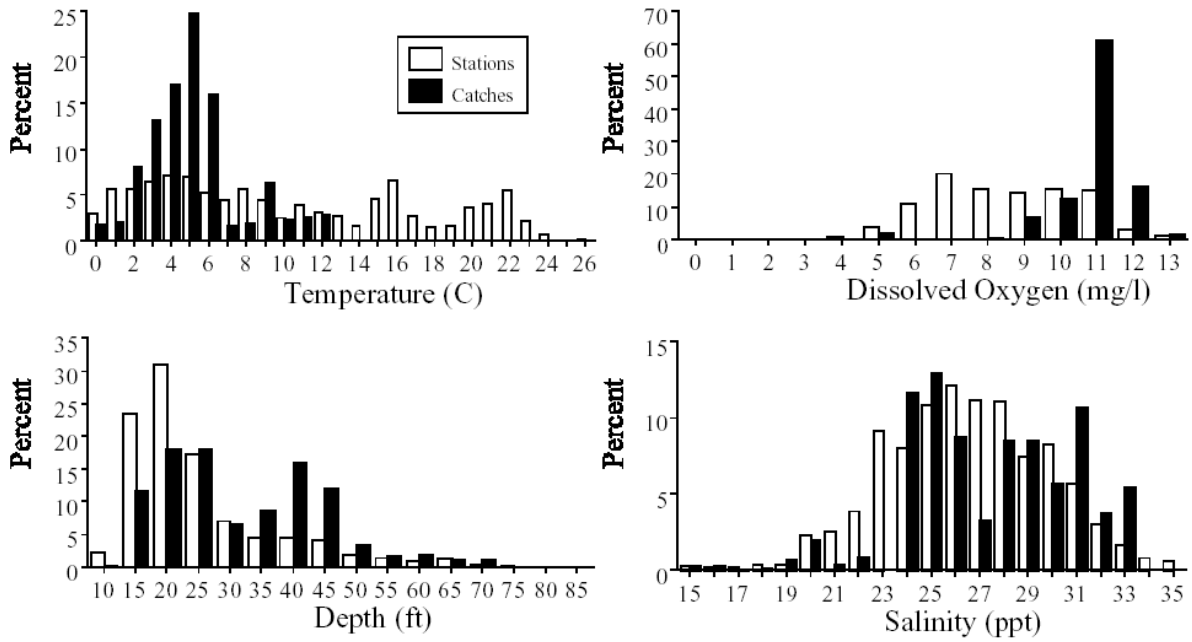


Figure 2: Distributions of adult Atlantic herring in the Hudson-Raritan Estuary relative to mean water temperature, depth, dissolved oxygen, and salinity. Based on the Hudson-Raritan trawl surveys, 1992 to 1997. Open bars represent stations surveyed and closed bars represent fish collected. (Reproduced from Gregory et al. 1997)

The distribution and size composition of finfish, American lobster, and long-finned squid in Long Island Sound based on the Connecticut Fisheries Division Bottom Trawl Survey, 1984-1994 (Gottschall et al. 2000)

Gottschall et al. (2000) reported on a decade of data from a large survey of Long Island Sound, USA. The survey covered many species and reported the occurrence in relation to depth and substrate type. They state, “Aggregate abundance generally increased with depth in the spring and summer periods, whereas in fall and November abundance was highest between 9 and 27 m.” This is a useful study as the areas in the 4 depth bands selected are relatively even (Figure *3*). To illustrate this, we selected herring to analyse, as it is a species common to the UK. Figure *4* shows the original figure, with a replotting of the depth bands to illustrate the relative importance of each zone. It can be seen from these plots that the percentage of herring in each depth band does not decline rapidly with depth for most of the year.

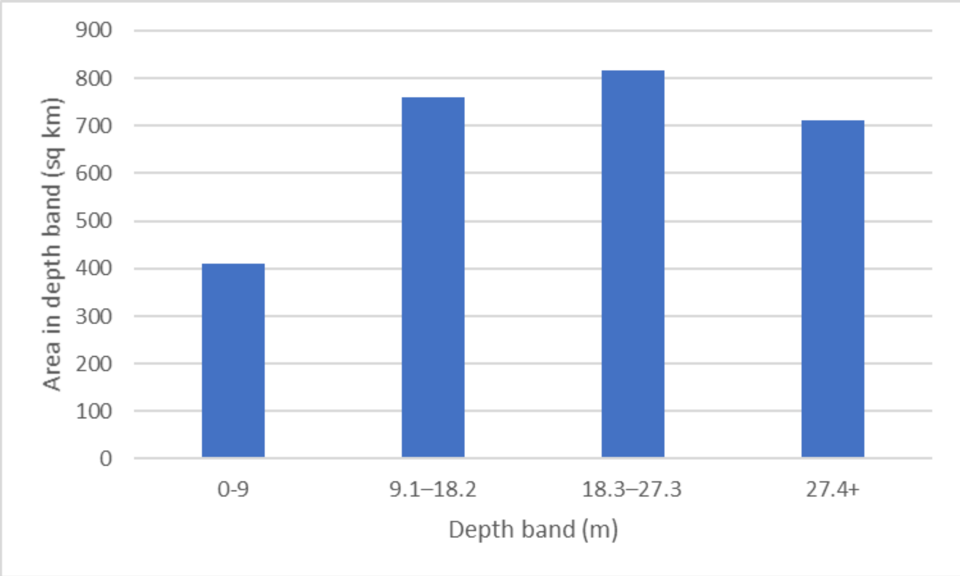
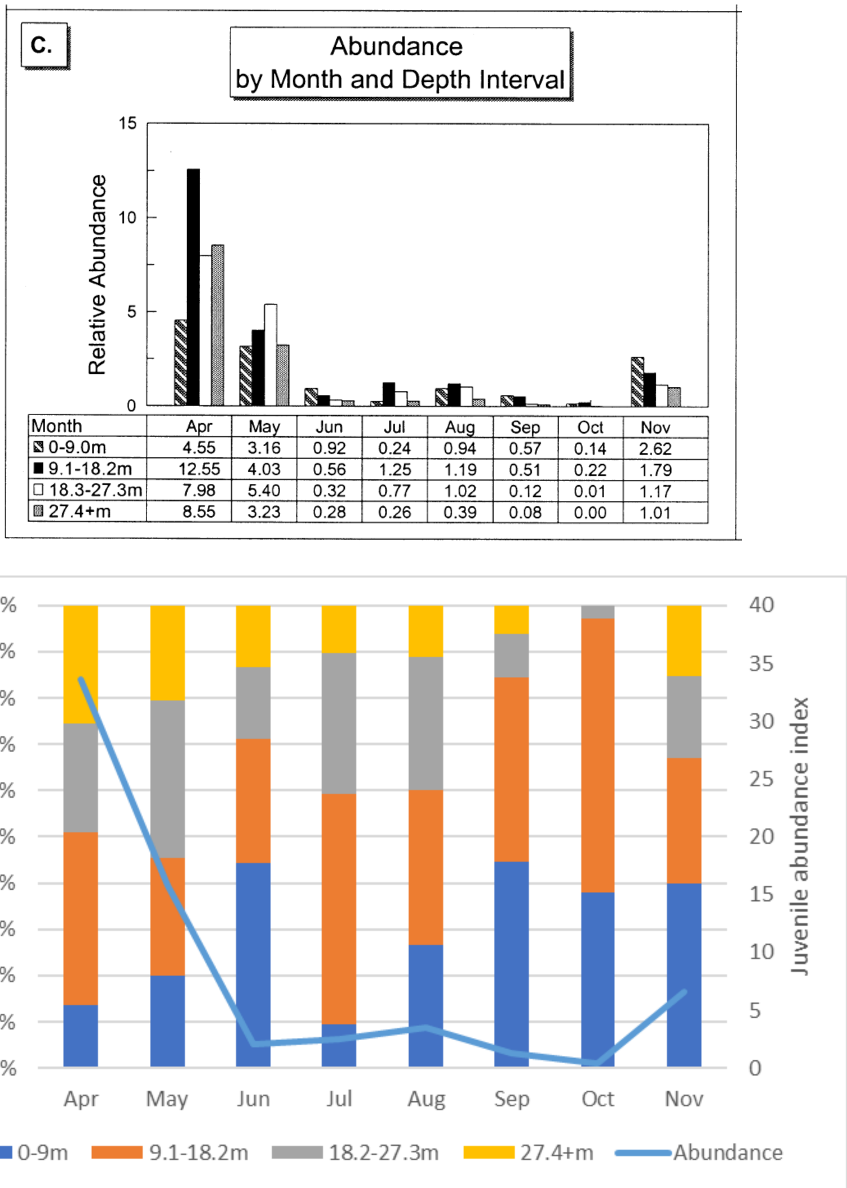


Figure 3: The total stratum area (sq. km) sampled by depth band (Reproduced from Gottschall et al. 2000)



Month	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
0-9.0m	4.55	3.16	0.92	0.24	0.94	0.57	0.14	2.62
9.1-18.2m	12.55	4.03	0.56	1.25	1.19	0.51	0.22	1.79
18.3-27.3m	7.98	5.40	0.32	0.77	1.02	0.12	0.01	1.17
27.4+m	8.55	3.23	0.28	0.26	0.39	0.08	0.00	1.01

Figure 4: Depth and abundance of herring in Long Island Sound. Original figure at the top and replotted at the bottom to show depth bands (Reproduced from Gottschall et al. 2000)

Individual-based models (IBM)

Predicting Entrainment of Ichthyoplankton at a Power Plant Intake on the East River, NY (Ahsan et al. 2003)

This is a study using a random-walk particle-tracking model of the East River, New York Harbour, Long Island Sound and New York Bight. They used the model to predict the distribution of ichthyoplankton and their probability of entrainment at the cooling water intake. The authors state that the results in terms of predicting entrainment are highly dependent on location and time of the release of the particles, and the assumption that ichthyoplankton behave like neutrally buoyant particles.

Use of a particle-tracking model for predicting entrainment at power plants on the Hudson River (Blumberg et al. 2004)

In this study, the authors highlight some of the differences between an empirical transport model (ETM) and a particle model to predict entrainment. They show that entrainment in this system is highly dependent on a factor that is not included in the ETM at this site.

Can IBMs tell us why most larvae die in the sea? Model sensitivities and scenarios reveal research needs (Peck et al. 2012)

The study looked at the reliability of IBM estimates of spatial and temporal changes in mortality rates of marine fish early life stages, as well as the various processes that contribute to those changes. It examined the biological parameters used within the models, and reviewed several studies, including looking in more detail at herring models, a highly-studied species. They found fewer than 25% of reviewed papers included formal sensitivity analyses of parameters. The authors then highlighted 5 areas that need more research to improve the robustness of the ichthyoplankton model studies. These are to:

- better understand the behaviour of early life stages
- increase knowledge on growth physiology of target species/life stages
- examine prey fields and the sensitivity of coupled models
- recognise the assumptions of applying mortality functions
- develop approaches to estimate prey–predator overlap

Hydrodynamic models to understand salmon migration in Scotland (Guerin et al. 2014)

This document focuses on migratory behaviour of salmon in Scotland, and the Pentland Firth in particular, in coastal waters during the outward and return migrations. It examines the use of hydrodynamic models and 'particle tracking models' (PTMs) as a possible method of better understanding the interaction of salmon with various renewable power technologies. Salmon are a well-studied animal, and there are existing data on migration patterns and behaviour. The authors state that it is possible to use hydrodynamic models to produce:

- information on the probability of migrating salmonids passing through specific development sites
- estimates of the relative number of potential encounters with arrays positioned in a variety of locations
- estimates of cumulative encounter rates where there are multiple arrays

Even with a well-studied area and species, the authors suggest that the models developed are provisional and need refining. They also emphasise that the model cannot serve on its own as a method of assessing risk to migratory fish. It requires coupling to a larger-scale model to understand fish arrival, and to a small-scale model to understand the nature of any interactions between devices and fish.

Freshwater and coastal migration patterns in the silver-stage eel Anguilla Anguilla (Barry et al. 2016)

Downstream migration of eels was studied in Ireland. Migration was found to be related to freshwater flow. Other influences were light, tidal direction and lunar phase.

Migration behaviour of silver eels (Anguilla anguilla) in a large estuary of Western Europe inferred from acoustic telemetry (Bultel et al. 2014)

This study looked at the estuarine migration of female silver eels in the Loire River. Mean directional migration speed was found to be correlated with total length and body weight and daily escapement rate was highly influenced by river flow.

Linkage Between Coastal Conditions and Migratory Patterns and Behavior of Atlantic Salmon Smolts Along the Halifax Line (Dever et al. 2016)

This study focuses on the migratory patterns and behaviour of Atlantic Salmon smolts tagged in the Penobscot River (ME, USA). It links inter-annual temporal and spatial variability to co-located oceanographic data collected from many different platforms. The migratory behaviour (heading, patterns in repeated detection, time spent at the line) is described, and cross-shelf movement are compared to oceanographic variables. It shows that tidal current does not explain the cross-shore movement of the smolts.

Heading south or north: novel insights on European silver eel Anguilla anguilla migration in the North Sea (Huisman et al. 2016)

This paper observed the southward migrating silver eels in the North Sea. Eels were tagged during their spawning migration. Some of the population of eels migrates towards the English Channel, while others went north over Scotland.

Assessing estuarine and coastal migration and survival of wild Atlantic salmon smolts from the Narraguagus River, Maine using ultrasonic telemetry (Kocik et al. 2009)

Using ultrasonic transmitters and a large network of fixed receivers, smolt migration in the Narraguagus River, Narraguagus Bay, and coastal environment of the western Gulf of Maine was monitored.

Migration pathways, speed and mortality of Atlantic salmon (Salmo salar) smolts in a Scottish river and the near-shore coastal marine environment (Lothian et al. 2018)

In a study of smolts, the authors found that the majority of smolts leaving the river did so in darkness and on a flooding tide. Migration success was linked to nights of lower lunar brightness for both fresh and marine phases. Marine migration speed decreased with increasing environmental noise levels. The migration pathway in the early marine environment did not follow obvious geographical features, such as the coastline.

Continuous acoustic studies of overwintering sprat Sprattus sprattus reveal flexible behaviour (Solberg et al. 2012)

In this study in a Norwegian fjord, sprat were shown to have a flexible behavioural repertoire, displaying different overwintering strategies within a population, depending on environmental conditions.

Ecology of overwintering sprat (Sprattus sprattus) (Solberg et al. 2015)

Sprat behaviour was monitored in a Norwegian fjord. Sprat shoaling behaviours varied between day and night and between years.

The home range and behaviour of yellow-stage European eel Anguilla anguilla in an estuarine environment (Walker et al. 2014)

In a study of eels in Poole Harbour and associated rivers, the authors found that activity was generally, but not exclusively, nocturnal, with the start and end times closely associated with sunset and sunrise, respectively. The direction of travel nor average ground speed was influenced by tidal flow direction, and seasonal declines in water temperature did not appear to influence behaviours.

Offshore islands

The Central Electricity Generating Board (CEGB) considered options for offshore intake islands during the 1960s, but did not progress the idea. Issues with access for maintenance in all weathers, security and navigation were cited as possible reasons. No evidence of operational artificial offshore island intakes has been identified in this review.

4.1.3 Review synthesis

Fish density with inshore/offshore

The position of the intake obviously depends on the positioning of the power station. This is not a simple decision, and the ability to place the intake in the least damaging area is not necessarily one of the major factors in the decision. In the case of the new nuclear power station fleet, the government has licensed a limited number of sites (DECC 2011). Given that the location of the station is constrained, the best place for the intake at that site must be decided. Traditionally, the cooling water intake for the site was at most a few hundred metres from the power station. Some of the new stations are planned with intakes about 4 km from the site. This allows more flexibility with the placing of the intake.

If the general position of an intake is fixed, it must then be determined whether placing the intake further offshore can reduce the potential number and biomass of the fish and invertebrates caught.

Moving the intake a few kilometres offshore does not, for much of the UK, place it in deep water. For example, the North Sea is relatively shallow across much of the inshore area, as are areas such as Morecambe Bay. Intakes are designed to be always covered in water at the lowest tide possible when combined with the lowest wave trough predicted.

The habitat of close inshore waters can be an important nursery ground for some species. For example, some of the flatfish can be found in the surf zone when young (Riley et al. 1981); other species are found in large numbers in salt marshes and creeks (Green et al. 2009). Other species are not dependent on the shallow coastal waters. The pelagic species that, at some sites, can make up the majority of impinged fish, perhaps unsurprisingly show little variation between the very close inshore and further offshore (Henderson 1989). For some proximo-benthic species such as cod, the presence of suitable substrate determines where they reside.

Fish show complex behaviours, which vary through time. Solberg et al. (2012, 2015) examined the behaviour of sprat in a fjord in Norway, and found that not only were the fish showing more than one diurnal vertical migration pattern, but that within the population there were variations both at shoal and individual levels, depending on seasonality and environmental conditions.

It is possible that moving an intake further offshore will result in larger fish being caught. Whether this is desirable depends on the species involved, and the protection desired.

Moving an offshore intake into much deeper water may possibly reduce the number of fish captured, but would potentially increase the barotrauma experienced by the fish during the entrapment. Barotrauma is discussed in other sections of this report.

It is therefore impossible to state with any degree of certainty that moving an intake further offshore in the UK would reduce the impingement and entrainment rate. The effect will be highly site-specific and will depend on the factors such as the species composition of the area, the presence of preferred habitats, and depth profile of the shore.

Individual-based models (IBM)

Individual-based models (IBM) are not yet robust enough to provide the level of certainty required to assess effects of various positions of the capture rate of an intake at a station. These models rely on the assumptions and estimates of a wide range of factors. An IBM to predict the capture rates of an intake would require background information on the environment at and around the site, for example:

- tidal velocity at all states of tide over a range of tidal cycles
- the daily temperatures over several years
- the effect of local riverine inputs
- changes in seabed morphology over the life of the station
- impacts of fouling on the intake structure
- patterns of station operation and shutdown
- operating procedures at the station (such as reduced CW pumping in winter)

The IBM might also need a range of biological parameters such as:

- which species are present and in what number
- species' likelihood of intake encounter – for example, whether a flatfish is as likely to encounter an intake as a pelagic species
- swimming ability for each species:
  - at different temperature
  - at different salinities
  - at different seasons – for example, spawning may affect the swimming ability
- for each species, the likelihood of the correct escape behaviour being used
- for each species, the ability to detect the intake
- size of the fish for each species, throughout the year – for several years
- diurnal effects on capture rates
- impact of turbidity on the species' ability to detect the intake
- the individual's previous experience – for example, the individual may have exhausted itself escaping a predator or the intake previously

For an IBM to work for the entire community, the level of knowledge required is much higher than we currently have, and probably higher than we could ever have in a dynamic system such as inshore coastal waters.

Single-species studies using fish-tracking techniques and fixed listening arrays, such as those carried out by Guerin et al. (2014), Kocik et al. (2009), Dever et al. (2016) and Lothian et al. (2018) on salmon, or Bultel et al. (2014), Walker et al. (2014) and Barry et al. (2016) on eels, could lead to better understanding of the migratory routes of individual species in the environment. To date, most of these studies have concerned the migratory species in estuaries or other confined bodies of water. Some studies have looked at the movement of species such as eel in the sea (Huisman et al. 2016), but as yet the areas studied, and the amount of data collected, is small.

Therefore, to run any IBM at either the individual species level or community level, many assumptions are required, both of physical and biological parameters. How these assumptions impact the estimates of capture and whether the assumptions interact with each other would need to be understood.

If the position of the intake depends on the likelihood of capture of a single species (presumably rare or valuable), then building an IBM may be possible. However, if the animal is rare, it is unlikely that the level of study required has been undertaken, since working on rare animals is difficult in the field.

Offshore islands

No evidence of operational artificial offshore island intakes has been identified in this review.

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. There is no precedent for the use of CW intake offshore islands in the USA (Environment Agency 2018).

4.1.4 Evidence scoring for optimising cooling water intake siting to minimise impacts on aquatic biota

Fish density inshore/offshore

4.1.4 Evidence scoring for offshore inshore intake position

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Distribution of juvenile Atlantic cod (*Gadus morhua*) relative to available habitat in Placentia Bay, Newfoundland. Gregory et al. (1997).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence of a species found around the UK. **Applicability of evidence** The paper is based on fish species found in the UK. The activities assessed are not power station impingement but the data on location of fish are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors deeming that habitat preference is as important as depth in the distribution of young cod.	**High (15)**

4.1.4 Evidence scoring for offshore inshore intake position

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Settlement length and temporal settlement patterns of juvenile cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and whiting (*Merlangius merlangus*) in a northern North Sea coastal nursery area. (Bastrikin et al. (2014).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence from the UK. **Applicability of evidence** The paper is based on sampling of young gadoid species in the UK. The activities assessed are not power station impingement but the data on location of fish are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors showing the complexity of the habitat choices of fish in inshore waters.	**High (15)**
Sampling of fish and crustaceans at the cooling water intake of an estuarine power plant: a comparison with stow net fishery. Maes et al. (2001).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence on species in the UK. **Applicability of evidence** The paper is based on sampling in the Zeeschelde Estuary, Belgium. The activities assessed were related to power station impingement, and the data on fish captures are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors showing the difficulty of assessing the likely captures of an intake using different methods.	**High (15)**

4.1.4 Evidence scoring for offshore inshore intake position

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Essential fish habitat source document: Atlantic herring, *Clupea harengus*, life history and habitat characteristics (2nd edition). Stevenson et al. (2005).	Report	5	5	5	**Quality of information source** This is a report published by a well-respected body, with high levels of scientific credibility and based on direct empirical evidence on species found in the UK. **Applicability of evidence** The paper is based on sampling of the Atlantic herring on the east coast of the USA. The activities assessed were not related to power station impingement, but the data on species are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors showing the range of depths at which herring are found.	**High (15)**

4.1.4 Evidence scoring for offshore inshore intake position

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
The distribution and size composition of finfish, American lobster, and long-finned squid in Long Island Sound based on the Connecticut Fisheries Division Bottom Trawl Survey, 1984-1994. Gottschall et al. (2000).	Report	5	3	5	**Quality of information source** This is a report published by a well-respected body, with high levels of scientific credibility and based on direct empirical evidence on some species found in the UK. **Applicability of evidence** The paper is based on sampling of the fish in Long Island Sound, on the east coast of the USA. The activities assessed were not related to power station impingement, but the data on species are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors showing the seasonality of presence and of depth preference in a range of fish, which includes several UK species. Analysis of herring (as common UK fish) shows that when the percentage of fish in each depth band is plotted, for most of the year, the number does not decline rapidly with depth.	**High (13)**

4.1.5 Evidence scoring for individual-based models (IBM)

4.1.5 Evidence scoring for individual-based models

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Predicting Entrainment of Ichthyoplankton at a Power Plant Intake on the East River, NY. Ahsan et al. (2003).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper. The modelling principles are relevant to UK entrainment at water intakes. **Applicability of evidence** The results are based on a random-walk particle-tracking model based on ichthyoplankton behaving as neutrally-buoyant particles, used to predict the entrainment at a power plant. The assumption that ichthyoplankton is a neutrally-buoyant particle makes the predictions of the model unreliable for some life stages of ichthyoplankton in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors showing that the results of the model in terms of predicting entrainment are highly dependent on location and time of the release of the particles, and the assumption that ichthyoplankton behave like neutrally-buoyant particles.	**11**

4.1.5 Evidence scoring for individual-based models

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Use of a particle-tracking model for predicting entrainment at power plants on the Hudson River. Blumberg et al. (2004).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper. The modelling principles are relevant to UK entrainment. **Applicability of evidence** The paper compared an empirical transport model (ETM), and a particle-tracking model to predict entrainment. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors showing how assumptions that vary between the models influence the results of the model.	**11**
Can IBMs tell us why most larvae die in the sea? Model sensitivities and scenarios reveal research needs. Peck et al. (2012).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper. The modelling principles are relevant to UK entrainment. **Applicability of evidence** Reviewing a range of IBMs and critically appraising the sensitivity analysis of the models. The authors highlight some of the areas where improvement is needed to understand behaviour of the animals to allow them to be modelled. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors showing that more data are needed to build reliable models, even for the well-studied species.	**High (15)**

4.1.5 Evidence scoring for individual-based models

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Hydrodynamic models to understand salmon migration in Scotland. Guerin et al. (2014).	Report	5	5	5	**Quality of information source** This is a report for the Crown Estate. It is on a UK estuary and a UK species. The modelling principles are relevant to UK entrainment. **Applicability of evidence** Focuses on migratory behaviour of salmon in Scotland, and the Pentland Firth in particular. Highlights some of the strengths and weaknesses of the approach. Discusses the application of the model in environmental impacts assessment. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors summarising the state of knowledge on salmon migration through the Pentland Firth.	**High (15)**

Offshore islands

No data found.

4.1.6 Evidence review conclusions for optimising cooling water intake siting for minimising impacts on aquatic biota

This review of the evidence for differences in fish density depending on the location of the intake, suggesting that moving the intake 1000 m or more from the shore will reduce impingement and entrainment, is inconclusive. Some species are more abundant in the inshore waters, particular young flatfish and saltmarsh specialists. It is not clear, however, that the reduction in the catches of these species will be greater than the possible increase in other species.

The majority of the catch in several UK stations is dominated by shoaling pelagic species such as sprat or herring (Henderson 1989, Greenwood 2008). These species show complex patterns of behaviour, with seasonal migration and diurnal movement up and down the water column. In contrast, benthic and proximo-benthic species often show a preference for the substrate type, and appear not to be influenced by the water depth (Araujo et al. 2000, Henderson 1989).

The decision on whether an intake near shore or further from shore is preferable requires site-specific data. Each site will have a unique distribution of species, and the species that are of concern will also vary. A difference in the average size of fish between 2 sites is likely. Inshore sites often have more juvenile fish present. Survival of impingement and entrainment is likely to vary in different-size fish and this may impact the assessment.

The balance between different locations in terms of environmental damage may be decided based on which of the fish in the community is of greatest concern. Placing an intake close to shore and impacting large numbers of sand smelt and young clupeids may be preferable to moving it further from shore where it might catch higher numbers of eels, shad, lamprey or salmon. We do not have the data to resolve the differences in density of these fish in coastal waters in the UK. Arguments made based on reducing the impact of the intake should be based on high-quality site-specific studies.

In reviewing individual-based models (IBM), we conclude that they are not yet robust enough to predict the capture rates of an intake from a model alone. IBMs may help if the decision on where to place the intake is based on one or two of the well-studied species. The parameters needed to model the entire community are beyond our current level of knowledge. The knowledge gained by building IBMs and comparing them to the behaviours of animal in the environment is valuable. Even where the models do not predict movements or animals well, understanding the gaps in our knowledge can allow targeted research.

4.1.7 Subject area scoring

4.1.7 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Is siting a cooling water intake offshore likely to minimise impacts on aquatic biota?	3	3	3	**Quality of evidence base** There are limited studies of the depth preferences of marine species around our coast in sufficient detail to predict the difference in captures from one site to the next. Many species live over a wide range of depths. Evidence from elsewhere suggests that site-specific variation is large and no generalisation can be made. Site-specific surveys are required. **Applicability of evidence** Where direct evidence from power stations exists, there are confounding factors that make it difficult to separate location and depth from the different design and operation of the intakes. A definition of what constitutes minimising the impacts on the aquatic biota is required for each intake. **Degree of concordance** The evidence suggests that distance offshore is only one of the factors influencing fish captures. Intake design and operation, the species present at a site, and the desire to protect particular species could all impact on the decision as to which site minimised the impact on the aquatic biota.	**Medium (9)**

4.1.7 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Can individual-based models (IBM) be used to predict impingement and entrainment, and so help in the positioning of intakes?	3	1	1	**Quality of evidence base** IBMs are being developed for single-species issues. There are no models found by this review that would produce reliable estimates of the impingement or entrainment of a community. **Applicability of evidence** If the position of an intake is to be decided by the impact on a single well-understood species, it may be possible to create a model that would help in predicting capture rates. For community-based assessment, no such models exist. **Degree of concordance** Many parameters need to be known for a robust model to be developed. No agreed values exist for many of the parameters. No agreed standard for the modelling is known.	**Low (5)**

4.2 Intake head designs

4.2.1 Introduction

Low Velocity Side Entry intakes

Traditional offshore intakes were vertical shafts with water potentially being drawn from all sides. In the Environment Agency (2005) guidance, the design for the best practice intake was changed. The new specification was for the intake to be a side-opening design, which when aligned with the tidal current produces a more even intake velocity across the face.

In the Environment Agency (2010a) report, a default nominal CW intake approach water velocity of 0.3 m s^{-1} was recommended for intakes. The Environment Agency (2005) best practice guidance suggested that, following a suitable risk assessment, this velocity might be varied. It is possible to create intakes that have this water velocity as an average across the intake openings (Environment Agency, 2010a). It should be noted that local variations in the actual intake velocities are still likely.

In the Environment Agency (2018) report, the key challenges to the design of intake heads were outlined as:

- achieving compliance with nuclear safety
- ensuring maintainability
- being able to construct it away from site and deploy at site
- developing a design with uniform approach velocities
- design and maintainability of fish protection technologies

One design has been developed to the point where it has been modelled; the proposed intake for Hinkley Point C. This is called a Low Velocity Side Entry (LVSE) intake.

This section looks at the evidence for using side-opening intakes as a fish protection measure.

Onshore intakes

Onshore intakes have been commonly used on power stations in the UK (Henderson 1989). These are sometimes built into docks in the harbour walls, such as Heysham and Marchwood, built in sheltered water, for instance Pembroke and Hartlepool, or directly on the shore, as is the case at Wylfa or Torness. Some large stations, such as Fawley, have been built with their own canal leading to the intakes.

From a fish protection point of view, there are some advantages to these onshore intakes. The fish are unlikely to suffer significantly from barotrauma as the intakes are not very deep, and the time from entrapment in the intake to the release from the fish return system is short. Whether fish capture rates are higher than those for a comparable offshore intake at the same site would depend on site-specific factors.

Using breakwaters to protect the intake structure is considered in relation to creating sheltered fish habitat close to an intake.

4.2.2 Documents reviewed

LVSE intakes

Assessment of Effects of CW Intake Velocity on Fish Entrapment Risk at Hinkley Point (Turnpenny Horsfield Associates Ltd 2010)

In 2010, Turnpenny Horsfield Associates produced a report for Jacobs Ltd on the Low Velocity Side Entry (LVSE) intake design proposed at Hinkley Point C. In this document, the authors attempted to give an indication of the effectiveness of the LVSE in protecting fish. To do this, they took data from a hydraulic modelling exercise undertaken by Jacobs (2010) (unseen by us) for the proposed intake, at a tidal flow up to 1.5 m/s. In this model, the tidal flow was aligned exactly along the long axis of the intake, and the velocity of the water entering the intake at each point estimated. From this model, the authors calculated the proportion of water entering the intake at each velocity range across its entire aperture. The table reproduced below sets out the results of those calculations.

Table 2 Distribution of entrance velocities and flows for the Jacobs Finals Design intake at tidal velocities of 0.6, 0.85 and 1.5 ms-1 (Extracted from Jacobs 2010) From Turnpenny Horsfield Associates Ltd (2010)

Intake velocity range ms^{-1}	Jacobs Final Design					
	Tidal stream velocity					
	0.6 ms^{-1}		0.85 ms^{-1}		1.5 ms^{-1}	
	Flow (m3s^{-1})	% of flow	Flow (m^3s^{-1})	% of flow	Flow (m^3s^{-1}))	% of flow
0.1	2.59	8%	1.39	4%	1.15	3.5%
0.2	4.97	15%	6.65	20%	3.49	10.7%
0.3	15.21	47%	13.86	43%	14.51	44.6%
0.4	5.74	18%	4.12	13%	9.85	30.3%
0.5	3.99	12%	2.86	9%	0.82	2.5%
0.6	0	0%	3.63	11%	1.15	3.5%
0.7	0	0%	0	0%	0	0.0%
0.8	0	0%	0	0%	1.53	4.7%
0.9	0	0%	0	0%	0	0.0%
Total	32.5	100%	32.5	100%	32.5	100%

To put this into context for Hinkley C, the authors used the impingement data from 2009 for 6 species (shad, cod, whiting, sole, bass and herring) and calculated the swimming ability for each individual, based on the size of the fish and a seasonal temperature. From these 2 estimated factors, they calculated the proportion of the fish that would be entrapped. There are several weaknesses in this analysis:

1. All the flows are calculated, not measured.
2. The effects of tidal flows not aligning with the structure are not investigated.
3. Fish swimming performance for shad is taken from a generic clupeid figure.
4. As noted by the authors, fish that can swim against the current to escape are assumed to do so, even in a turbulent, high sediment - low visibility environment.
5. A percentage reduction is given based on a weighted value for the 6 species used; although these are representative of the shapes of fish and commercial species, they do not represent the catch at Hinkley in its entirety.
6. Hinkley Point B uses a 10 mm screen, and, as such, the sampling does not measure anything that is not retained by the mesh. Since small or juvenile fish, fish larvae and eggs are more vulnerable to capture, and are not considered or measured in this data, this could skew the results.

The authors give a range of estimated reductions in impingement that would be provided by the LVSE intake, depending on the measure of swimming ability used in the calculation (that is, mean, 90^{th} percentile and combined). From these, a range of values for the reduction in the number of fish entrapped by the intake is calculated. The best estimate is given at a reduction of 16.1%, compared to the current Hinkley B intake. The greatest reduction is 27% and the worst is 7%.

As stated by the authors, several important species, such as eel and lampreys, will not benefit from improvements in the intake design.

The modelling is undertaken on a single LVSE intake head, designed to abstract 32.5 $m^3 s^{-1}$. Given that the proposed intake at Hinkley Point C is about 4 times larger than the current one at Hinkley Point B, the actual entrapment of these species is likely to increase at the site. The increase may be due to both the increase in intake volumes and a possible non-linear relationship in fish entrapment with increasing intake flows (see section 4.3.5).

Fish-protection devices at unscreened water diversions can reduce entrainment: evidence from behavioural laboratory investigations (Poletto et al. 2015)

This paper examines the effect of various pipe end treatments in a flume. Large reductions are noted when various structures are fitted to the end of the pipe. The intake pipe was flowing at 3.4 m/s. This was much higher than found in large-scale intakes. All the attachments used in the study reduce the velocities at the point of encounter for the fish. The high velocity of the intake pipe in this study, and the large variation in effective velocity with the different capping arrangements, make the findings of little value in the assessment of large industrial intakes.

A comparison of fish impingement rates at Sizewell A & B Power Stations (Fleming et al. 1994)

The only known study of contemporaneous sampling of capped and uncapped intakes from a single geographical locality in the UK was undertaken at Sizewell A & B Nuclear Power Stations in 1994. During March and April 1994, 24-hour samples were collected daily between March 21 and April 29, from both the A and B station CW intakes. The A station intake was uncapped and situated inshore of the capped B station intake. Because the intakes were placed at different depths and distances, offshore and pumped at different rates (full capacity pumping rates: A station 30.4 $m^3 s^{-1}$ and B station 50 $m^3 s^{-1}$), this study does not allow a simple comparison of the capture rates at a capped and uncapped intake.

The study summarised the main results and noted that for some commercial fish the capture rate per cubic metre of pumped water was lower at the A station. However, no significant difference in capture rates per unit volume was found for cod, whiting and herring. Furthermore, while bass numbers captured per unit volume were significantly lower at the capped intake, the weight of captured fish was not. Examination of the size frequency distribution showed that, for bass, the B intake caught proportionately more, larger (older) bass.

A problem encountered during this study was that during March, when preliminary planning indicated seasonal presence for many species was at a maximum, the pumping rate of the A station varied greatly, and often only 1 or 2 pumps were operating. The A station only operated all 4 pumps from 18 to 29 April. The results presented in the study compared the geometric mean capture rate over the entire period from March 21 to April 29, and therefore encompassed considerable variability in the A station's pumping rate. As the authors noted, "no effective correction can be made for the effect on intake velocity of altering the pumped flow."

If analysis of the data is restricted to the 12 days from 18 April when both stations were working at typical fully operational flows (A station: 4 pumps, B station: 3 pumps), differences in capture rate remain, but they are not great. The 2 exceptions to this are sole and sprat. Unfortunately, over this study sprat numbers were not always collected; only the weights captured daily were available. It would generally be anticipated that a velocity cap would reduce the capture of fish from the water column but have little effect on those living on or close to the sea bed. The patterns observed hint that it was the difference in water depth or distance offshore that was the key factor in reducing the capture rate of some species, rather than the velocity cap. This interpretation is consistent with the fact that the B station intake captured a higher proportion of larger individuals. For example, while a greater number of plaice per unit volume were captured by the A station, there was no statistically significant difference in the total weight of plaice catches on the A and B station intakes.

As it is not possible to separate the other variables, depth, distance offshore, pumping rate variation, intake velocity and the presence of a large intake structure, from the influence of a velocity cap, these data cannot be used to estimate the value of a velocity cap in reducing impingement losses. The only clear conclusion that can be reached is that the B station did not catch the number of sole and sprat per unit volume that would be expected from A station capture rates. This conclusion cannot be attributed to any individual difference in design, configuration or operating procedure between the 2 stations.

Scattergood Generating Station Clean Water Act Section 316(b) Velocity Cap Effectiveness Study (MBC Applied Environmental Sciences 2007)

This study was conducted at a Californian power station (Scattergood Generating Station (SGS)) in Santa Monica Bay, close to Los Angeles. The station has a capped intake 488 m offshore at a bottom depth of about 9 m. The intake riser is 5.3 m in diameter and projects about 4 m above the sea floor. The opening below the cap is about 1.5 m and the intake structure rises to about 3.5 m from the surface. The discharge pipe is 366 m from shore in around 8 m of water, and has the same dimensions as the intake, but no velocity cap.

The station uses heat treatment to prevent biofouling. The heated water is recirculated in the station to produce a temperature lethal to fouling organisms. To allow the biofouling of the intake to be controlled, the station can reverse the flow of the cooling water, allowing it to take water in from the outfall and discharge it via the intake.

In this study designed to look at the effectiveness of the cap as a fish protection technology, the impingement of animals was recorded over a 10-week period, with the flow reversed every 2 weeks. This gave 3 periods of normal flow and 2 of reversed flow.

The authors found a very large reduction in catches under normal flow conditions, which they attributed to the presence of the velocity cap.

“The overall effectiveness of the SGS velocity cap for all fishes determined from the impingement sampling was a 97.6 percent reduction in abundance and a 95.3 percent reduction in biomass. The statistical analyses detected a significant reduction in abundance, although no significant reduction was detected in biomass. This was most likely attributable to the impingement of high-biomass species, such as Pacific electric ray and thornback, during the final normal flow survey period.”

At this site 94.2% of the abundance was the Pacific sardine, *Sardinops sagax*. This is an abundant pelagic species found all along the California coast. Since this one species dominated the sampling, we investigated the effect of removing it from the calculations to see what level of protection was afforded to the other species present.

Table 4.2.3: A summary of data from the Fish Impingement Abundance by Species and Survey Period (IM&E Characterization Study, Velocity Cap, and Heat Treatment Impingement Surveys) – showing the effect of removing pacific sardine (reworked from table 5-4 and 5-5) of ref MBC Applied Environmental Sciences. 2007

Intake via	Cap	Open	Cap	Open	Cap	Average cap	Average open	% reduction
Sample volume m^3	16,911,607	22,263,200	13,739,444	28,176,876	29,255,423			
All fish including Pacific sardine per million m^3								
No. caught	62.3	9,884.7	76.4	14,613.2	554.4	305.8	12,526.1	97.6%
Wt. caught kg	3.1	333.7	10.3	274.4	22.3	14.1	300.6	95.3%
All fish excluding Pacific sardine per million m^3								
No. caught	26.2	77.4	63.0	728.6	480.3	256.4	441.2	41.9%
Wt. caught kg	2.1	11.0	9.5	37.8	20.8	12.9	26.0	50.2%

As can be seen from these data from the SGS study, the level of protection is highly dependent on the species that are present around the intake, and varies greatly in time. It seems evident from the results at this site that the velocity cap at this station is protective for the Pacific sardine.

The fish population associated with an offshore water intake structure (Helvey and Dorn 1981)

This document reports the abundance of fish found around an intake structure on a large sandy bay. The authors highlight how an intake structure can act as artificial reef, increasing the fish diversity and numbers.

Monitoring of reef associated and pelagic fish communities on Australia's first purpose built offshore artificial reef (Becker et al. 2016)

This study examined the population of fish to a purpose built offshore reef, relative to control reefs. Fish were observed immediately following deployment, but the artificial reef fish assemblage remained distinct from the 3 natural control reefs throughout the monitoring period. Fish length data indicated that the artificial reef was providing resources for both juvenile and adults of a number of species.

Artificial reef research: a review with recommendations for future priorities (Bohnsack and Sutherland 1985)

Artificial reef structures and the effects on fish are reviewed. Recommendations of future work are made.

Office of National Marine Sanctuaries Science Review of Artificial Reefs (Broughton 2012)

The author reviews reef structures and how they accumulated fish and other organisms. Artificial structures provide similar ecological functions as natural habitat, including developing epibiotic communities that create microhabitat for motile species, locally concentrate planktonic and pelagic food resources, alter current flows to provide sheltered areas, provide visual reference points, and create spawning sites.

Artificial reefs: the importance of comparisons with natural reefs (Carr and Hixon 1997)

This paper suggests that artificial reefs with structural complexity and other abiotic and biotic features similar to those of natural reefs create fish populations, and assemblages are close to natural reef populations.

The role of constructed reefs in non-indigenous species introductions and range expansions (Sheehy and Vik 2010)

This paper focuses on how constructed reefs can contribute to non-indigenous species' (NIS) introductions or range expansions. The authors state that habitat provided by reefs placed in areas devoid of natural hard bottom or structure may be colonised by NIS propagules dispersed from natural or anthropogenic sources. A network of reef structures may also create NIS corridors for linking previously unconnected areas.

Analyses of hydraulic performance of velocity caps (Christensen et al. 2014)

The hydraulic performance of a velocity cap was investigated. Computational fluid dynamics were used to examine the flow through the cap openings and further down into the intake pipes. A particular issue with flow going all the way through the structure was revealed and some solutions to solve the issue suggested.

Velocity Cap efficacy estimation for use in Best Technology Available determinations (Neider 2018)

This document describes the procedures for allowing velocity cap efficacies to be included as a component of best technology available for the purposes of meeting the legal requirements in New York state.

Onshore intakes

There is no published work found by this review comparing inshore and offshore intakes.

4.2.3 Review synthesis

We could find no large, low-velocity side entry-intake systems in operation during this review. How the fish will react to the intake is therefore largely unknown. Turnpenny Horsfield Associates (2010) calculated possible capture rates by using the predicted velocities through the intake and comparing them to swimming performance for a selected number of species. There are several assumptions within the calculations that reduce the confidence in the prediction. The fact that large fish are caught at existing intakes, with low intake velocities, suggests that the likelihood of capture is based on more than simply the swimming ability of the species and water velocity at the intake.

It is well proven that low velocities allow fish to escape impingement from in front of travelling screens. How these studies apply to a fish being drawn into a much larger opening, possibly with a degree of lateral movement, in turbid and turbulent water is not clear.

The relationship between the velocity of the water entering the station and the volume abstracted is generally linked in such a way that separating the effect in the data is very difficult. As the field observations can only be made fortuitously, since power stations naturally vary their cooling water demand, it is impossible to control the many factors that influence fish captures.

Velocity caps on an intake have several functions apart from fish protection, such as avoiding air entrainment and sediment in the system (Christensen 2014). Velocity caps have been shown to protect pelagic species (Poletto et al. 2015). The evidence for the strength of the effect, particularly for non-pelagic species, in UK waters is complex – the only comparative study undertaken at Sizewell had several confounding factors (Fleming et al. 1994). The 2 stations were not operating at design capacity, which influenced the intake velocity, the intakes were different distances from the shore, and not all animals were counted. The sampling period was also only for a short period (March and April), so that any estimate for total annual effectiveness is an extrapolation. From a range of studies reviewed in the US by the New York State Department of Environmental Conservation (Neider 2018), the reduction in catch for all species is around 76% +/- 14.7% and benthic-dominated catches about 57%. These values come from averaging several studies, including the Fleming et al. (1994) study discussed above, which has several flaws.

A factor that needs to be considered is that large structures on the sea bed are often attractive to fish. Intake structures have been shown to act as attractors (Helvey and Dorn 1981). The building of artificial reefs is a common practice to enhance fish communities around the world (Broughton 2012, Carr and Hixon 1997, Becker, Taylor and Lowry 2016). Artificial reefs can effectively accumulate fish and other organisms (Bohnsack and Sutherland 1985, Sheehy and Vik 2010). They can provide similar ecological functions to a natural habitat. They will develop epibiotic communities, possibly concentrate planktonic and pelagic food resources, alter local current flows to sheltered areas, create visual reference points, and possibly become spawning sites. How the attraction of the structure interacts with the capture rate of fish is difficult to predict.

No studies were found comparing offshore and onshore intakes. Data exists for many stations around the UK and Europe, and such an analysis may be possible. Given that fish survival in return systems may be high with onshore systems, there could be advantages in some cases with onshore intakes.

4.2.4 Evidence scoring for intake head designs

Low velocity side entry intakes

4.2.4 Evidence scoring for intake head designs

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Assessment of effects of CW intake Velocity on Fish entrapment Risk at Hinkley Point. Turnpenny Horsfield Associates Ltd (2010).	Report	3	5	3	**Quality of information source** This is a report to EDF. It is not peer-reviewed as far as we can tell. It is directly relevant to the UK. **Applicability of evidence** The report uses fish swimming ability to give an indication of the effectiveness of the LVSE in protecting fish. There are some significant assumptions made that could affect the estimates. The data is presented as a % reduction of a single intake head – no estimate of overall station catch is made. **Strength of conclusion** The conclusions of the study are clearly documented, with supporting tables. The authors exposed the working and assumption of the calculations. In terms of predicting catches at a station, the estimates are uncertain.	**Medium (11)**

4.2.4 Evidence scoring for intake head designs

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Fish-protection devices at unscreened water diversions can reduce entrainment: evidence from behavioural laboratory investigations. Poletto et al. (2015).	Paper	5	1	1	**Quality of information source** This is a peer-reviewed paper. **Applicability of evidence** The paper looks at different intake heads in the laboratory. Pipe intake velocities were over 3.4 m/s and the species used (sturgeon) make the applicability low. **Strength of conclusion** The conclusions of the study are clearly documented but not relevant to UK intakes.	**Medium (7)**

4.2.4 Evidence scoring for intake head designs

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
A comparison of fish impingement rates at Sizewell A & B Power Stations. Fleming et al. (1994).	Report	5	3	1	**Quality of information source** This is a report to Nuclear Electric. It is not peer-reviewed. It is directly relevant to the UK. **Applicability of evidence** The report examines the captures at Sizewell A and B using contemporaneous sampling at both sites. As well as the capping arrangement at the intakes, several other factors were different between the intakes. As it is not possible to separate the effects of depth, distance offshore, pumping rate variation, intake velocity and the presence of a large intake structure from the influence of a velocity cap, these data cannot be used to estimate the value of a velocity cap in reducing impingement losses. The only clear conclusion that can be reached is that the B station did not catch the number of sole and sprat per unit volume that would be expected from A station capture rates. **Strength of conclusion** The conclusions of the study are clearly documented, with supporting tables. Operational variations at the sites along with the physical differences in the intakes make extracting the effect of a velocity cap impossible.	**Medium (9)**

4.2.4 Evidence scoring for intake head designs

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Scattergood Generating Station Clean Water Act Section 316(b) Velocity Cap Effectiveness Study. MBC Applied Environmental Sciences (2007).	Report	5	3	3	**Quality of information source** This is a report. It is not peer-reviewed. **Applicability of evidence** This report is from the Pacific, but does give insight into possible reduction of fish captures between capped and uncapped intakes. The 2 intakes are between 350 and 450 m offshore. The study found large reductions in the capture rate of the pelagic species Pacific sardine (*Sardinops sagax*) when the intake with a velocity cap was in operation. Excluding the sardine from the calculations reduces the reduction from 97% to 41%. **Strength of conclusion** The conclusions of the study are clearly documented, with supporting tables. Although in a different ocean, pelagic fish similar to the Pacific sardine are common in UK waters. The study suggests that velocity caps can protect pelagic fish.	**Medium (11)**
The fish population associated with an offshore water intake structure. Helvey and Dorn (1981).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper. **Applicability of evidence** The paper highlights how fish species can be attracted to structures in the sea. The species and location are not UK-based. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**Medium (11)**

4.2.5 Evidence review conclusions for intake head designs

A novel design has been proposed for the NNB site at Hinkley Point C. The Low Velocity Side Entry intake (LVSE) is an elongated rectangular capped intake that is orientated with its long axis aligned with the local currents. The ends facing the flows are not open, so it draws water from the sides, which reduces the effect of tidal current on the velocity of the water entering the intake, and allows a more constant water intake approach velocity. No direct evidence of the likely efficiency of the intake at reducing fish entrapment was found. Using fish swimming ability to estimate the capture of fish at the LVSE intake, the reductions in impingement are predicted to be around 16% from the Hinkley Point B baseline for the species that respond to the water velocities. The LVSE intakes will not reduce entrainment rates. It should be noted that the NNB cooling water intakes are likely to be several times larger than the Hinkley Point B cooling water intakes, so actual impacts at the site will potentially increase compared with Hinkley Point B.

The LVSE intake may reduce impingement due to the capped nature of the intake. No definitive studies were found that allowed direct comparison between capped and uncapped intakes in the UK. The most commonly-cited study at Sizewell, (Fleming et al. 1994), has several confounding factors that make conclusions about the effect of the cap difficult. Not only did the new intake have a cap, it was further offshore, and the 2 stations were abstracting different amounts of water at different times throughout the study. Evidence from studies in the USA suggests that pelagic species are protected, and other species may be protected but by a lower percentage. Direct field experiments on capped and uncapped intakes are not possible in the UK. No station is known to be operating with 2 similar intakes, with one capped and one uncapped.

Estimating the likelihood of capture in the intake using fish swimming ability as a proxy value for their vulnerability is useful but has limitations, particularly in the case of sideward-drawing intakes. Fish swimming speed studies in the laboratory generally involve the fish swimming away from a grid that is perpendicular to the current. No studies were found into the effect of water being drawn into the side of a long intake. Fish swimming away from the downstream end of the intake, along the flow line of the water entering the intake, may move in such a way as to put themselves at risk further upstream along the face of the structure. An applied study investigating side-drawing intakes would help to understand the use of fish swimming ability as a proxy for the vulnerability to capture.

4.2.6 Subject area scoring

4.2.6 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Will Low-Velocity Side-Entry intakes reduce impingement and entrainment?	1	3	3	**Quality of evidence base** There are no known examples of LVSE intakes. Swimming ability of 6 species has been used to predict capture rates, based on modelled velocities. The data comes from a single internal report. **Applicability of evidence** Swimming speed has been used as a proxy for an individual fish's vulnerability to capture. How fish react to a side-drawing intake is unknown. There is no working intake with such a design in operation. **Degree of concordance** Only one study on the efficiency of the LVSE intake is known. It uses published swimming speeds. Intake velocities are from an internal report unavailable to this review.	**Medium (7)**
Do capped intakes capture fewer fish than uncapped intakes?	5	3	5	**Quality of evidence base** Several velocity cap studies have been undertaken. All are opportunistic observations, where power stations are next to each other or have suitable intake/outfall systems to allow testing. **Applicability of evidence** Capped intakes studies vary in size and location. They are not directly comparable. **Degree of concordance** The studies indicate that there is a higher level of protection for pelagic species than for benthic and proximo-benthic species.	**High (13)**

4.3 Approach/escape velocity

4.3.1 Introduction

Two related factors that influence the capture rates of fish at intakes are the approach velocity of the inflowing water and the escape velocity attainable by an individual fish when trying to remove itself from the perceived threat (Environment Agency, 2005).

Once a fish is in the body of water that will enter the intake, it can only avoid capture if it can swim to a safe area. As the distance from the intake reduces, there will come a point where an individual fish can no longer escape capture by the intake. This theoretical 'point of no return' will vary for each individual. Some species can swim faster and for longer periods than others. Even within a single species, the swimming ability will be specific to the individual. Therefore, the point of no return will vary for each individual, based on the species concerned, the size of the fish, the environmental conditions and the physiological condition of the fish. The actual point of no return will depend on several other factors, such as the ability of the fish to detect the intake as a threat, the direction it chooses to swim in to respond to the threat, whether it is avoiding a greater perceived risk (such as predatory fish), or is following its shoaling behaviour.

Much of the work in the field of fish swimming speed has been on fish swimming in front of relatively fine screens (either in a flume or in front or travelling screens), and is focused on the general swimming ability and physiology of species, rather than directly examining how fish interact with cooling water systems (EPRI 2000). Although informative on the fish's ability to react and swim away from the screens, it is not obvious if this ability can be applied to an animal being drawn into the coarse screens which it will encounter at the offshore intake structure. A fish passing through the gap between the coarse grids may consider itself in danger. It is obvious from impingement samples that large fish with swimming abilities much greater than that needed to escape the intake are still caught.

The approach velocity is usually measured just in front of the coarse screens protecting the intake. The Environment Agency (2010a) stated that "for most power plant intake purposes a design fish-escape velocity of 0.3 m s^{-1} will be suitable and meet best practice requirements." Design velocity is an undefined term, which is often taken to mean the average intake velocity (that is, the volume abstracted divided by screen area). This is not very useful for fish protection, as the actual velocities can vary across the intake depending on several factors, such as tidal current, positioning of the intake relative to the flow, and fouling.

For a fish to escape this intake, it must be able to swim above the speed of the water flowing into the intake, and to orientate itself so that it is moving away from the intake. It must also be able to maintain this speed for long enough to either swim out of the flow field or be washed past the intake by a bypass current until it is out of danger. There are several assumptions and questions that may need to be considered:

- The measurement of approach velocity may be difficult. In a real-world situation, particularly with a LVSE system, tidal current will create cross flows of different strengths at different times, and in different areas of the screen.
- Whether the orientation of a fish can maximise its escape chances. If a fish orientates itself for the best escape chance, does it know how fast and how far it must swim to get away, or will it just hold station until exhausted?
- Whether a fish drawn into an intake from the side is likely to react the same as a fish drawn onto a screen from behind.
- What are the costs of escape? Are there sub-lethal effects from stress or from expending energy?
- Are any of the swimming speed measurements suitable to measure the likelihood of escape for an individual? If so, why are large fish regularly caught at power station intakes?
- Is the volume of water abstracted at a site a factor in a station catch?

4.3.2 Documents reviewed

Intake velocities

The velocities around intakes are complex and are influenced by tidal conditions, local morphology, and intake design and blockage.

Technical Evaluation of the Utility of Intake Approach Velocity as an Indicator of Potential Adverse Environmental Impact under Clean Water Act Section 316(b) (EPRI 2000)

This document reviews the geometry of water and fish approaching intake screens. It finds that there are several relevant velocity components:

- approach velocity – at a distance from the screen
- approach velocity – close to the screen
- through-screen velocities
- sweeping velocities (and other vectors at an angled screen)
- heterogeneity of all velocities in a complex hydraulic environment of an intake structure

These components interact with swimming behaviour and abilities of specific fish, and the environmental factors (such as temperature, salinity, turbidity) that all affect the risk of impingement.

The authors concluded that:

- approach velocity is an appropriate regulatory parameter
- approach velocity should be measured with detailed attention to the intake's geometry (preferably as a vector parallel to the main water flow at a distance from the screen)

- a single regulatory value probably should not be applied considering the variety of organisms and sizes at a site (a site-specific analysis using site geometry and data on swimming speeds of local fish is recommended)
- a screening criteria value of 0.5 f/s (15.25 cm s^{-1}) would be useful to delineate cooling water intake structure (CWIS) where significant impingement is unlikely, except under unusual environmental circumstances or for specific poorly-swimming species

This document also reviews the swimming performance of fish. It points out that schooling fish save significant locomotion energy by utilising the wakes of other fish in the shoal. The authors suggest that this might be, in part, why schooling fishes are often disproportionately caught at intakes. Their reliance on uniform and predictable hydraulics may be interfered with by the hydraulic effects of the intake. The report also quotes from a review undertaken by Hammer (1995) and lists some of the factors that influence critical swimming speed; species specificity, race and population, size, season, time of day, temperature, sex, pollutants, light, food, training, and ambient gas content. Hammer (1995) states that most of these relationships were incompletely defined. He concluded that the utility of critical swimming speed studies was compromised as individual variability was not often quantified.

In a discussion of the swimming ability of bottom-living fish, the authors point out that many species display complex swimming behaviour in response to increased velocities. Some species hold the bottom until the velocity is too great, then use a burst and hold strategy as the velocity increases. Others use methods of sticking to the bottom, either with suckers or using fins to exert a downward force. The document points out that some species are behaviourally unable to respond to the flows in such a way as to minimise capture. For example, a downstream-migrating animal may be inclined to follow the flow into the intake.

In a discussion on alternative measures to swimming ability for predicting impingement rates, EPRI states that “Reliance on a single criterion, i.e., approach velocity measured near or at the face of a fish screen, may be of limited value for predicting whether a fish is likely to get impinged. Although approach velocity has a major, perhaps primary, influence on impingement, there are many other contributing factors related both to characteristics of the fish community and the intake design.”

The authors recommend that if only one velocity is to be defined, then it should be measured parallel to the main water movement in the intake, between about 7.5 cm and 30 cm from the screen face. This should be prior to where the flow diverges to flow past screen structures.

Influence of approach velocity and mesh size on the entrainment and contact of a lowland river fish assemblage at a screened irrigation pump (Boys et al. 2013)

This study in Australia tested the likelihood of fish contacting the screen during irrigation pumping. The study looked at 2 approach velocities (0.1 and 0.5 m/s) and a range of mesh sizes to stop fish entering the pump. All fish were more likely to encounter the screens at the higher velocity, and the size of the mesh was not significant. At the lower velocity, screen size did affect the number of fish that contacted the screen. They found that that smaller fish (<150 mm) were significantly more susceptible to entrainment and screen contact, especially at higher approach velocities. They also found the rheotaxic behaviour had a significant impact on the likelihood of screen impact. Fish that orientate to swim away from the screen were much less likely to impact the screen at both velocities. Fish orientating across the current or swimming with it were much more likely to impact the screen.

Assessing the use of vibrations and strobe lights at fish screens as enhanced deterrents for two estuarine fishes (Mussen and Cech Jr 2018)

In this study, shiner surfperch (*Cymatogaster aggregate*) and staghorn sculpin (*Leptocottus armatus*) were exposed to a wedge-wire fish screen in a laboratory flume with a 0.3 m s^{-1} water velocity. Fish contacted the screens less frequently during the day than at night. At night, the screen was either vibrated or illuminated with a strobe light. *Cymatogaster aggregata* contacted the screens significantly less frequently when they were vibrating, compared with their night-time controls, suggesting useful mechanoreceptive guidance. *Leptocottus armatus* contacted the screens significantly less frequently under strobe-light illumination, compared with their night-time controls, suggesting useful visual guidance.

Quantifying behaviour of migratory fish: Application of signal detection theory to fisheries engineering (Kemp et al. 2012)

A review of the application of signal detection theory (SDT) to fish passage research, particularly of downstream migrating fish. SDT consists of 2 parts: 1) the relationship between magnitude and perceived intensity of a stimulus (signal), 2) the ability to discern between the signal and noise within the environment. The review highlights the inter-individual variability, as well as temporal variations in response. The authors discuss whether previous experience of a stimulus can alter later responses.

Masking a fish's detection of environmental stimuli: application to improving downstream migration at river infrastructure (Kerr and Kemp 2018)

In this study, the authors examined whether turbulence could mask the stimuli (in this case a velocity gradient) for downward-moving sea trout (*Salmo trutta*) in a flume. They found that the artificially-created turbulence influenced the sensory ability of the fish to detect the velocity gradient and react to it, but the results were contradictory, and some fish behaviours did not show sensory masking. The authors suggest that masking may be more evident with greater levels of artificial turbulence.

Sub-lethal effects

Fish that either undergo acute startle response or must use maximum swimming speed to escape, show signs of stress. In this section, non-lethal impacts are reviewed.

Stress and fish reproduction: the roles of allostasis and hormesis (Schreck 2010)

Schreck (2010) reviewed the impacts of stress on fish. He describes the highly-complex relationship between the type of stress, the frequency of the stress, the physiological state of the fish at the time of the stress and the species involved. In this paper, he quotes his earlier work, where he found that the energetic cost of a single brief handling event equated to approximately 25% of the total energy available for activity for the fish.

Behavioural responses of sardines, Sardina pilchardus, to simulated purse-seine capture and slipping (Marçalo et al. 2013)

In this paper, the authors studied the effect of forced swimming of sardines in simulated fishing nets in the laboratory. They held the fish for 20 or 40 minutes as if swimming to escape a purse seine net, before releasing them (known as slipping, the process where fish are deliberately released from fishing gear). This study found that fish, after exposure to the stress of forced swimming, showed several behavioural differences from the control animals. The stressed fish had lower swimming speeds, allowed predators to approach closer than control fish, and had higher mortality. They also found the structure of the shoal to be altered, with higher nearest-neighbour distances (a wider school area) than controls. These differences were found at both stress levels. These effects were observable for up to 3 days after the stress occurred; the length of the experiment.

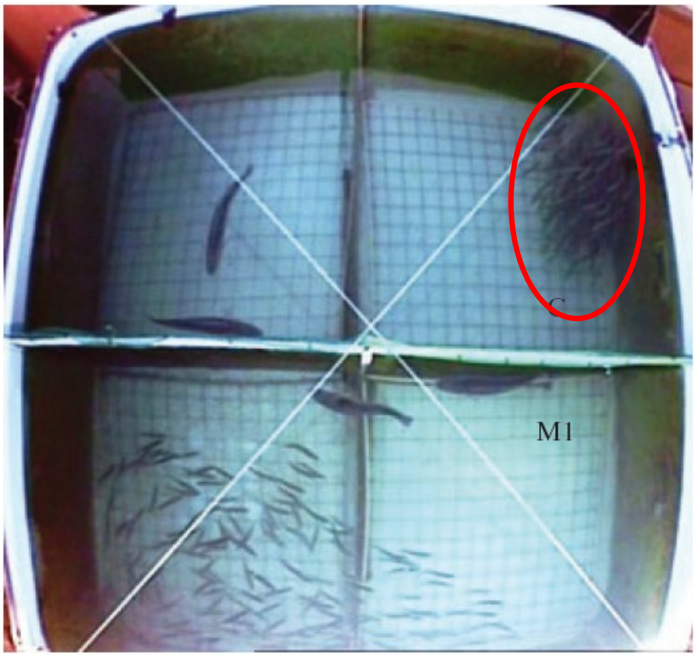


Figure 5 Image from experiment 1, showing Sardina pilchardus behaviour aspects in the control (C treatment) tank (top) and in the fished (M1 treatment) tank (bottom) immediately after framed lateral panels for both control and fished compartments were lifted and removed, allowing the interaction of S. pilchardus with the 2 Dicentrarchus labrax – Red circle added to illustrate the size of the control shoal. (Fig. 6 from Marcalo et al. 2013)

Accumulation and Long-term Effects of Stress in Fish (Schreck) in The biology of animal stress: basic principles and implications for animal welfare (*Moberg and Mench 2000)*

In this chapter, Schreck argues that there may be a long-term cost to stress events in fish. He argues that exposure to stressors can shift the performance capacities of fish. These effects are related to the energetic cost of the reaction, and can lead to impacts on growth development and reproduction. He highlights the interactions between multiple stressors, both simultaneously and sequentially. There have been some studies on simulation stressors, for example, capture and elevated temperature or sub-lethal heavy metals and crowding. Less work has been done on the sequential stressors and the effect of the time between stresses. The effect of intermittent stress can be both positive (positive conditioning) and negative. Fish can show adaptation to repeated stress. Others show negative responses, with each period of stress having a cumulative effect.

Behavioural impairment after escape from trawl codends may not be limited to fragile fish species (Ryer et al. 2004)

Two species were exposed to simulated trawling. It was found that juvenile sablefish (*Anoplopoma fimbria*) are more resistant to direct mortality resulting from physical damage and stress than walleye pollock (*Theragra chalcogramma*). However, the sablefish suffered the same behavioural impairments as walleye pollock; stressed fish swam slower, shoaled less cohesively and allowed predators to approach closer than controls. When trawl-stressed fish were exposed to a live predator (Lingcod (*Ophiodon elongatus*)), they were eaten in greater numbers than the control fish. Although differing in susceptibility to potentially-lethal stressors, both species exhibited similar impairments in response to sub-lethal stressors. This suggests that for numerous fish species, behaviourally-impaired individuals escaping stressed situations may be consumed by predators, contributing to unobserved mortality.

Effects of simulated trawling on sablefish and walleye pollock: the role of light intensity, net velocity and towing duration (Olla et al. 1997)

Two species were exposed to similar towing stresses. Pollock showed no effect of being in a net until the velocity increased to a point where fish came in contact with the mesh of the net. These fish then exhibited significant alterations in feeding behaviour, predator evasion and increases in plasma cortisol concentrations. Marked increases in stress-induced mortality also occurred, in some cases after a delay of 6 days, and eventually reaching 100%. Sablefish were much more resistant to post-capture stress. Net-entrained fish caught for 15 minutes showed no detectable changes in feeding and cortisol levels and 0% mortalities. After 2 hours, no changes in feeding were observed, although mortality increased to 19%. Towing for 4 hours caused significant alterations in feeding and cortisol levels, with feeding recovering to control levels by 6 days and cortisol by 3 days; mortality was 25%.

Stress indicators in fish (Sopinka et al. 2016)

Fish experience stress when exposed to a threat in their environment, and some level of stress is an inherent component of the life of all fish. Fish undergo a range of physiological changes that can be measured, which allow stress levels to be analysed for different scenarios.

Abstraction volume and the relationship with catch rate

Fish mortality by impingement on the cooling-water intake screens of Britain's largest direct-cooled power station (Greenwood 2008)

In a study of Longannet Power Station, Greenwood puts the captures in context by analysis of the impingement at 19 other stations in north-west Europe. The analysis shows a power relationship between the number of fish impinged and abstraction volume. No data from biomass was analysed.

Biomass and number of fish impinged at a nuclear power plant by the Baltic Sea (Bryhn et al. 2013)

The authors looked at the biomass of fish captured at Forsmark Nuclear Power Plant in Sweden, and compared it to various sites from tidal waters in north-west Europe (from Greenwood 2008), the brackish non-tidal Baltic, and Taiwan. They found a highly-significant power relationship between the number of impinged fish and the volume of water pumped (Figure *6*). Forsmark has a double screening system, one of 40 mm and one of 2 mm.

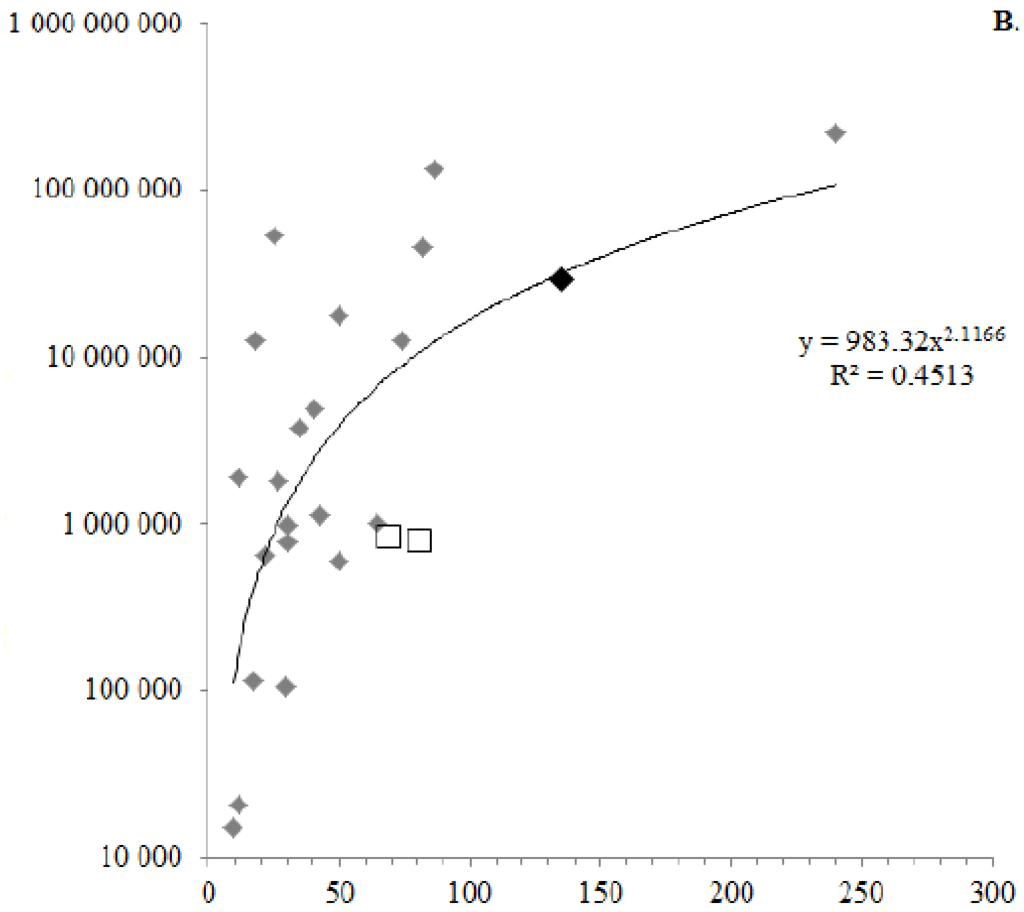


Figure 6: Cooling water use and number of impinged fish in thermal power plants. Grey dots represent data from Greenwood (2008) on power plants in NW Europe. The black dot represents Forsmark data from the Bryhn et al. study. Unfilled squares represent Taiwan's 1st and 2nd NPP. Number of data: 24; $p < 0.001$. The y-axis has a $\log_{10}$ scales of fish impinged, the x-axis is in m3/s (Fig 5b from Bryhn et al. 2013)

The study also compared electrical output (MWe) with fish capture, and found a similar result for the Great Lakes and Baltic stations. The Great Lakes data from Kelso and Milburn (1979) only used electrical output as a factor. Bryhn et al. (2013) state that they found no correlation between impinged fish biomass and volume of water used at thermal power plants, but since most of the data came from Greenwood (2008), who did not analyse biomass, this is not surprising.

They predicted that increasing the abstraction at the Forsmark plant from 135 to 170 $m^3 s^{-1}$, would increase both the number and biomass of the fish impinged at the plant by 63%.

Effect of Operational Changes in Reducing Fish Impingement at a Power Plant in Ohio, USA (Patrick et al. 2015)

This paper studied the effect of reducing the volume of water abstracted at a power plant in Ohio from Maumee River beside Lake Erie. The modifications included installing a fish-return system, installing fish-friendly exclusion screens, and 2 operational changes - intake volumetric flow reduction and intake through-screen velocity reduction. The site was studied over 2 periods, from May 2005 to April 2006, and April 2013 to March 2014.

Before 2012, intake flow rate was 33.5 $m^3 s^{-1}$, with a through-screen velocity of 79.2 cm s^{-1}. No fish return system was present.

After 2012, the intake flow was 9.1 $m^3 s^{-1}$, with through-screen velocity of 11.6 cm s^{-1}, with a fish return system fitted.

Impingement fell by 85% from 46 million in 2005 to 2006 to 6.5 million in 2012 to 2014. When the gizzard shad was excluded (as it suffers natural winter mortality when it becomes very vulnerable to impingement), the reduction of all other species was 96.6%.

The study also looked at the sustained swimming speed of the fish impinged in 2005 to 2006. All the fish had sustained swimming speeds greater than the 11.6 cm s^{-1} through-screen velocity at the modified station, suggesting that this allows the fish to swim away from the station.

Fatigue and exercise tests with fish (Hammer 1995)

This paper reviewed swimming speed metrics, and how they are measured. The paper discussed how critical swimming speed (CSS) is dependent on factors such as race and population, size, season and temperature, sex, pollutants, light, food, training and ambient gas levels.

4.3.3 Review synthesis

Intake velocities

At the time of writing, no large side-entry intakes are known to be in operation to the authors. Low velocities have been seen as protective for many years, with regulators using them as a proxy value to create a less-damaging intake.

Most of the work on swimming speeds has been undertaken in laboratory conditions, and uses some form of flume with a fixed grill behind the fish. The experiment then tests the fish's swimming ability by increasing the speed of the water passing through the flume. There have been several measures of swimming ability used, such as the maximum burst speed, the sustained speed and the cruising speed, all of which have different physiological demands on the fish. These measures of swimming ability give an indication of the fish's straight-line swimming ability. EPRI (2000) suggest that these types of tests are not reliable for predicting a fish's ability to avoid capture. Individual variability is large and many of the factors that influence fish swimming ability are unstudied.

Studies which look at the ability of a fish to avoid a larger mesh size, of the type encountered at the offshore intake of a power station, are less frequent. The LVSE intake heads to be used at Hinkley Point C appear to be about 40 m long and have about 36 baffle plates (Turnpenny Horsfield Associates Ltd 2010), which would make the gap between each plate around 1 m. Each opening is to have 3 bars, which gives an opening of 0.26 m (Hinkley Point C 2016). This is much larger than the meshes tested in most flume studies. If the gap between the bars is 0.26 m, the ability of fish to detect the intake may be decreased.

Mussen and Cech (2018) examined the behaviour of 2 estuarine fish (shiner surfperch (*Cymatogaster aggregata*), and staghorn sculpin (*Leptocottus armatus*)) in the presence of a wedgewire screen in a flume. They found that contact rates with the screen increased at night compared to the day. For *Cymatogaster aggregata*, vibrating the screen at night reduced the contact rate. For *Leptocottus armatus*, illuminating the screen with strobe lights reduced the contact rate. This suggests that these 2 species use different senses to avoid screen contact.

If the water flow round the intake is turbulent, then the work by Kemp et al. (2012) and Kerr and Kemp (2018) suggests that the detection of the intake may be lower than it would be in non-turbulent flow. Further work by Vowles et al. (2014) found that there was a day/night difference in deflection of salmon smolts at screens or bypass entrances, suggesting that visibility is a factor in navigating or avoiding structures.

Sub-lethal effect of intakes

In this section, we examine some of the impacts that could occur when a fish interacts with an intake but is not killed. Fish experience stress when exposed to a threat in their environment, and some level of stress is an inherent component of the life of all fish (Sopinka et al. 2016). Fish undergo a range of physiological changes that can be measured, which allow stress levels to be analysed for different scenarios.

Escaping from an intake can have a metabolic cost to the individual. If a fish has to alter its normal behaviour, by for example increasing its swimming speed to evade capture, it will be using some of its finite energy reserve. This will not then be available for it to use until it has been replenished. Schreck (2010) discusses the complex relationship between type of stress, the frequency of the stress, the physiological state of the fish at the time of the stress and the species involved. A single traumatic event can use 25% of the fish’s total energy available for activity. Fish that have been exhausted can show behavioural changes. Marçalo et al. (2013) showed that the sardine, which is a shoaling species, did not form such tight shoals after being forced to swim to avoid a net. The exposed animals also allowed predators to approach more closely and had a higher mortality rate. The effects of forced swimming on the fish were still seen 3 days after exposure. Ryer et al. (2004) and Olla et al. (1997) tested 2 species, sablefish (*Anoplopoma fimbria*) and walleye pollock (*Theragra chalcogramma*). Sablefish had lower initial mortalities than pollock, but both species showed similar sub-lethal effects, with looser shoaling, alteration in feeding behaviour and weaker predator-avoidance behaviour. Ryer et al. (2004) exposed the tested fish to a predator, and found that trawl-stressed fish were eaten in greater numbers than unstressed fish. Olla et al. (1997) observed sub-lethal effects for up to 6 days after simulated trawling, with highly-stressed fish dying up to 6 days after the trial.

It is possible that a fish that escapes from an intake using the fight or flight reaction will experience repeated stress events during its life. Little is known about how often an individual fish may be impacted by an intake. If the populations are local, then it seems possible that they might interact with the intake several times in their lives, even if they are not caught by it. Such multiple stress events can have long-term effects on an individual (Schreck 2000).

If a fish, once captured in an intake system, expends energy trying to escape, the time taken for it to be returned to sea (assuming a successful fish recovery system) will be important in its survival. Fish that have expended much of their energy reserve behave differently and have different survival rates from unaffected fish (for example, Schreck 2010 and Marcalo et al. 2013). This reduction in probable survival may counteract any reduction in impact gained by lower fish density around an intake if placed a long way offshore.

Intake volume

It is likely that the relationship between station catch and abstraction volume is non-linear Greenwood (2008), Bryhn et al. (2013), Henderson (2018). The papers suggest that doubling the flow into a station would more than double the number of fish impinged. However, separating out the effects of intake velocities, volumes abstracted and location effects is problematic and there are unlikely to be enough studies to provide firm conclusions. Experiments on the scale of industrial intakes are impossible. Patrick et al. (2015) reported the effect of reducing the intake flow of a power plant on Lake Erie. The intake volume dropped from 33.5 m^3 s^{-1} to 9.1 m^3 s^{-1}. Intake velocity fell from 79.3 cm s^{-1} to 9.1 cm s^{-1}. Comparing annual catches before and after the flow reduction, the authors showed that the catch of the station fell dramatically. Excluding moribund gizzard shad, the reduction was 96.6%, including the moribund gizzard shad, the reduction was 85%.

4.3.4 Evidence scoring for approach/escape velocity

Intake velocities

4.3.4 Evidence scoring for intake velocities

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Technical Evaluation of the Utility of Intake Approach Velocity as an Indicator of Potential Adverse Environmental Impact under Clean Water Act Section 316(b). EPRI (2000).	Report	5	5	5	**Quality of information source** This is a report from a respected industry body. A wide range of species are reviewed, some of which are found in the UK. **Applicability of evidence** The report summarises the issues with using approach velocity as a regulatory measure. It highlights how fish swimming speed is complex and highly variable, and how some organisms are behaviourally unable to respond in a way that increases survival. **Strength of conclusion** The conclusions of the study are clearly documented, the authors give recommendations on the ways of measuring velocities in cooling water systems. There is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**

4.3.4 Evidence scoring for intake velocities

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Quantifying behaviour of migratory fish: Application of signal detection theory to fisheries engineering. Kemp et al. (2012). Masking a fish's detection of environmental stimuli: application to improving downstream migration at river infrastructure. Kerr and Kemp (2018).	Paper	5	3	3	**Quality of information source** These papers are peer-reviewed. **Applicability of evidence** These papers look at whether signal detection theory impacts on migratory fish. The work is on a freshwater species (*Salmo trutta*) occurring in the UK. The results are contradictory and suggest that the signal noise the fish were exposed to was not high enough. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. The study is of interest into how fish might perceive intakes.	**Medium (11)**
Influence of approach velocity and mesh size on the entrainment and contact of a lowland river fish assemblage at a screened irrigation pump. Boys et al. (2013).	Paper	5	3	3	**Quality of information source** This paper is peer-reviewed. **Applicability of evidence** The paper is on Australian riverine fish. The experiment is simple but shows that approach velocity is important to how many fish contact the screens. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**Medium (11)**

4.3.4 Evidence scoring for intake velocities

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Assessing the use of vibrations and strobe lights at fish screens as enhanced deterrents for two estuarine fishes. Mussen and Cech Jr (2018).	Paper	5	3	3	**Quality of information source** This paper is peer-reviewed. **Applicability of evidence** The paper is on non-UK fish species. The experiment examines how species differ in their ability to avoid screens in the light and dark. One species avoids the screen more in the dark when the screen is vibrated, one when it is light. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**Medium (11)**

Sub-lethal effects

4.3.4 Evidence scoring for sub-lethal effects

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Stress and fish reproduction: the roles of allostasis and hormesis. Schreck (2010).	Paper	5	3	3	**Quality of information source** This paper is peer-reviewed. **Applicability of evidence** The paper looks at stress in general terms and reviews the impact of different types of stress on the reproductive success of fish. It contains relevant theories on the impact of stress on impinged or entrained fish. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**Medium (11)**
Behavioural responses of sardines, *Sardina pilchardus* to simulated purse-seine capture and slipping. Marçalo et al. (2013).	Paper	5	5	5	**Quality of information source** This paper is peer-reviewed. **Applicability of evidence** The paper is on a UK species, and tests swimming ability and the sub-lethal effects of the stress of capture in a net on sardine. A range of behavioural differences are shown that are relevant to fish at intakes and return systems. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**

4.3.4 Evidence scoring for sub-lethal effects

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Accumulation and Long-term Effects of Stress in Fish. (Schreck) in The biology of animal stress: basic principles and implications for animal welfare. Moberg and Mench (2000).	Chapter of book	5	5	5	**Quality of information source** This book chapter is by an author with extensive publication record. **Applicability of evidence** The chapter addresses multiple stresses and their impact on fish; impingement and entrained fish undergo multiple stressors. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**
Behavioural impairment after escape from trawl codends may not be limited to fragile fish species. Ryer et al. (2004).	Paper	5	3	5	**Quality of information source** This paper is peer-reviewed. **Applicability of evidence** The paper is not on a UK species. It looks at the mortalities from enforced swimming ability. A hardy species showed similar sub-lethal effects of trawling, including higher chance of predation as the less hardy species. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**

4.3.4 Evidence scoring for sub-lethal effects

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Assessing the use of vibrations and strobe lights at fish screens as enhanced deterrents for two estuarine fishes. Mussen and Cech Jr (2018).	Paper	5	3	5	**Quality of information source** This paper is peer-reviewed. **Applicability of evidence** The paper is not on a UK species. It looks at the mortalities from enforced swimming ability. Stressed fish showed mortalities which increased with the time stressed. Mortalities occurred up to 6 days after the trials. Effects on feeding and hormone levels lasted up to 6 days. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**

Abstraction volume and the relationship with catch rate

4.3.4 Evidence scoring for abstraction volume

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Fish mortality by impingement on the cooling-water intake screens of Britain's largest direct-cooled power station. Greenwood (2008).	Paper	5	5	5	**Quality of information source** This paper is peer-reviewed. **Applicability of evidence** The paper is on Longannet Power Station. It puts the captures there into context with other stations around north-west Europe. The author finds a non-linear relationship between fish caught and the intake flow. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**
Biomass and number of fish impinged at a nuclear power plant by the Baltic Sea. Bryhn et al. (2013).	Paper	5	5	5	**Quality of information source** This paper is peer-reviewed. **Applicability of evidence** The paper is an extension of Greenwood (2008). It adds several power stations in the brackish area of the Baltic and in Taiwan to the analysis. The relationship between fish caught and the intake flow is still non-linear. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**

4.3.4 Evidence scoring for abstraction volume

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Effect of Operational Changes in Reducing Fish Impingement at a Power Plant in Ohio, USA. Patrick et al. (2015).	Paper	5	3	5	**Quality of information source** This paper is peer-reviewed. **Applicability of evidence** The paper is a demonstration at an operating power plant of the effect of reduction in volume abstracted and through-screen velocities. It is a freshwater site, with species not found in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**

4.3.5 Evidence review conclusions for approach/escape velocity

Approach velocities influence the likelihood of a fish being able to escape an intake. Once a fish is in the body of water that will enter the intake, it can only avoid capture if it can swim to a safe area. The lower the intake approach velocity, the higher proportion of the fish that can escape. However, just because a fish is capable of escaping, does not mean that it will. Large fish with swimming abilities that mean they should escape capture are regularly caught on power station screens. How fish detect the objects such as intakes is still being studied. Factors examined have included the effect of light and dark on detection probability, the effect of vibrating a screen, the impact of intake velocity and the hydrodynamic signals caused by flow around structures.

Several studies suggest that even after escape there are sub-lethal impacts on fish that have been stressed by prolonged swimming efforts. Shoaling fish lose coherence and have lower responses to predators. Some studies have shown higher predation rates on stressed fish. Few studies have been undertaken on UK species.

The volume abstracted and the approach velocity are interrelated. Since power stations have fixed-size intake structures and vary the pumping rate, it is difficult to untangle the relationship. Attempts made by authors by analysing several studies from different power stations indicate that there is a power relationship between the abstraction volume and the fish capture. A single study by Patrick et al. (2015) was found where a power station modified its flow by reducing the volume abstracted from 33.5 to 9.1 $m^3 s^{-1}$ and intake velocities from 79.3 cm s^{-1} to 9.1 cm s^{-1}. The reductions in annual impingent were large at between 85 and 96.6%.

4.3.6 Subject area scoring

4.3.6 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Are low velocity intakes more protective of fish?	5	3	3	**Quality of evidence base** There are many studies looking at the swimming performance in fish. Most are laboratory studies, and most are on species not found in the UK. There are data for several UK marine species. **Applicability of evidence** Swimming speed has been used as a proxy for an individual fish's vulnerability to capture. There is evidence that fish use different senses to escape intakes. The effects of turbidity, turbulence and intake design are not clear. **Degree of concordance** There are several measures of swimming performance, and no agreed standard to use for estimating the likelihood of entrapment in an intake.	**Medium (11)**
Does decreasing intake volume make intakes more protective of fish?	3	5	3	**Quality of evidence base** There are few studies that look at intake volume and capture rates. Recent papers have analysed the volume abstracted and found a relationship. **Applicability of evidence** One of the papers is based on UK power station data. Others develop the same dataset and add a range of different stations. There has been one study where a power station changed its intake volume; this showed dramatic declines in catches. **Degree of concordance** There have been studies that do and others that do not find relationships.	**Medium (11)**

5 Passage through the station – excluding screening

If an organism is to survive capture by a power station, it must survive all parts of the transport through the system. The mortality rate is limited by the part of the system with the lowest survivability. It is therefore important to consider all parts of the intake and discharge system to look at the impacts of each part, and then consider any synergistic effects.

There are several major impacts that an organism must survive as it passes from the sea via the intake to the screening area and back to sea. These are:

- barotrauma – the effects of pressure changes
- abrasion and collision – touching parts of the station or other organisms and debris in the intake water
- biocide – chemical control to kill biofouling
- exhaustion/stress – from fighting again the flow, avoiding capture at the screens, fear
- predation within the system

Barotrauma is the damage done by changes of pressure that are too rapid for the organism to cope with. The gas within the body expands, damaging various organs of the body. Most of the research in this field is related to the impacts on fish passing through turbine systems, and on the effect of fishing, where fish are brought up from depth. The fish passing through turbines experience a very rapid change in pressure, which is more extreme than that seen in raising fish from offshore to the station height. The swim bladder of fish in some groups connects to the gut via the pneumatic duct (the physostomous condition). In others, there is no pneumatic duct, resulting in a closed gas bladder (the physoclistous condition). It is generally understood that fish with open swim bladders are less susceptible to barotrauma effect, as the air can escape from the swim bladder. Typical visual signs of barotrauma are stomach protruding into oesophagus or out of the mouth, bulging eyes, prolapsed anus or haemorrhages in the eyes or sub-dermally. Abrasions and collisions will occur with the station structures, other animals within the intake and material in the cooling water.

The effects of stress are reviewed in section 4.3.2 **Sub-lethal effects**.

If intakes and fish return outfalls are to be placed further offshore, potentially in deeper water, then the risk of damage during the passage through the tunnel or pipe is increased. A deeper intake increases the chance of barotrauma. Longer intake tunnels increase the transit time for the organism. This could increase the exhaustion and stress, the chance of contact with the walls and the total exposure to biocides.

5.1 Cooling water system tunnels: pressure change effects

5.1.1 Introduction

In this section, we examine the potential impacts on an organism as it passes along the cooling water tunnels. Short-term increases in pressure are not generally harmful for fish because of the contraction of air spaces within the body (Turnpenny 1992). Depth of the intake is more important than the depth of the tunnel the fish must pass through before being raised up into the station.

Earlier studies at Sizewell showed that physoclistous species (fish with no direct swim bladder connection to the outside) had lower survival (Seaby 1994). No new published studies of barotrauma were found relating to the impact of passage through intake tunnels at power stations. An unpublished study from Thameside Power Station was reported in Hinkley Point C Cooling Water Infrastructure Fish Protection Measures (2016). This indicates that with a depth change of around 40 m, about 30 to 40% of the gadoids had damaged swim bladders. Most studies on barotrauma are related to fish survival when released after fishing (trawling, potting or in angling competitions) or from passage of fish through hydroelectric turbines. Some recent references on biota protection measures at in-river structures and pumping stations are provided in a bibliography at the end of the Reference section of this report. They have not been reviewed in depth as they are on smaller scale structures, but may have wider relevance to the subject area.

The fishing studies generally look at the survivability of fish from discards, where fish are brought rapidly to the surface before being released. These studies are relevant to the trauma experienced by entrapped animals, but are complicated by the additional factors that are specific to fishing, such as net damage or handling. Studies looking at turbine effects are generally less useful in this context, as the pressure changes are very rapid, often have negative pressures, and are complicated by the issues of blade strikes.

5.1.2 Documents reviewed

Catch rates and selectivity among three trap types in the US South Atlantic black sea bass commercial trap fishery (Rudershausen et al. 2008)

The authors studied the mortality rates of black sea bass (*Centropristis striata*) after capture in traps. The study was for one winter, at depth of 12 to 30 m. They found that the level of visible barotrauma was low at between 0.8 and 4.16% at the time of capture, with the amount of barotrauma observed correlated with depth. They did not study the fish long term to assess sub-lethal or delayed mortality rates. They also noted that, when at high densities in the trap, the fish often showed other signs of damage, such as opaque eyes caused by scratches.

Severity of barotrauma influences the physiological status, post-release behavior, and fate of tournament-caught smallmouth bass (Gravel and Cooke 2008)

This paper examines the impact of barotrauma on the smallmouth bass (*Micropterus dolomieu*) during angling tournaments in Ontario. This lake has a mean depth of 9.8 m. The anglers target fish from a range of depths within the lake. 64 fish that had been caught and weighed were intercepted by the study and analysed for obvious signs of barotrauma. 76% of fish had signs of barotrauma. The study looked for bloating (caused by an expanded swim bladder) and broken blood vessels. Blood samples were taken for analysis. From this sub-sample, they selected 12 fish with either negligible (one or no signs of barotrauma) and 10 fish with severe (2 or more signs of barotrauma) and fitted them with radio tags. Of the initial 64 fish, 64% had haemorrhages, and 42% had bloating. All the bloated fish had problems with equilibrium when swimming, and floated on the water surface. Larger fish showed greater levels of barotrauma than small fish. All the injured fish had blood compounds related to stress present. Of the fish with severe barotrauma that were tagged and released, 40% mortality was observed. No mortality was observed in the negligible barotrauma group. The severe barotrauma group were much slower to move out of the release area.

Physiological effects of swim bladder overexpansion and catastrophic decompression on red snapper (Rummer and Bennett 2005)

Laboratory investigations into the impact of rapid changes in pressure were carried out on the red snapper (*Lutjanus campechanus*). Fish were wild-caught from 30 to 60 m deep, had the gas released from their swim bladders, were treated to reduce infections and kept for 14 days. The fish were then acclimated to 101.2 (ambient), 405.3 (low), 608.0 (medium), and 1,215.9 kPa (high). This simulated depths of 0, 30, 50 or 110 m, respectively. The rate of pressure changes was at 10.1 kPa/s. This study used lateral and dorsal X-ray imaging in combination with necropsy to examine the damage done by decompression in fish. The study revealed over 70 different injuries, the most severe being to vital organs. There was a relationship with degree of pressure change (depth) and injury (Figure *7*). Even in the fish decompressed from 30 m (low in the graph), about 50% showed liver damage, and 20 to 30% showed digestive tract damage, swim bladder damage or external injuries.

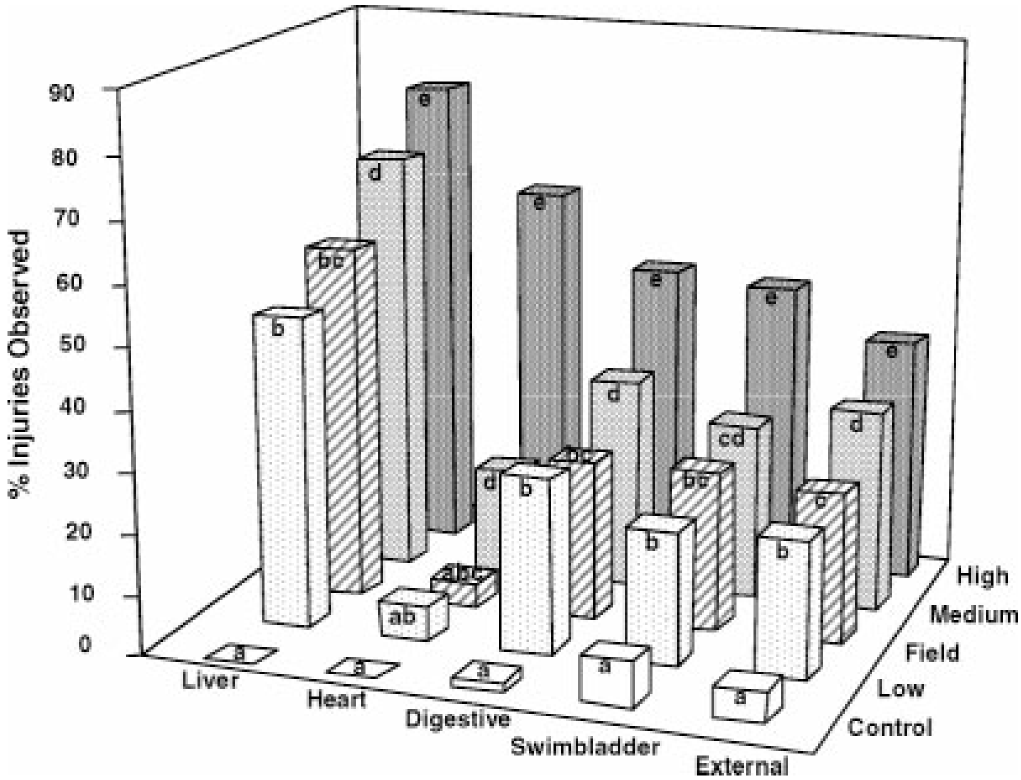


Figure 7: Frequency histogram of injuries occurring within 5 major organ systems of Gulf of Mexico red snapper in field and control (101.3 kPa), low (405.3 kPa), medium (608.0 kPa), and high (1,215.9 kPa) laboratory groups exposed to laboratory-controlled simulated depths to assess catastrophic decompression related physiological and anatomical injury. Values with different letters indicate significant differences between field, control, and low-, medium-, and high-pressure groups within each organ system (one-way ANOVA and Student–Newman–Keuls test; a 5 0.05). From Figure 2. Rummer and Bennett 2005)

Swimbladder healing in Atlantic cod (Gadus morhua), after decompression and rupture in capture-based aquaculture (Midling et al. 2012)

This was a study of the ability of commercial-sized cod (about 3 kg) to repair the swim bladder which was ruptured by the decompression of the fish during capture. These fish were captured at 130 to 200 m deep, and all fish suffered ruptured swim bladders. Batches of 20 fish were then dissected at 0, 24, 72 and 384 hours post capture. Swim bladders are constructed of 2 layers, the *tunica interna* and *tunica externa*. When a swim bladder bursts, a hole is formed in the 2 layers. As the bladder collapses, the 2 layers move in relation to each other and the hole is partially sealed. Even fish dissected directly after being captured were able to hold some air in the bladder. As time post capture increased, so did the ability of the bladder to hold pressure. The hole size varied (in these cases, from 1 to 2 mm to over 11 mm), and this correlated with the ability to hold air and the amount of time repair took.

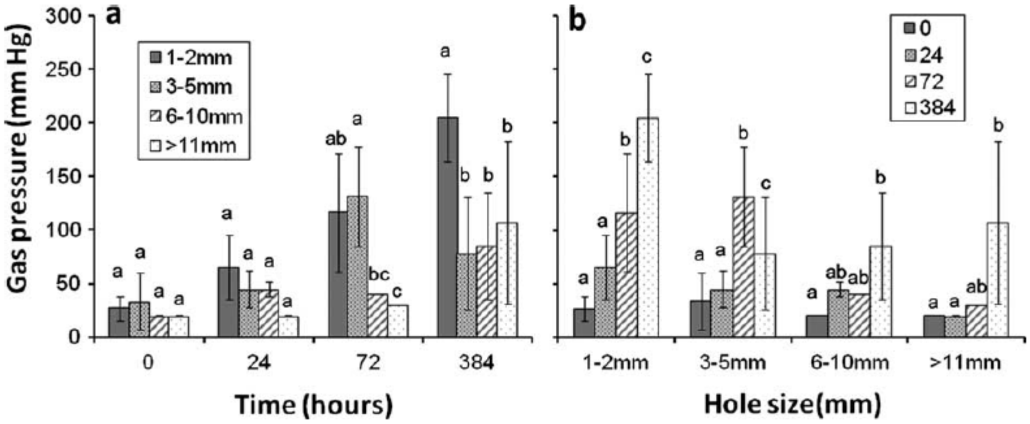


Figure 8: Strength of swim bladder in Atlantic cod following ruptures due to decompression during capture. The strength was measured as the pressure (mmHg) at which the swim bladders rupture again after healing of damage induced during catch. To ease the presentation of statistical comparisons, the 2 panels show the same data sorted by size of holes at (a) different times and (b) time after rupture (b). Different letters above columns indicate significantly differences (pB0.05) between groups. From Figure 3 (Midling et al. 2012)

During the recovery period, after an initial period at the bottom of the recovery cage (ranging from a few minutes to a few hours), no mortality, gross behavioural problems such as uncontrollable tendencies to sink or float, or erratic abnormal movements were observed. This indicates that in larger cod the burst swim bladder is repairable.

Dive to survive: effects of capture depth on barotrauma and post-release survival of Atlantic cod (Gadus morhua) in recreational fisheries (Ferter et al. 2015)

In this study, cod captured from various depths from 0 to 90 m were either held in surface pens or allowed to dive to depth after release. Surface-kept animals showed higher mortality rates than those that could dive into deeper water. The fish in the surface pen showed a significant relationship between depth of capture and mortality (Figure *9*).

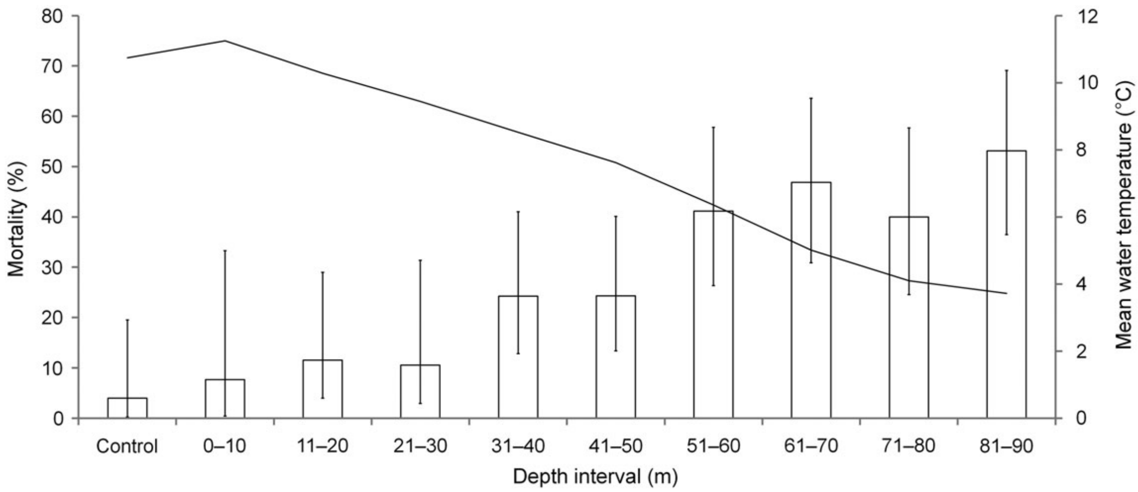


Figure 9: Mortality of cod in the floating-net-pen study by depth interval (open bars). Error bars indicate the 95% upper and lower Wilson's confidence intervals. The continuous line shows the temperature at capture depth of the control group (10 m), and the mean temperatures in each of the depth intervals (based on the temperature/depth profile in the centre of the Kattfjord on 4 August 2013). (Figure 2 of Ferter el al. 2015)

Repeating the study, but with the fish held in a much deeper holding pen, the mortality reduced, with 97.8% of fish able to dive, and with no mortality recorded. Fish unable to dive were assumed to have died in a natural setting, but when placed in a cage at depth they too showed no mortality. Barotrauma injuries were depth-related, and the signs of barotrauma had disappeared in one month.

A synthesis to understand responses to capture stressors among fish discarded from commercial fisheries and options for mitigating their severity (Cook et al. 2019)

This study reviewed fish discards survival. Although in fishing discards, damage and stresses are different from those of fish entering a cooling water system, much of the evidence is relevant. The authors state, "This synthesis identifies exhaustion and injury as the most detrimental and ubiquitous stressors experienced by discarded fish, with few options for mitigating their effects." They identify 5 major stressors related to mortality of captured fish:

1. hypoxia/air exposure
2. injury
3. exhaustion
4. barotrauma
5. predation

All of these, except for air exposure, are likely to be experienced to some degree by fish caught in cooling water systems. The authors find that the tolerance of and susceptibility to the stressors are dependent on context (for example, species, water temperature, size), and magnitude of exposure.

A comparative analysis of marine fish species susceptibilities to discard mortality: effects of environmental factors, individual traits, and phylogeny (Benoît et al. 2012)

Benoît examines the time to death of a wide range of species from short 30-minute trawls after exposure to air. The study looks at a range of factors that influence the time to mortality, including species, trawl depth, temperature, fish size, and some physical properties of the fish such as hardness, mucus production, swim bladder type and sedentary nature. The strongest predictor of death was the size of the fish, with small fish dying faster than large ones. Temperature at time of capture was also significant, as was the depth of the trawl. Of the biological traits examined, sedentariness most affected time to mortality, with species classed as sedentary taking longer to die. The fast-swimming species such as the mackerel were found to die very rapidly.

Sub-lethal effects of catch-and-release fishing: measuring capture stress, fish impairment, and predation risk using a condition index (Campbell et al. 2009)

In a study of sub-lethal effects, the authors exposed red snapper (*Lutjanus campechanus*) to rapid decompression from 4 depths, (15, 30, 45 and 60 m) and half the fish to a temperature shock. They studied the barotrauma effects and looked at the behaviour of the fish to a simulated predator. The frequency of occurrence of barotrauma and lack of reflex response exhibited considerable individual variation. The fish showed significantly lower burst swimming speed, and allowed predators to approach more closely, with greater effect being seen at greater depths. Fish from shallow depths were also impaired to a greater extent if they were transferred into warmer water. The study also found that the time to recover varied with depth, with fish decompressed from deeper water taking longer to recover.

5.1.3 Review synthesis

Barotrauma in fish is related to the depth from which the fish are taken. Deep-water intakes will potentially have higher levels of barotrauma than fish catches at shallow water intakes. The travel time within cooling water systems is not long enough for the physoclist species to adapt to changes in depth. The rapid rise to the surface in the forebay or fish return system will cause rapid pressure changes within the body of the fish and potentially lead to barotrauma.

The following questions then arise:

1. How deep does an intake need to be for barotrauma to be seen in fish captured?
2. What is the mortality rate of fish with barotrauma?
3. Can fish recover from barotrauma?

In a range of studies of fish from fishing, relatively few look at the shallow inshore water where most industrial intakes are placed. The variations in the amount of barotrauma observed between studies even at similar depths are large. Rudershausen et al. (2008) found that for black sea bass (*Centropristis striata*) in the US, in fish captured in traps between 12 to 30 m, the level of visible barotrauma was low, at between 0.8 and 4.16%. Gravel and Cooke (2008) looked at tournament-caught smallmouth bass (*Micropterus dolomieu*), caught in a lake with an average depth of 9.8 m. This study found that 76% of fish had a least one sign of barotrauma. Rummer and Bennett (2005) undertook a laboratory investigation into the impact of rapid changes in pressure on the red snapper (*Lutjanus campechanus*). The animals were then acclimatised to different depths and exposed to rapid depressurisation. Of the fish decompressed from 30 m, about 50% showed liver damage, and 20 to 30% showed damage to the digestive tract, swim bladder or external injuries. Barotrauma is species-specific, and can occur at depths of as little as 10 m in some species.

The mortality rate of fish with barotrauma depends on a wide range of factors. These include the species, the severity of the trauma and the post-trauma condition. In studies on cod, Ferter et al. (2015) and Midling et al. (2012) examined the ability of cod to repair the swim bladder after barotrauma. Midling et al. (2012) found that cod could rapidly refill a burst swim bladder, and even in fish dissected directly after rupture the bladder could still hold some air. The ability of the damaged swim bladder to hold pressure increased with the time after rupture and decreased in relation to the larger rupture size. After 16 days, some of the cod swim bladders were still not fully healed. Ferter et al. (2015) studied the effect of post-capture behaviour on cod that had barotrauma. Fish that were allowed to dive into deeper water survived much better than cod that were kept in surface tanks. This is interesting in relation to fish return systems. If fish are returned to depths similar to those at which they are captured, the mortality rate due to barotrauma might be reduced.

Cook et al. (2019) reviewed the current understanding of capture stresses in fish discards from commercial fisheries. They suggest that barotrauma is normally observed in fish captured below 20 m but can be observed in fish from 5 m deep. The paper suggests that although instant mortality from barotrauma is possible, indirect mortality is more common. The loss of equilibrium and buoyancy control makes fish more vulnerable to predation and can expose them to less optimal surface conditions. Damage to eyes, blood embolisms and everted stomachs can also impact foraging behaviour, increase stress levels and potentially increase infection risks resulting in latent mortality.

Sub-lethal effects of barotrauma include a reduction in swimming ability and a reduction in the avoidance response to predators, and are synergistic with higher temperature (Campbell et al. 2009).

Barotrauma is highly species-specific, with some fish (physoclist) being much more vulnerable than others. Fish can survive barotrauma injuries, but there must be a metabolic cost. Sub-lethal effects have been observed in fish with barotrauma.

If intakes are moved further offshore into deeper water, the potential of barotrauma increases. The damage caused by barotrauma may be reduced if the fish return releases fish to a suitable depth, but the risk for thermal shock should be avoided.

No recent studies on barotrauma relating to UK intakes have been found in the course of this review.

5.1.4 Evidence scoring for cooling water system tunnels: pressure change effects

Pressure change effects

4.14 Evidence scoring for pressure change effects

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Catch rates and selectivity among three trap types in the US South Atlantic black sea bass commercial trap fishery. Rudershausen et al. (2008).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper is based on fish species not found in the UK. The activities assessed are not power station impingement, but the data on barotrauma in fish are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. Barotrauma is low in this species under the conditions tested.	**High (13)**

4.14 Evidence scoring for pressure change effects

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Severity of barotrauma influences the physiological status, postrelease behavior, and fate of tournament-caught smallmouth bass. Gravel and Cooke (2008).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper is based on fish species not found in the UK. The activities assessed are not power station entrainment, but the data on barotrauma in fish are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. Barotrauma is high in this species under the conditions tested.	**High (13)**
Physiological effects of swim bladder overexpansion and catastrophic decompression on red snapper. Rummer and Bennett (2005).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct laboratory evidence. **Applicability of evidence** The paper is based on fish species not found in the UK. The activities assessed are not power station entrainment, but the data on barotrauma in fish are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. Barotrauma is low in this species under the conditions tested.	**High (13)**

4.14 Evidence scoring for pressure change effects

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Swimbladder healing in Atlantic cod (*Gadus morhua*), after decompression and rupture in capture-based aquaculture. Midling et al. (2012).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper is based on fish species found in the UK. The activities assessed are not power station entrainment, but the data on barotrauma in fish are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. Swim bladder damage is repairable in cod.	**High (15)**
Dive to survive: effects of capture depth on barotrauma and post-release survival of Atlantic cod (*Gadus morhua*) in recreational fisheries. Ferter et al. (2015).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper is based on fish species found in the UK. The activities assessed are not power station entrainment, but the data on barotrauma in fish are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. Swim bladder damage is repairable in cod and the release conditions are important to survival.	**High (15)**

4.14 Evidence scoring for pressure change effects

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
A synthesis to understand responses to capture stressors among fish discarded from commercial fisheries and options for mitigating their severity. Cook et al. (2019).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper reviewing the stressors in discarded fish. **Applicability of evidence** The paper is a general review. The activities assessed are not power station impingement, but the data on barotrauma and stress in fish are relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**
A comparative analysis of marine fish species susceptibilities to discard mortality: effects of environmental factors, individual traits, and phylogeny. Benoît et al. (2012).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper looks at the susceptibility of fish to discard mortality. It groups fish by several factors such as mucus production or sedentary behaviour and looks at general survival for different groups. Includes some species found in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**

4.14 Evidence scoring for pressure change effects

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Sub-lethal effects of catch-and-release fishing: measuring capture stress, fish impairment, and predation risk using a condition index. Campbell et al. (2009).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper looks at the sub-lethal impacts of barotrauma on a species not found in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. It illustrates sub-lethal term impacts on swimming ability and behaviour.	**High (13)**

5.1.5 Evidence review conclusions for cooling water system tunnels: pressure change effects

Rapid pressure changes in fish can cause injury as gases within the body expand. This is called barotrauma. Few studies of barotrauma were found on species that are caught at UK intakes. Fishing mortality related to angling, and discards from commercial vessels have been studied. Some of the studies cover a depth range that is relevant to industrial intakes placed in coastal waters. Barotrauma is related to the depth from which a fish is raised and also the speed of the pressure changes. The deeper the fish is caught, the greater the amount of damage. Barotrauma is highly species-specific, with some fish with sealed swim bladders (physoclist) being much more vulnerable than others.

In a review by Cook et al. (2019) into understanding on capture stresses in fish discards from commercial fisheries, the authors concluded that it is normally observed in fish captured from below 20 m, but can be observed in fish from 5 m deep. Barotrauma is not always a mortal injury. Cod, for example, have been shown to recover well after suffering a burst swim bladder, particularly when the fish was able to return to depth soon after the injury. As with swimming stress, fish with barotrauma injuries can show sub-lethal behaviour and physical changes, with damage to the eyes and digestive tract common, along with a loss of equilibrium and buoyancy control, impacting foraging behaviour, predator avoidance, increased stress levels and potentially increased infection risks, resulting in latent mortality.

Barotrauma is only one part of the stress experienced by an animal passing through a power station, and other stresses encountered by the fish will probably be synergetic.

Moving intakes into deeper water would increase the risk of barotrauma on fish caught at the station.

No recent studies on barotrauma relating to UK intakes have been found in this review. Studies of barotrauma over the range of pressures found at UK intakes would help inform the decision on whether deeper intakes are beneficial. If fewer fish are caught because of a deeper intake, the reduction could be offset by an increase in mortality in the fish return system caused by barotrauma.

5.1.6 Subject area scoring

5.1.6 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Is barotrauma a significant cause of injury in fish at offshore intakes?	5	3	5	**Quality of evidence base** There are many studies looking at barotrauma. Not many of them are from a depth range that is applicable to UK intakes. **Applicability of evidence** Most data on barotrauma in marine fish are from studies of angling and fishing discards. The injuries are similar and are applicable to injuries that could be sustained during impingement. Injuries range from mortality to sub-lethal effects. The damage varies from species to species and can be size-dependent. **Degree of concordance** There is evidence of barotrauma in some species brought to the surface from 5 to 10 m deep. It is therefore probable that some fish are experiencing damage from this factor.	**High (13)**

5.2 Forebay and screenwell design, including hydraulic conditions

5.2.1 Introduction

Water entering the forebay is normally moving rapidly, and can be highly turbulent. Turbulence and high velocities can be desirable as they can reduce sedimentation and biofouling issues. However, fish within the water body are subjected to many stressors that might influence chances of survival.

If the intake tunnel rapidly rises before it enters the forebay, animals within the water body would experience a rapid change of pressure. These barotrauma issues are covered in the previous section.

In the turbulent forebay waters there can be shear forces that could damage organisms as they pass between bodies of water flowing at different speeds or in different directions.

The report 'Cooling water options for the new generation of nuclear power stations in the UK' (Environment Agency, 2010a) states, "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 100 Wm^{-3}. This particularly applies to any fish sampling or holding facility that may be incorporated for fish impingement monitoring purposes." It is probably impractical to achieve these energy dissipation levels (below 100 Wm^{-3}) around the tidal cycle with the large volumes of water entering a station at around 2 to 3 $m\ s^{-1}$.

The 100 Wm^{-3} criterion was taken from the Environment Agency Fish Pass Manual (Environment Agency 2010b). It was set to use in fish pass resting pools and is not obviously relevant here. These levels of energy dissipation may be relevant within a fish recovery system, but where fish are delayed for a shorter period of time (<6 hrs), power dissipation of 100 to 150 Wm^3 may be appropriate (Environment Agency, 2010b). This would have to be determined on a site-specific basis, taking into account factors such as passage times.

When exposed to shear stresses, fish undergo differential forces along their body. Shear stress is known to lead to mortality in some species of fish, particularly during the yolk sac and post yolk sac stages in young fish (EPRI, 2012b). The shear stresses that are associated with adult fish injury are higher. Neitzel et al. (2004) reported that injuries classified as 'significant major' were not observed for any of the species tested at or below a strain rate of 517/s (velocity of 9.1 m/s over 1.8 cm).

The turbulence within the forebay and screenwell could also increase the chance of contact with the walls and other structures within the system. For example, if a design has structures within the forebay to dissipate the flow or improve sediment clearance, or the flow from the intake pipe impinges directly on to a solid surface, the fish in that water body would have a higher chance of direct contact with solid surfaces.

If within the forebay and screenwell there are areas of lower flow, these might be refuges for fish to hold station until exhaustion, predation, starvation or chance moves them to the next area of the station. If fish are not cleared quickly from the system, this increase in residence time in the system could lead to higher stress levels and possibly higher mortality rates.

In some power stations, there are large predatory fish living within the screenwell and forebay areas. When screenwells are drained, it is common in some areas to find large conger eels living in them. These animals are assumed to live in the system for some time and must therefore be feeding.

Design features that might increase damage to fish would include rapid changes in direction of the flow and structures within the forebay and screenwell. Water passing from the forebay into the screenwell often flows into the screen from the side. Within the intake area there are several objects that fish could impact, such as access ladders and platforms, coarse screens, and the structures of the screens themselves.

5.2.2 Documents reviewed

Survival estimates for juvenile fish subjected to a laboratory-generated shear environment (Neitzel et al. 2004)

This study subjected a rainbow/steelhead trout (*Oncorhynchus mykiss*), Chinook salmon (*Oncorhynchus tshawytscha*) and the American shad (*Alosa sapidissima*) to shear stress in a flume. The authors found that no damage was observable to any species at strain rates of 495/s, which equates to water at around 9.1 m/s over a distance of 1.8 cm. Fish entering the flow head first had greater damage than those entering tail first. There was no relationship between size of fish and damage. Shad were more easily damaged than the salmonids, and were damaged more when entering the flow head first.

Evaluation of fish-injury mechanisms during exposure to turbulent shear flow (Deng et al. 2005)

This study on Chinook salmon (*Oncorhynchus tshawytscha*) involved exposing fish to different shear stresses using a slow-fish-to-fast-water mechanism. The study found minor injuries occurred on 10% of fish from 3 m/s, with major injuries starting at 12.2 m/s. At velocities over 16.8 m/s, immediate or delayed mortalities were recorded.

Injury and mortality of juvenile salmon entrained in a submerged jet entering still water (Deng et al. 2010)

This study is the reverse of Deng et al. (2005). It involved exposing fish to different shear stresses using a fast-fish-to-slow-water mechanism, in which test fish were carried by the fast-moving water of a submerged turbulent jet into the slow-moving water of a flume. In this case, injuries were first observed at water moving at 15.2 m/s. The fish experienced different injuries than when they were exposed to slow fish-to-fast-water experiments, where injuries started at 12.2 m/s.

Swansea Tidal Lagoon STRIKER v4 Fish Turbine Passage Modelling, Environmental Impacts Statement Appendix 9.4 (Turnpenny 2014a)

This document summarises the impacts of tidal turbines. There is a section on shear stress and turbulence and also a reworked table showing the shear stress level effects of some UK fish.

Table 5.2.1: Effects of shear stress levels on fish in laboratory experiments reported by Turnpenny et al. (1992). Note: mortality data corrected against control (zero shear stress) values. (Table 2 from Turnpenny 2014a)

Fish species	Shear stress level Nm^{-2}			
	206	774	1,920	3,410
Salmonids: Atlantic salmon, age 2-group smolts	No detectable effect.	No detectable effect.	Slight mucous and scale loss. 28% of fish with eye injury. 4% mortality after 7 days.	Slight mucous and scale loss. 32% of fish with eye injury. 8% mortality after 7 days.
Salmonids: Brown trout, age 1 to 2-group	No detectable effect.	No detectable effect.	Slight mucous and scale loss. 10% of fish with eye injury. 20% mortality after 7 days.	Slight mucous and scale loss. 10% of fish with eye injury. 10% mortality after 7 days.
Clupeids: Herring, age 0-group	Light mucous and scale loss. 100% mortality within 1 hour.	>20% mucous and scale loss per fish. Eye haemorrhage in 60%. 100% mortality within 1 hour.	Average 58% mucous and scale loss per fish. 60% eye injury. 40% with torn jaws/operculum. 100% mortality within 1 hour.	Average 90% mucous and scale loss per fish. 40 to 60% eye injury. 20% with torn jaws/operculum. 100% mortality within 1 hour.
Clupeids: Twaite shad	Not tested.	Not tested.	Not tested.	Average 90% mucous and scale loss per fish. 40% eye injury. 20% with torn jaws/operculum. 100% mortality within 1 hour.
Flatfish: Sole	Not tested.	No detectable effect.	Heavy loss of mucous. 65% mortality within 7 days.	Heavy loss of mucous. 75% mortality within 7 days.

European eel	No detectable effect.	No detectable effect.	Some mucous loss. 7-day survival not affected.	Some mucous loss. 7-day survival not affected.
Percids: Bass	Not tested.	Not tested.	Average 9% mucous and scale loss per fish. 13% with gill injury. 7% bleeding into body cavity. No survival data.	Average 10% mucous and scale loss per fish. 8% with gill injury. No survival data.
Gadoids: Whiting	Not tested.	Not tested.	Average 5% mucous and scale loss per fish. 20% with eye injury. 20% with torn jaws/operculum. 100% mortality within 1 hour.	Average 5% mucous and scale loss per fish. 28% with eye injury.

Turnpenny suggests that the US Department of Energy's (USDOE) 'environmentally friendly' turbine programme shear stress fish injury threshold of 1,600 Nm^{-2} (Cada et al. 2007) was appropriate considering the data in Table 2. However, the clupeids are very fragile and damage even at the lowest shear stresses tested (206 Nm^{-2}) and so would not be protected.

Evaluation of the effects of turbulence on the behavior of migratory fish (Odeh et al. 2002)

In a laboratory study on juvenile freshwater fish in the US, the authors created turbulent conditions, which were not damaging, to observe the effects on fish behaviour. They found that exposure to an average turbulence with Reynolds shear stresses that are higher than 50 N/m^2 for a period of 10 minutes may induce minor injury to some species, but does not incur significant mortality over a 48-hour post-exposure period. At shear stresses higher than 30 N/m^2 for 10 minutes, rainbow trout did not show reduced startle responses to predators, but the hybrid bass and Atlantic salmon both did. The startle response had returned to pre-trial levels after 24 hours.

Abrasion

Chronic stress impairs the local immune response during cutaneous repair in gilthead sea bream (Sparus aurata) (Mateus et al. 2017)

This study found that increasing the stress levels of fish slowed their ability to repair scale loss. Fish that were kept in crowded conditions showed lower plasma osmolality, which is a sign that the skin had a reduced barrier function.

5.2.3 Review synthesis

Fish naturally undergo shear stress in their natural environment. Tidal currents, eddies, waves and even other fish passing them will expose them to some level of shear stress. It is likely that freshwater fish experience more shear stresses than pelagic marine species.

Most of the research into shear stress has been related to hydroelectric dams, and often concerns freshwater and/or migratory species. The impacts of shear stress are species-specific (Neitzel et al. 2004). Laboratory studies have also shown that how the fish is exposed to shear stresses can influence damage. Neitzel et al. (2004) showed that shad entering head first into the fast-flowing water were more susceptible to damage than when they were presented tail first. The authors have shown that there is a difference in the susceptibility to damage in slow-fish-to-fast-water mechanism (Deng et al. 2005) and fast-fish-to-slow-water mechanism (Deng et al. 2010).

In the only review found on British marine fish, in tests on 8 UK species at 206, 774, 1,920 and 3,410 Nm^{-2}, Turnpenny (2014a) suggests that a stress fish injury threshold set in the US of 1,600 Nm^{-2} is relevant in the UK.

The study found that herrings did not survive any shear stress, with 100% mortality even at the lowest tested level. Four of the species, including 2 migratory salmonids and the eel, were tested at 774 Nm^{-2} and showed no damage. At 1,920 Nm^{-2} all showed damage, and most species showed some level of mortality. The predicted shear stress in the forebay at the new build Hinkley Point C is below these levels at 15 Nm^{-2} (Hinkley Point 2016).

The value of 1,600 Nm^{-2} is probably suitable for migratory fish such as salmonids and eel. The evidence for marine species is less convincing. The only marine fish (not including the herring) tested at 774 Nm^{-2} was the sole, which showed no detectable effect, but at 1,920 Nm^{-2}, 65% of the sole were dead within 7 days. The whiting and bass were also tested at 1,920 Nm^{-2}. While there are no mortality data available for bass, 13% had gill injuries and 7% were bleeding internally. The whiting all died within one hour. Shear stress testing is required to understand the amount of damage likely at levels that are experienced within intakes.

No data were found for British marine fish on the relationship between turbulence and any increase in the likelihood of impacting structures within the forebay.

5.2.4 Evidence scoring for forebay and screenwell design, including hydraulic conditions

Shear stress

5.2.4 Evidence scoring for shear stress

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Survival estimates for juvenile fish subjected to a laboratory-generated shear environment. Neitzel (2004).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper looks at the impacts of shear stress on a freshwater species that is not found in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. The study illustrates that the effects of shear stress are species-specific, and vary depending on how the stress is encountered.	**Medium (11)**

5.2.4 Evidence scoring for shear stress

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Evaluation of fish-injury mechanisms during exposure to turbulent shear flow. Deng et al. (2005).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper looks at the impacts of shear stress on a freshwater species that is not found in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. The study measured the impact of slow-fish-to-fast-water mechanism.	**Medium (11)**
Injury and mortality of juvenile salmon entrained in a submerged jet entering still water. Deng et al. (2010).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper looks at the impacts of shear stress on a freshwater species that is not found in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. The study measures the impact of fast-fish-to-slow-water mechanism.	**Medium (11)**

5.2.4 Evidence scoring for shear stress

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Swansea Tidal Lagoon STRIKER v4 Fish Turbine Passage Modelling, Environmental Impacts Statement Appendix 9.4. Turnpenny (2014a).	Report	5	5	5	**Quality of information source** This is a report forming part of an Environmental Impact Assessment (EIA). The relevant data are taken from published works. **Applicability of evidence** The paper looks at the impacts of shear stress on a range of British fish in relation to tidal power generation. It does contain some marine species that are found in the UK. Most of the study is on migratory fish such as salmonids, shads and eels. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. The data are very sparse on marine species.	**High (15)**
Evaluation of the effects of turbulence on the behavior of migratory fish. Odeh et al. (2002).	Report	5	3	5	**Quality of information source** This is a report forming part of an US Department of Energy document. **Applicability of evidence** The paper looks at the impacts of turbulence and shear on migratory species, one of which is found in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. The study looked at behavioural effects of turbulence at levels below which mortality occurred.	**High (13)**

5.2.5 Evidence review conclusions for forebay and screenwell design, including hydraulic conditions

Water entering the forebay is normally moving rapidly and can be highly turbulent. Turbulence and high velocities can be desirable as they can reduce sedimentation and biofouling issues. High turbulence can lead to shear stresses that could damage organisms as they pass between bodies of water flowing at different speeds or in different directions.

The Environment Agency report 'Cooling water options for the new generation of nuclear power stations in the UK' (Environment Agency, 2010a) recommended that energy dissipation throughout the system should be kept at or below 100 Wm^{-3}. This is the same level as recommended in the Environment Agency Fish Pass Manual. This is probably not a practical level in a larger scale intake forebay.

There are few studies that are directly relevant to shear stress found in the intake system of a power station. Most studies have examined the potential injuries of fish passing turbine blades. The most relevant of these comes from the Swansea Tidal Lagoon Environmental Impact Assessment (EIA) (Turnpenny 2014a), which reports data from Turnpenny (1992) who suggested that the US Department of Energy's (USDOE) 'environmentally friendly' turbine programme shear stress fish injury threshold of 1,600 Nm^{-2} was appropriate, considering the data presented.

This value could be too high for marine species; there is only one data point below, at 774 Nm^{-2} and that is for the sole, generally considered a hardy species. At 1,920 Nm^{-2}, 65% of the sole were dead within 7 days. The whiting and bass were also tested at 1,920Nm^{-2}. While there are no mortality data available for bass, 13% had gill injuries and 7% were bleeding internally. The whiting all died within one hour. The predicted shear stress in the forebay at the new build Hinkley Point C is below these levels at 15 Nm^{-2} (Hinkley Point 2016).

Shear stress testing is required to understand the amount of damage that could be caused by turbulence in the intake system.

Turbulence could also increase the number of times a fish encounters a solid object within the system. No data were found related to turbulence and impacts for British marine fish.

5.2.6 Subject area scoring

5.2.6 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
What level of shear stress causes injury in fish?	1	1	3	**Quality of evidence base** There many studies on shear stress. Most are for freshwater species and are often related to fish passage in rivers. Only one study was found on marine species in the UK. **Applicability of evidence** Very little data are available on marine fish. The use of the USEPA standard of 1,600 Nm^{-2} (Cada et al. 2007) is possibly too high for marine species in the UK. There are not enough data to set a standard. **Degree of concordance** With so few data there is no concordance.	**Low (5)**

5.3 Entrainment - Cooling water systems downstream of fine screens

5.3.1 Introduction

Entrainment is a widely-used term describing the passage of animals and plants through a power station cooling water system that have been inadvertently caught during the extraction of the water. They are typically small organisms able to pass through a mesh on the travelling screens and then pass through the condenser tubes, before being discharged back to the environment with the heated cooling water (CW) effluent.

Because planktonic life is so plentiful, and the volumes of water used by once-through power plants are so large, the absolute numbers of organisms entrained are huge, often exceeding 10^{12} individuals per year for a single animal species. It is now widely believed that entrainment of fish larvae and eggs is the single most important aquatic environmental issue for power stations with once-through cooling. Entrainment mortalities were the single most important factor which led the Environmental Protection Agency (EPA) in the USA to rule that all new-build projects should use closed-cycle cooling or equivalently-protective technologies.

Entrained animals are subject to a range of impacts. Studies have been carried out in the field at power plants, and in equipment that simulates conditions experienced by the organisms.

Entrained organisms, while passing through a power station, suffer a combination of impacts, including:

- mechanical stress of contact with the walls of the CW system, pumps and any biofouling present
- a series of rapid pressure changes as the water passes through the screens, pumps and condensers
- shear stress of water as it is accelerated and decelerated
- chemical stress, if the organism is exposed to the biocides used to control fouling
- thermal stress as the water is rapidly warmed by around 10 °C in the condensers

Factors that affect entrainment rates at a site include:

- CW intake location in relation to spawning grounds
- life history of species present
- habitat preferences of species
- seasonal movements of species
- swimming ability of potentially entrained animals
- growth rates and morphology

Much of the work in this field was carried out in the USA. The work originates from 2 distinct periods. In the 1970s, a great deal of work was carried out on entrainment survival. Many of those projects are now viewed as experimentally flawed by the US regulator (USEPA 2003), with very short sampling periods, low numbers of animals used, inconsistent determinations of death, and a range of uncontrolled factors leading to difficulties in interpreting the results. In the UK in the 1990s a number of studies were carried out on entrainment survival using simulated power station CW systems.

Previous studies on entrainment can be classified into 3 divisions, each of which is reviewed separately below:

- laboratory testing of individual entrainment factors
- simulations of power plant entrainment
- field-based observations

Laboratory studies of entrainment survival allow for each factor potentially involved in the mortality of an organism to be examined, separately and in combination. These studies tend to be relatively simple but give good information on the mechanism involved. Specific studies on the larvae of fish or invertebrates carried out under such controlled conditions allow for the testing of organisms in adequate numbers and the precise control of the environmental characteristics. This allows a more precise determination of which of the environmental changes are responsible for any mortality, but does not simulate the entire experience of an animal being entrained.

Simulation-based tests such as the Entrainment Mimic Unit (EMU) rig (Bamber and Seaby 2004) are designed to simulate some of the major impacts of the power station. They generally take the form of a holding area for the organisms, where pressure is varied to simulate the pressure profile of the intake to forebay passage. There is then a series of sudden pressure changes representing the passage through the pumps and screens, before passing the organisms via a simulated condenser where the water is warmed. The animals pass to a final stage, where they then sit in another holding area while the pressure profile of the discharge is applied. Animals are collected, assessed and observed over various times. Biofouling control (in the EMU's case, chlorine) can be added at the start of the experiment.

This sort of experimental investigation has the advantage of being able to manipulate different stressors separately or in combination, which allows the different factors to be examined. It has the disadvantage of being in confined laboratory conditions, so factors such as the physical movement through the power station CW system, which might have impacts, such as abrasion, turbulence, shear stresses and repeated biofouling control, are not simulated. In the case of the Fawley EMU, it was always kept dry when not in use, so any potential fouling inside the pipe was minimal. This is not the case in a real power station, where much of the surface is covered in bacterial slime, and in some cases, in barnacles, mussels and other attached organisms.

Power station-based studies have the advantage of summarising the entire experience of the organism, but generally individual impacts of the system such as pressure or temperature cannot be varied. Experiments at power plants have to use what is found at the site at the time of sampling. It is difficult to plan sampling regimes that coincide with the erratic arrival and short residence time of eggs or larvae of fish, for example. Linked to the chance nature of the presence of the animals to be studied, the numbers of animals found are often too small to allow robust analysis. These issues are exacerbated by the problems of sampling delicate organisms before and after entrainment. Post-entrainment sampling is particularly problematic, since any of the animals killed in the entrainment process break up and are very difficult to capture and identify. These problems can lead to biases in the analysis. A review of the problems with many of these studies is found in the EPA review of entrainment survival undertaken for the 316b ruling (EPA 2003).

No new examples of laboratory entrainment survival studies have been found. The Centre for Environment, Fisheries and Aquaculture Science (Cefas) has been carrying out EMU-type studies in relation to large-scale cooling waters for NNB power stations, but has not published the results.

With the lengthening of the intake and discharge tunnels proposed at the NNB plants, organisms will be exposed to the stressors in the intake and discharge for much longer than in the existing stations. Assuming velocities of 2.5 m s^{-1} in the systems, the time from the intake to the screens along a 4 km tunnel will be about 25 minutes. Similarly, with a 3 km outfall, the transit time will be around 20 minutes. This gives a total trip time through the station of around 45 minutes. To put this into context, in the Fawley EMU simulation for Sizewell B, the total trip time was around 8.5 minutes, with around 4 minutes in the intake tunnel, 1.5 minutes passing through the pumps and condensers and 3 minutes to the outfall.

At most stations, multiple pumps draw from a single intake and forebay structure. Therefore, these timings are a minimum passage time, as they assume that all the CW pumps are running at the designed rate, which is often not the case due to operational issues at the individual site. Stations switch CW pumps on and off for a range of reasons. If the station is having an outage, then often CW pumps are taken out of service. If the incoming water is cold, the station might not need all the CW pumps. In addition, variable speed pumps are sometimes fitted as a fish protection measure. These allow the station to match its cooling water requirements to environmental conditions much more closely than with the traditional on/off type pumps. There is also a cost saving for the station in power used.

If the organism passes the screens, it will pass through the condensers, and from that point on will experience elevated temperatures and possibly biocides until its discharge into the environment. At the point where the cooling water will mix with the receiving water and start to cool, it could experience a rapid fall in temperature.

5.3.2 Documents reviewed

Entrainment of organisms through power station cooling water systems in Operational and environmental consequences of large industrial cooling water systems (Bamber and Turnpenny 2012)

In this book chapter, Bamber and Turnpenny (2012) review some of the UK studies on entrained organisms using the EMU based at Fawley, and mostly carried out in the 1990s (Bamber and Seaby 1993, 1994a b c, 1995, 2004). They highlight the wide range of effects on different organisms at different stages. In some species, namely a copepod (*Acartia tonsa*) and Pacific oyster (*Crassostrea gigas*), pressure alone caused significant mortality. In other tests on flatfish eggs, the combination of pressure and ΔT (change in temperature) caused the mortality. For some delicate life stages, the physical stress features tested by the EMU caused mortality. In larval turbot and lobster larvae, it was caused by the separation of body parts. Total residual oxidant (TRO) from chlorination caused mortality in sole post-larvae, bass larvae, elvers (young eels), mussel spat, Pacific oyster larvae, *Crangon* larvae and *Acartia* adults. Thermal stress caused significant mortality in bass eggs and larvae. Synergistic effects between the factors increased mortality in some species tested.

The review of the impacts does not try to place these effects in context of actual power station conditions or mention some of the limitations of the EMU. For example:

- only a small subset of the potentially entrained animal species was tested –the findings may not be transferable to other species
- all the experiments were carried out in clean, filtered seawater – higher turbidity may affect survival
- it is not known how often organisms would interact with tunnel walls over the hundreds of metres of intake and discharge pipe they are travelling down (possibly several km in the NNB)
- the presence of bacteria and fungi within the fouling community of the intake and outfall has an unknown effect on mortality
- the shear stress experienced by the organisms in the power station is not reported. In the EMU, shear stress was only present while passing through the condenser, which was 16.77 m in length

The chapter does comment on the lack of understanding of the longer-term effects of entrainment on organisms.

Tolerance of copepods to short-term thermal stress caused by coastal power stations (Jiang et al. 2008)

This study investigated the tolerance of marine copepods to short-term thermal stress, measured by the median lethal temperature (LT_{50}) tests in a laboratory. Animals were exposed to a range of temperatures for 15, 30 and 45 minutes. The LT_{50} of copepods decreased (that is, they died at lower temperatures) with increasing exposure time, but increased when the animals were acclimatised to higher temperatures. Different species showed different thermal tolerances.

Thermal impacts of a coal power plant on the plankton in an open coastal water environment (Choi et al. 2012)

A long-term study of copepods and other plankton was carried out in Korea. This study found that thermal stresses were positively correlated with mortality of the most dominant copepod present (*Acartia hongi*). At this station, the travel time is around 20 minutes from chlorine dosing point to outfall. Chlorine was dosed continuously at nominal concentrations of < 0.1 ppm. Sampling was from

30 m downstream of the outfall. The mortality rate of *A. hongi* from the intake was on average 10%, at 30 m from the discharge it was on average 20%. The study found discharge mortality of *A. hongi* adults is significantly and positively correlated with water temperature differences (between 1 and 4 °C ΔT) between the intake and discharge. The authors also found that the mortality difference of *A. hongi* adults between the intake and discharge is significantly and negatively correlated with absolute discharge temperature, suggesting for this species that mortality is higher at lower water temperature. During laboratory tests, the authors found that at temperature differences of more than 4 °C, copepod mortality tends to increase substantially. In lower temperatures, they also found that the egg production rates for the copepod increased with temperature.

Chlorination for power plant biofouling control: potential impact on entrained phytoplankton (Vinitha et al. 2010)

This study on phytoplankton in India showed that there was a significant reduction (15 to 80%) in chlorophyll *a* as water passed from the intake point to the outfall, and partial restoration of chlorophyll a values as the discharged water mixed with the ambient sea. The station dosed continuously to a total residual oxidant (TRO) level of 0.1 to 0.3 mg l^{-1}. The station also employed a TRO level of about 0.4 to 0.65 mg l^{-1} once a week. In laboratory studies, Vinitha et al. found that growth rate, chlorophyll a and primary productivity of chlorine-treated diatoms decreased, depending on dosage. Some species were much more sensitive than others.

Combined Effect of Heat Shock and Chlorine Fails to Elicit Acquired Thermal Tolerance in Labeo rohita Spawns (Fernandes et al. 2016)

In this paper, one-day old *Labeo rohita* were exposed to chlorine and mild heat shock. Before the experiment, the critical thermal maxima (CT_{max}) of the young *L. rohita* was found to be 38 °C.

Fish were exposed to non-lethal heat shock (ambient of 28 °C to 37 °C for one hour) with and without chlorine (at 0.08 ppm) and left to recover for 48 hours. No mortalities were observed.

The fish were then exposed to temperatures close to or above their thermal tolerance. No chlorine was used in the second test. Fish only exposed to heat shock were found to have increased the CT_{max} from 38 °C, with 100% survival at 40 °C and 30% at 41 °C. Fish exposed to heat shock and chlorine also showed higher CT_{max} than the control, but lower than the heat shock alone group. For this group, survival at 40 °C was down to 40%, with 30% surviving 41 °C. No fish survived 42 °C. Fish exposed to both stressors took longer to recover than fish exposed to heat alone.

The authors also studied a range of metabolic markers. They found that the dual effects of heat shock and chlorine affected the young fish to a greater degree than when they were exposed to heat shock alone. This suggests that the dual stress of heat and chlorine has a greater impact than a single stress.

Husbandry stress during early life stages affects the stress response and health status of juvenile sea bass (Dicentrarchus labrax) (Varsamos et al. 2006)

In this laboratory study, the authors looked at the effect on young bass of disturbance by temperature fluctuations. In addition to direct mortality, they measured several physiological responses to stress. They also inoculated the young fish with a virus (nodavirus, which causes whirling disease and death) and observed the mortality rates. In this study, they found fish that were stressed during early life stages showed poorer survival and a lower disease resistance as juveniles. This was a long experiment (3 months) and shows the effect of chronic stress on young fish.

Effects of a thermal discharge from a nuclear power plant on phytoplankton and periphyton in subtropical coastal waters (Chuang et al. 2009)

The authors examined the effects of elevated water temperatures and residual chlorine from a thermal discharge at a coastal nuclear power plant on the biomass and productivity of periphyton and phytoplankton in subtropical Taiwan. They found that phytoplankton productivity was greatly affected by residual chlorine, but periphyton productivity was more affected by elevated water temperatures.

Mortality of European glass eel (Anguilla anguilla juveniles) at a nuclear power plant (Bryhn et al. 2014)

Glass eels were captured before and after passing through the cooling water system of the Ringhals Nuclear Power Plant in Sweden. Results showed that 13.4% of the glass eel passing through the Ringhals plant cooling water system died as a result of mechanical stress, temperature changes or pressure changes during the passage. The authors note serious shortcomings in the field sampling and other aspects of the sampling. For this reason, no weight is given to the results in this review, but the work is interesting and further studies should be recommended.

5.3.3 Review synthesis

Little work has been published on entrainment survival in the UK in recent years. Reviews such as Bamber and Turnpenny (2012) are still largely based on laboratory experiments carried out in the 1990s. These studies were designed to replicate the entrainment experience of an organism passing through the then newly-built Sizewell B Power Station. The studies went on for 3 years and were performed based on the availability of test organisms. The tests were never carried out for many of the common British species, as sources of eggs and larvae could not be identified.

Recently, there have been several studies on stations in much warmer parts of the world. In a laboratory study on the temperature tolerance of copepods, Jiang et al. (2008) found that the animals died at lower temperatures as the length of exposure to elevated temperatures increased. They also showed that different species had different tolerances. Choi et al. (2012) studied the copepod (*Acartia hongi*) at the intake and outfall of a power station. They found that the low level of chlorine used at this site (nominal concentrations of < 0.1 ppm) did not increase mortality. Temperature did increase mortality, with the mortality rate of the copepods rising from 10% at the intake to 20% at the discharge sampling point, some 30 m from the outfall. For this species, temperature increases as low as 4°C would increase mortality.

Phytoplankton also showed similar patterns, with Vinitha et al. (2010) finding significant reductions (15 to 80%) in chlorophyll a as water passed from the intake point to the outfall. In laboratory studies, they found that growth rate, chlorophyll a and primary productivity of chlorine-treated diatoms decreased, depending on dosage. Some species were much more sensitive than others. These reductions in chlorophyll a have been found in other studies (Chuang et al. 2009) and have been found to be caused by different factors for phytoplankton and periphyton productivity.

Synergistic and sub-lethal effects are also observed. Fernandes et al. (2016) showed that in one-day old *Labeo rohita* temperature and chlorine can act synergistically. Fish were exposed to non-lethal heat shock (ambient of 28 °C to 37 °C for one hour) with and without chlorine (at 0.08 ppm) and left to recover for 48 hours. When exposed to a second heat shock, close to their thermal death point, fish exposed to heat shock alone survived at higher temperatures than the fish that had been exposed to heat and chlorine. Varamos et al. (2006) looked at the effect of disturbance and temperature change on young bass. In this study, the authors looked at direct mortality of the impacts, but also inoculated the surviving fish with a virus. They found fish that were stressed during early life stages show poorer survival and a lower disease resistance as juveniles. The combination of the stressors experienced by an entrained animal will result in higher mortalities (Schreck et al. 2000).

5.3.4 Evidence scoring for cooling water systems downstream of fine screens

Cooling water systems downstream of fine screens

5.3.4 Evidence scoring for cooling water systems downstream of fine screens

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Entrainment of organisms through power station cooling water systems. In Operational and environmental consequences of large industrial cooling water systems. Bamber and Turnpenny (2012).	Chapter of book	5	3	3	**Quality of information source** This is a chapter published by a respected publishing company. **Applicability of evidence** The chapter reviews entrainment and its effects. The data on UK species are old and generally in internal reports, without peer review. A limited range of species had any data. **Strength of conclusion** The conclusion of the chapter only gives a partial insight into entrainment mortality in the UK.	**Medium (11)**

5.3.4 Evidence scoring for cooling water systems downstream of fine screens

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Tolerance of copepods to short-term thermal stress caused by coastal power stations. Jiang et al. (2008).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper reports on the thermal impact on copepods in the laboratory, on a species that is not from the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. It illustrates that the length of exposure to elevated temperature can be a factor in thermal mortality.	**Medium (11)**
Thermal impacts of a coal power plant on the plankton in an open coastal water environment. Choi et al. (2012).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper reports on the thermal impact on copepods, on a species that is not from the UK. The impact is measured on a working power station. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. It illustrates the increase in mortality rates downstream from the station.	**Medium (11)**

5.3.4 Evidence scoring for cooling water systems downstream of fine screens

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Chlorination for power plant biofouling control: potential impact on entrained phytoplankton. Vinitha et al. (2010).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper reports on the thermal impact on phytoplankton, on a species that is not from the UK. The impact is measured on a working power station. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. It illustrates reductions in chlorophyll a related to power station discharges.	**Medium (11)**
Combined Effect of Heat Shock and Chlorine Fails to Elicit Acquired Thermal Tolerance in *Labeo rohita* Spawns. Fernandes et al. (2016).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper reports on the thermal impact and chlorine on day-old fish in a laboratory study, on a species that is not from the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. It illustrates synergistic effects on the young fish of temperature and chlorine.	**Medium (11)**

5.3.4 Evidence scoring for cooling water systems downstream of fine screens

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Husbandry stress during early life stages affects the stress response and health status of juvenile sea bass (*Dicentrarchus labrax*). Varsamos et al. (2006).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence of a UK species. **Applicability of evidence** The paper reports on the thermal impacts on early life stages of bass. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**

5.3.5 Evidence review conclusions for cooling water systems downstream of fine screens

Little work has been published on entrainment survival in the UK in recent years. Survival rates of entrained animals in power stations are difficult to measure. Laboratory simulations are difficult to design so that they capture the entire entrainment experience. Studies from the 1990s focused on the then to be built Sizewell B. The duration of entrainment of animals will be much longer at the proposed new nuclear build (NNB), with the time from entrainment at the intake to release back to sea around 45 minutes minimum. Capturing enough animals in a working station is also difficult; not only are the animals fragile and can disappear when damaged, but timing the sampling so the organisms of interest are present is very difficult.

In the NNB sites, with much longer intake and outfall pipes, the increased length of exposure, particularly to the warmed water after the condensers, could increase mortality rates. Increased exposure to elevated temperatures has been shown to increase mortality in copepods. Synergistic effects are known between biocides, temperature and pressure.

Sub-lethal effects were found in young fish that had been thermally stressed. They became more susceptible to disease.

Investigations into the actual experience of an animal passing through a station, and its impacts, are needed. New technologies such as the Sensor Fish[1] could give insights into the pressure, temperature and mechanical experience of an entrained animal.

1) The Sensor Fish is a small autonomous device containing sensors that analyses the physical conditions through dams and other hydro structures. A smaller Sensor Fish Mini is now also available.

5.3.6 Subject area scoring

5.3.6 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Will a high percentage of entrained fish survive passage through a power station?	1	3	1	**Quality of evidence base** Survival of entrainment was studied in the 1990s. Little new work has been published since. New stations have likely longer transit times than the stations studied in the 1990s, with much longer exposure to turbulence, mechanical damage and thermal shock. **Applicability of evidence** There are many studies on entrainment survival from the US but a high proportion of them are flawed. Survival appears to be very species- and site-specific. **Degree of concordance** Not enough studies have been carried out in the UK to have confidence in the rate of survival of animals after entrainment. A wide range of organisms have been shown to be impacted by thermal shock, pressure changes, shear stress and biocides. Confidence that these impacts will affect survival rates following entrainment is high.	**Low (5)**

6 Screening and survival

Even when a return system is installed, it will not be certain that fish and other organisms will survive. Survival depends on the vulnerability of the organism to damage from the system, for example when it encounters a hard surface, as well as on other factors such as the presence of debris or predators in the release area, and the temperature at the time of capture. Open-water fish, such as the clupeid family, generally have low or negligible survival following impingement, because their skins are easily damaged.

6.1 Onshore screening, including fish recovery facilities

6.1.1 Introduction

Raked bar screens, bypass systems and fish-friendly rakes

Automatically-raked bar screens in the forebay in front of the main travelling screens are common at newer direct-cooled power stations. The size of gap of the proposed screen rakes is not known for the planned UK NNB power stations, but the gaps are commonly around 50 mm (Environment Agency 2010a). The Environment Agency stated that, "Regulators should be satisfied that the design and performance of any forebay raking system is compatible with fish recovery and return (FRR) requirements." Since 2010, various manufacturers are now offering fish-friendly raking systems.

Fish entering the forebay via an offshore intake that are too large to pass through the rake screen will be trapped in the forebay. Without some way of escape, either via a fish recovery system or by access back to open water, their fate is to die in the forebay before becoming impinged on the raked screen and collected by the automatic rake, or breaking up and passing on to the fine screens.

Offshore intakes do not have direct access back to the sea. In contrast, inshore intakes can have open access to the sea, and, as such, escape is at least possible for fish in front of the screens.

There are 2 approaches to removing fish entrapped by the rake screen. The first is to use the automatic rake that has been designed to be fish-friendly. These lift the fish which are impinged on the raked screen, keep them underwater and place them into the fish recovery system. The second is a bypass-based system which is designed to collect the fish at a site away from the rake system, and lift them into the fish recovery system from there.

There are problems with both methods. In the case of fish-friendly rake systems, if the velocity through the screen is low, then fish will presumably impact the bars and try to escape. This might happen repeatedly as the fish tries to hold station in the turbulent forebay. In this case, it is likely that only exhausted and injured fish would remain on the rake screen long enough for the periodic cleaning of the rake screen to remove them. If the velocity is high enough for fish to become impinged without being able to escape, then they are likely to be damaged while trapped waiting to be cleared by the automatic rake. For bypass systems, fish must find the bypass before becoming damaged or exhausted, then be removed to the fish return system. For a bypass to work effectively, the systems must be designed not to have areas where fish can be held in the forebay, the bypass must be attractive to the fish, and the removal must be frequent enough that crowding, predation and damage do not become issues.

Much of the behavioural research on using bypass systems to divert fish has been carried out in attempts to improve fish passage at hydropower stations. These tend to be focused on a single species that is migrating between different habitats.

If using a behavioural method of moving the fish to a safe refuge where they can be lifted into the fish recovery system, the stimulus to move to the refuge must be large enough to overcome the turbulence within the forebay. A forebay is a difficult environment in which to operate a behavioural fish guidance system due to high turbulence, turbidity, stressed fish and possibly biocides.

Ancillary screening systems

On NNB sites in the UK, band screens are generally restricted to the screening of auxiliary/essential seawater supplies. The cooling water (CW) screening duty is normally carried out by the large capacity drum screens. One factor in the choice of design of either type is any nuclear safety qualification, which is outside the scope of this document.

Making band screens fish-friendly adds complications to the design and operation of these screens. There are several designs commercially available and in use in power stations that are fish-friendly.

A detailed review of screening systems was reported in the Environment Agency 2010 report ‘Cooling water options for the new generation of nuclear power stations in the UK’ (Environment Agency 2010a).

6.1.2 Documents reviewed

Raked bar screen survival – bypass

Analysis of fish diversion efficiency and survivorship in the fish return system at San Onofre Nuclear Generating Station (Love et al. 1989)

This is a study of the efficiency of the fish return system at San Onofre Nuclear Generating Station (SONGS). It is an unusual design, with angled trash screens leading to a fish removal area which was emptied by a fish elevator. The study found most of the fish (around 80%) were diverted into the fish recovery system without being impinged. The authors found that strongly-swimming species were more likely to enter the fish recovery system than poorly-swimming species. Diversion into the fish recovery was variable by size; most species showed larger individuals to be more common in the return, but in a few the pattern was reversed, with small fish being more common.

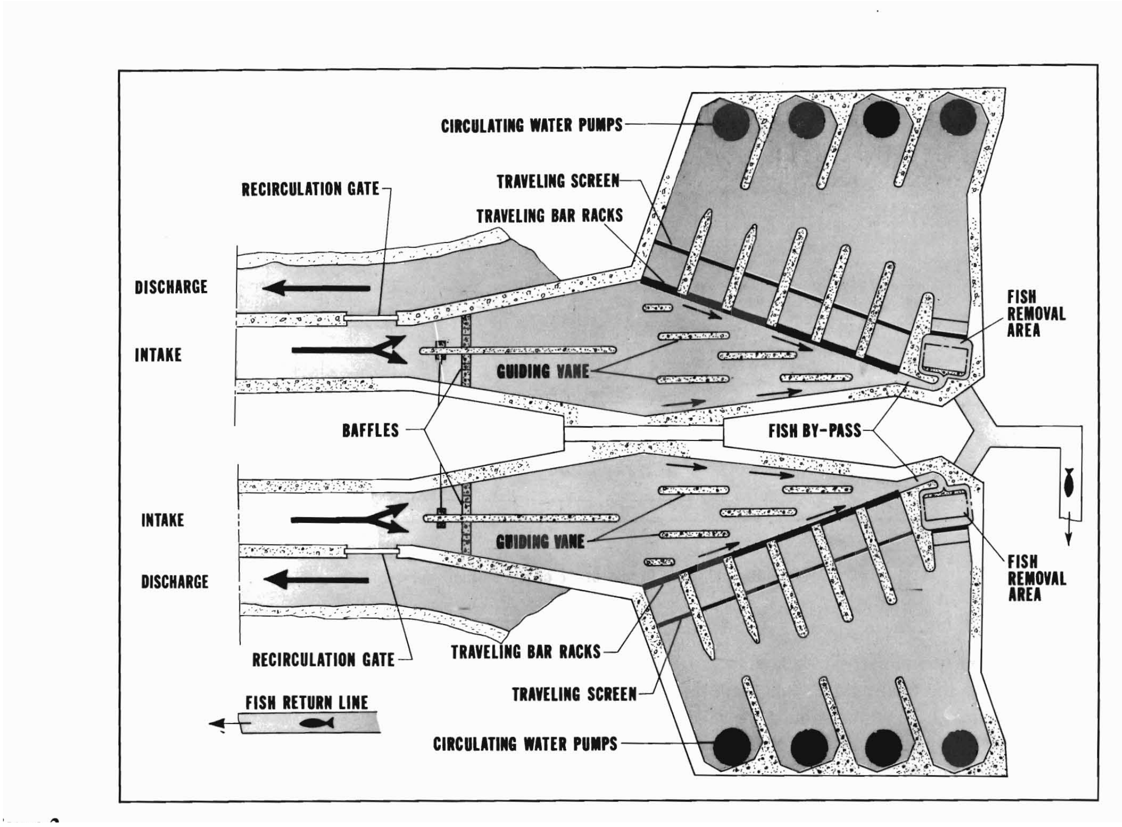


Figure 10: Fish return system of San Onofre Units 2 and 3, from intake through fish removal area (Figure 2 in Love et al. 1989)

The study went on to examine the survival of the fish that had passed through the system by capturing them at the end of the fish return discharge pipe. They found variable survival 96 hours after capture. Some species survived well, such as northern anchovy (*Engraulis mordax*) and white croaker (*Genyonemus lineatus*), while others, such as the anchovy (*Anchoa delicatissima*) did not.

Proposal for Information Collection San Onofre Nuclear Generating Station Southern California Edison (Bailey 2005)

This report describes the ‘fish chase’ procedure used at SONGS prior to recirculation of the heated effluent to control biofouling. This recirculation will kill any of the fish that remain in the forebay. To reduce this death, the station uses its fish return system (as described above) and a controlled increase of temperature to agitate any resident fish, so that they are swept into the fish elevators. The method is about 50% effective (in 2003, the ‘fish chase’ operations released over 46% of all fish by number, and over 56% of the biomass). The percentage of the fish recovered varied with species. For example, 53% of northern anchovy (*Engraulis mordax*) and 23% queenfish (*Seriphus politus*) were recovered, whereas 0% of the shiner perch (*Cymatogaster aggregata*) and deep-body anchovy (*Anchoa compressa*) were recovered.

Louver diversion efficiency

Evaluating a light-louver system for behavioural guidance of age-0 white sturgeon (Ford et al. 2017)

This is a laboratory study of sturgeon in a shallow flume, with a louver set up to one side and a bypass down the other. The authors released the sturgeon and recorded its movement in relation to the louver. They found that using a green (an attractant) and red (a repellent) light significantly increased the number of fish using the bypass.

It is difficult to imagine a system such as this being deployed in a working power station. These are migratory fish with an innate desire to move past such obstacles.

The behavioral responses of a warmwater teleost to different spectra of light-emitting diodes (Sullivan et al. 2016)

This was a study of the largemouth bass (*Micropterus salmoides*), a freshwater fish. Using light emitting diodes (LEDs) to manipulate light spectra and light-pulse frequency, the authors tested whether the fish were repelled by the light. In a large shallow arena made of mesh, inside a boathouse, largemouth bass were observed to move away from the light source, regardless of colour or light-pulse frequency.

Laboratory Evaluation of the Survival of Fish Impinged on Modified Traveling Water Screens (Black and Perry 2014)

In a test of a fish-friendly travelling screen, the authors exposed freshwater fish to impingement at a range of through-screen velocities (0.3, 0.6 and 0.9 m/s). These are relatively low velocities. They found high survival for all species tested and found that the 48-hour mortality was less than 5%, regardless of approach velocity. The study also looked at scale damage and other injuries. There was large interspecific variation in the level of damage, with 2 species having over 20% of fish injured. Of the injuries observed, haemorrhaging, disease or fungal infection and fin damage were more prevalent. Scale loss was very common in some groups and showed an increase with increased water velocity, and a decrease with increased length. Due to the design of the test equipment, the study had very short impingement times, with the maximum time of a fish being impinged on the screen of 40 seconds. The authors point out that this is a control test, where the fish are not under the same conditions as found in the field. The authors suggest further trials in a real-life situation.

Fish Protection at Cooling Water Intake Structures: A Technical Reference Manual – 2012 Update (EPRI 2012c)

This report provides a review of the fish protection technologies for use at power plant cooling water intake structures to meet requirements of §316(b) of the Clean Water Act (CWA). It evaluates fish protection technologies and examines project design, study methods and effectiveness.

Raked bar screen survival – Trash rakes

No data on British marine species survival have been found.

6.1.3 Review synthesis

Bypass systems are uncommon in power station applications (EPRI, 2012c). The only study identified was at San Onofre Nuclear Generating Station (SONGS) in California USA (Love et al. 1989). This system had angled travelling bar racks to move the fish into a fish removal area where they were lifted into a fish recovery system. The system was found to divert about 80% of the fish into the return system. Fish in the return system had variable 96-hour survival, with some species surviving well and some not. The fish chase procedure, used to clear the fish before the system is heated up for biofouling control, captures about 50% of the fish resident in the forebay at that time (Bailey 2005). Again, the recovery rates were species-dependent.

There are several studies looking at behavioural methods of improving bypass efficiency. Most of the studies are focused on freshwater systems where diversions around hydroelectric dams and water intakes are an issue. Light systems had been added to louver systems and shown to increase the diversion of white sturgeon in the laboratory (Ford et al. 2017). Largemouth bass (*Micropterus salmoides*) was found to avoid areas illuminated by LED lights (Sullivan et al. 2016). Louver systems are most suitable for situations where the flow is from one direction. In the marine environment, the reversal of tidal streams and the period of slack water around high and low water makes designing a system to reduce fish entrapment difficult.

Fish-friendly screens are available which have been shown to have low mortality rates for some species (EPRI 2012c, Black and Perry 2014). This high survival rate would only apply to the fish that can pass through the angle rake systems in front of the screen. There are no recent published reports on fish impingement survival for British marine fish.

No studies on the survival of British marine fish after removal from angle rake screens was found for this review.

6.1.4 Evidence scoring for onshore screening including fish recovery facilities

Raked bar screen survival – bypass

6.1.4 Evidence scoring for rake bar screen bypass

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Analysis of fish diversion efficiency and survivorship in the fish return system at San Onofre Nuclear Generating Station. Love et al (1989).	Report	5	3	3	**Quality of information source** This is report by the National Oceanic and Atmospheric Administration in the US based on direct empirical evidence. **Applicability of evidence** The report discusses a technology that could be applicable in the UK. It does not include UK species. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. A unique intake configuration and fish protection system.	**Medium (11)**

6.1.4 Evidence scoring for rake bar screen bypass

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Proposal for Information Collection San Onofre Nuclear Generating Station Southern California. Bailey (2005).	Report	5	1	3	**Quality of information source** This is report by EPRI, a respected industry body. It is based on direct empirical evidence. **Applicability of evidence** The report discusses additional features of the SONGS intake. It does not include UK species. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. Without a station with the unique layout of SONGS it has no application in the UK.	**Medium (9)**

Raked bar screen survival – Louver diversion efficiently

6.1.5 Evidence scoring for louver diversion efficiently

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Evaluating a light-louver system for behavioural guidance of age-0 white sturgeon. Ford et al (2017).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper is not based on a fish species found in the UK. It is a laboratory study of fish avoidance. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. There may be relevance in sites that use louver technology to reduce fish entrapment.	**Medium (11)**
The behavioral responses of a warmwater teleost to different spectra of light-emitting diodes. Sullivan et al. (2016).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence. **Applicability of evidence** The paper is not based on a fish species found in the UK. It is a field based experiment of fish avoidance. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. There may be relevance in sites that use louver technology to reduce fish entrapment.	**Medium (11)**

Travelling screen survival

6.1.5 Evidence scoring for louver diversion efficiently

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Laboratory Evaluation of the Survival of Fish Impinged on Modified Traveling Water Screens. Black and Perry (2014).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence of non-UK species. **Applicability of evidence** The paper is a laboratory study of fresh water survival on screens. It examines the effect of through-screen velocity for a range of species. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text. This is a small test screen with short impingement times.	**Medium (11)**

6.1.5 Evidence review conclusions for onshore screening, including fish recovery facilities

Once a fish enters the forebay of a station with an offshore intake it cannot generally escape. If it reaches the travelling screen, modern screens can have low mortality rates. Black and Perry (2014) used a test screen in the laboratory to impinge fish at various through-screen velocities. They found high survival for all species tested, and found that the 48-hour mortality was less than 5% regardless of approach velocity. The level of damage was species-specific.

Automatically raked bar screens in the forebay in front of the main travelling screens are common at newer direct cooled power stations. The size of gap of the proposed screens rakes for the NNB is not known, but the gaps are commonly around 50 mm. If a fish is too large to pass through the rake screen to the travelling screens, it will die unless it is captured and released. There are 2 possible methods for capture; a bypass system where fish are collected somewhere in the forebay and transported into the fish return system, or being captured on the automatic rake system.

Bypass systems are uncommon in power station applications (EPRI, 2012c). The only study identified was at San Onofre Nuclear Generating Station (SONGS) in California USA. This system was found to be about 80% effective at moving fish into the fish return system. Once in the return system, survival was species-dependent. Some methods have been tested to try to improve bypass efficiency at water intakes. Ford et al. (2017) used lights to divert sturgeon away from a louver system in a flume. Sullivan et al. (2016) used coloured lights to test the behaviour of the largemouth bass (*Micropterus salmoides*), a freshwater fish. Both systems influenced the fishes' behaviour.

Fish-friendly rake systems are sold by several companies. No published evidence could be found for fish-friendly rake systems for UK marine species.

This is an area that needs urgent research.

6.1.6 Subject area scoring

6.1.6 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Are bypass systems within the forebay relevant?	1	1	1	**Quality of evidence base** The technology is unusual, only known from a single power station. **Applicability of evidence** No UK intake designs are known where a similar bypass system would work. **Degree of concordance** Only one station was found, with several papers giving data.	**Low (3)**
Will fish collected by fish-friendly rake systems survive?	1	1	1	**Quality of evidence base** The technology available from manufacturers. **Applicability of evidence** No studies of marine fish were found. **Degree of concordance** None.	**Low (3)**
Can some species of fish survive impingement on travelling screens?	5	5	3	**Quality of evidence base** The technology is established and was understood in the 2010a Environment Agency report. New studies confirm that screens can be fish-friendly for some species. **Applicability of evidence** No recent published data on British marine species were found. **Degree of concordance** A wide range of studies has shown survival of impinged fish to be species-specific and vary from very high survival to 100% mortality.	**High (13)**

6.2 Fish return launders and discharge head design

6.2.1 Introduction

Once the fish and other organisms have been removed from the forebay, they must be handled in such a way as to maximise their chances of survival in the fish return system. At existing fish recovery systems, the animals are generally returned to sea via a series of channels.

The major risks to an animal once a fish is in the return system are:

- contact with surfaces:
    - direct contact such as hitting a channel side or bottom
    - abrasion against rough or biofouled surfaces
    - hitting any blockages that form in the system
    - any structures within the system
- shear forces – from other wash flows or water inputs, in high-turbulence areas or the release point
- exposure to bird predation – open gullies attract birds and need protection
- predation or injury by other organisms in the system
- impact with other debris in the system
- smothering or compression by large quantities of other debris
- exposure to biocides
- exposure to air
- temperature extremes, both hot and cold
- pressure changes – particularly with offshore release points
- violent release to sea – at low tide where there may be a gap between the end of the return system and the sea
- disorientation on release back into the environment
- relocation to a new place, including the dislocation from its shoal if relevant
- higher predation risk at release due to ground baiting effect
- returning into or close to the heated effluent
- recirculation into intake

Good practice guidelines have been discussed by the Environment Agency's 'Screening for intake and outfalls: a best practice guide (2005)'. For handling smolts at hydro stations this document recommends that fish handling within the fish return launders and at the return point should be as gentle as possible. This includes avoiding sharp bends, which it defines as a bend of 3-metre minimum radius, no sudden drops and no rough surfaces or irregularities that might cause abrasion. The document states that open, half-round channels are preferred.

There has been much research into fishways or passes around large man-made structures. Although not directly comparable, the experience of a fish passing down the artificial channel can in some cases be like that of one in a fish return system.

6.2.2 Documents reviewed

Trials and tribulations of fish recovery and return (Turnpenny 2014b)

Turnpenny (2014b) gives an outline of a good fish return system design. After capture and release into the fish launder, the key design features are listed as:

- smooth to prevent injury to fish
- minimum launder width of 0.3 m for individual screen branches
- minimum launder width of 0.5 m for main return conduits
- horizontal bend radius with a minimum radius of 3 m
- slope limited to 2% on main runs
- vertical bends should also be swept

The smoothness of the launder includes joints between sections, surface roughness or any other feature that can cause small-scale turbulence. Not only does this reduce damage to fish touching the surface, the small turbulent patches can cause areas that can encourage biofouling or lead to snags of debris forming.

For the discharge of the return systems, the author states that the return must be hydraulically separated from the intake to prevent recirculation of the organisms, and that the return point should be one metre below water to avoid discharging the fish into drying areas where they could become stranded.

The author suggests that the system must be able to be cleaned, even if it is a pipe or covered trough. Debris from the screens can build up within the system and will need removing from time to time.

Creating enough height at the inshore end to maintain the flow down the launder along the length of the return discharge system may require some form of fish-friendly pump. These are examined in section 6.3.

Fishway evaluations for better bioengineering: an integrative approach (Castro-Santos et al. 2009)

This paper reviews the factors that can impact fish in a fishway. The authors suggest considering an ideal fishway passing a river blockage. They suggest that it should have the following characteristics:

- any individual of any native species wishing to move upstream or downstream must be able to enter the fishway without experiencing any delay
- entry is immediately followed by successful passage
- no temporal or energetic costs
- no stress, disease, injury, predation, or other fitness-relevant costs associated with passage

The first point above is specific to fishways passing obstructions. For fish return systems, it could be replaced by “any individual, of any species, placed in the fish launder should move rapidly through to release without delay.”

In their review of the effect of turbulence, the authors find most studies show that increased turbulence increases the costs of swimming performance. There have been a few studies that either found no effect or found that some species could use turbulence to reduce the cost of swimming.

Effects of Fouling and Debris on Larval Fish Within a Fish Return System (EPRI 2012a)

In a laboratory experiment to examine the effects of flume substrate on larval fish survival using 4 American freshwater species (channel catfish, common carp, golden shiner, and bluegill), the authors found that survival was high for 3 species on all substrates, but the golden shiner had worse survival on fibre than on stone substrates. Fibre was being used here to simulate fouling. Across all species, fibre produced lower survival rates.

Debris testing was only carried out on 2 species (channel catfish and bluegill), but debris was not found to be a significant factor in survival. The experiment was on hardy species, which are more resilient than pelagic species, such as clupeids which can dominate entrainment at British sites. The author also points out that the results are from ideal laboratory testing conditions. Since the animals tested were laboratory-reared and introduced to the system, they had not undergone the capture stresses that a fish might encounter at an intake. There was no indication of how much debris was added with the animals. Debris used was mylar, tinsel, wood chips, plastic media, plastic beads and plywood pieces. The launder used was approximately 8 m long. This is a shorter launder than most found at current stations, and much shorter than the several hundred metre-long launder suggested at NNB sites.

Effects of distance and debris exposure on survival and injury of juvenile fish within a fish return system (EPRI 2013)

Several species of fish (alewife, bluegill, channel catfish, largemouth bass, hybrid striped bass, common carp, and golden shiner) were released with and without the presence of 3 types of simulated debris (woody, filamentous [grass/aquatic weeds] and plastic material) through 2 lengths of PVC pipe, simulating fish return systems (60 and 305 m long). After passage through the fish return systems, fish were held for 48 hours to assess latent mortality, injury and scale loss. The authors found low levels of damage for all the fish, with only the survival of alewife impacted by length of the pipe. Debris did not appear to be significant.

The summary available for this study does not indicate whether the fish were introduced to the return system after capture on screens or were from some other source. Synergistic effects of the organisms' capture experience at an intake, with the impact of length of return or debris loading, are not discernible from this abstract. This is a shorter launder than most found at current stations, and much shorter than the several hundred metre-long launder suggested at NNB sites.

Drops in fish launders

Mortality and injury rates for small fish passing over three diversion dam spillway models (Bestgen et al. 2018)

Three species of American freshwater fish were released in a laboratory spillway from 5.7 m into different receiving basin depths (2.5 ,15 and 30 cm). The species were fathead minnow (*Pimephales promelas*), hybrid rainbow x cutthroat trout (*Oncorhynchus mykiss* x *O. clarkii*) and small razorback sucker (*Xyrauchen texanus*). All the fish were either 25 or 50 mm long). Mean survival proportion was high in all tests (0.97 to 1.0) for all species, size-classes and flow conditions, except in the basin depth of 2.5 cm, where survival was lower (0.78 to 0.94). The spillway caused negligible injury to small fish if the receiving pool depth was 15 cm or deeper.

Fish passage in large rivers: A literature review (Linnansaari et al. 2015)

In a review of downstream mitigation methods at a dam, Linnasaari et al. state, "Impact velocities greater than 16.2 m/s will cause significant injury or mortality. This equates to a 13 m drop in water, beyond which the probability of mortality increases to 100% at approximately 55 to 60 m. For smaller fish, freefall is preferred because their terminal velocity is often less than the critical velocity. The risk of injury or mortality is similar for larger fish whether in water or in freefall." Damage is increased when the receiving waters are shallower. These are not heights likely to be experienced in a fish return system.

Response relationships between juvenile salmon and an autonomous sensor in turbulent flow (Richmond et al. 2009)

In a study to verify the use of the Sensor Fish recording device, Chinook salmon (*Oncorhynchus tshawythscha*) and the Sensor were exposed to a series of laboratory shear tests using a range of measurement systems. The Sensor and the fish correlated well, but the maximum accelerations encountered by live fish were larger than those by Sensor Fish. A 3rd-degree polynomial was developed to correlate live fish accelerations with Sensor Fish accelerations. The observed acceleration of live fish, and predicted live fish acceleration using Sensor Fish data agreed very well, with only minor discrepancies in the upper tails of the distributions corresponding to the maximum levels of acceleration. The majority of live fish accelerations fell within the 95% confidence intervals of the prediction. The authors give values for the level of acceleration that was damaging to the salmon.

Table 6.2.1: (Table 1 from Richmond et al. 2009). Accelerations (ms^{-2}) of Sensor Fish corresponding to an injury probability of 10% with 95% confidence intervals in parentheses

Injury type	Fast-fish-to-slow-water	Slow-fish-to-fast-water
Minor injury	272 (144 to 379)	132 (0 to 212)
Major injury	513 (277 to 643)	260 (119 to 333)

Physical and ecological evaluation of a fish-friendly surface spillway (Duncan et al. 2018)

This study used Sensor Fish devices that contained 3 transducers, including a three-axis gyroscope, three-axis accelerometers, a pressure sensor, a temperature sensor, a three-axis magnetometer, a radio-frequency transmitter, a recovery module, and a communication module. Each device's mass was approximately 42.1 g, and it was neutrally buoyant in fresh water at deployment, with its size and density similar to those of a yearling salmon smolt. The recovery module allowed the Sensor Fish to become positively buoyant, bringing the unit to the water surface for recovery after a pre-programmed time. The Sensor Fish also contained on-board light-emitting diodes that flashed after the completion of data acquisition, allowing for visual detection in low-light conditions. This allowed the researchers to measure the physical conditions experienced by a fish passing over the spillway of a dam. It allowed them to analyse the number of collisions occurring during passage, the shear stresses experienced and the pressure changes. They found that the Sensor Fish data and live fish injury results correlated with the probability that a fish would be injured during passage, increasing proportionately with the number of severe collisions and shear events observed during Sensor Fish releases.

This technology would give valuable insights into the experience of an animal passing through a power station intake and fish return system.

Environment Agency fish pass manual (Armstrong et al. Environment Agency 2010b)

A review of the factors and designs for fish passes. The focus is on freshwater habitats and species, with migratory fish being of particular concern. The review examines the factors that affect survival in fish passes.

6.2.3 Review synthesis

For fish return systems to be effective, the launders ideally would not cause any additional damage to the fish, not increase the level of stress, or lead to further exhaustion (Castro-Santos et al. 2009). For this to be the case, the system must be able to handle the largest fish likely to be caught at the site. If trash rake fish are returned via the system, these should be considered, as they will generally be the largest animal. The shape of the animal must also be considered – a large salmon is a very different shape from a thornback ray. The shape and size of the launder must be able to cope with fish of all shapes. Turnpenny (2014b) suggests 0.3 m width for single arms and 0.5 m for the combined arms of a launder. These should be large enough to allow free passage of all fish if the water is deep enough within the launder. The depth of water in the launder should always keep fish covered while the fish is in its natural orientation.

Contrary to the design of a fishway, which is designed to allow fish to move both ways, fish launders must only allow fish to move down them. A fish holding station or moving up the launder is expending energy and increasing its exposure time to the station. Turnpenny (2014b) suggests a 2% slope to maintain flow.

At many stations with fish return systems, there is a two-stage screen washing process, with a low-power wash for the fish return, followed by a high-power wash for other debris. These streams can be kept separate (Turnpenny, 2014b). EPRI (2012a) carried out a series of experiments with young freshwater fish to examine the effects of fouling in the fish launder, and whether the presence of debris impacted on the survival of the fish compared to a clean launder experience. The EPRI authors found a small reduction in survival for some species regardless of substrate in the launder. For one species tested, fibre mats in the launder caused 25% mortality. Debris was not found to increase mortality. This study was on a limited range of fish, which were all very small, over a short launder. It is likely that larger animals, while travelling several hundred metres in a launder, might interact with the debris and fouled surfaces more frequently. Similarly, in an EPRI 2013 study on the length of exposure to debris, it is impossible to tell from the summary available the amount of debris involved.

Drops within the systems should be minimised as they cause turbulence and stress to the fish. Low levels of turbulence can affect the fishes' behaviour, which is likely to increase the chance of injury (Odeh 2002). Given this, if drops must occur in the fish return system, they are unlikely to be large enough to cause mortality from the fall alone. Linnansaari et al. (2015) suggest that, for freshwater fish, the drop required to cause mortality is 13 m or more. However, the design must also include a receiving area that contains enough water. Bestgen et al. (2018) on a test on small fish (<50 mm long) found mean survival decreased when the receiving water was 2.5 cm deep. It would seem likely that larger fish would need deeper pools to land safely in, but no evidence was found to support this. Without any further evidence on UK marine fish, the Environment Agency guidance on pool and weir fish passes (Environment Agency 2010b) is likely to be a good starting point: "The minimum depth must be at least twice, and preferably three times, the head drop in plunging flow passes. A minimum depth of 1.2 m is generally used for large migratory salmonids. For trout and coarse fish, the pool sizes may be reduced subject to satisfactory power densities being present. However, lengths and widths less than 1.8 m and 1.2 m respectively and depths less than 0.6 m would not normally be satisfactory."

The Sensor Fish technology gives a method of directly measuring the experience of a fish passing through an intake (Duncan et al. 2018, Richmond et al. 2009). This technology could not only give a measurement of the experience of a fish passing through the stations, but it could also be used to examine how many times interactions with debris in the system occur.

If fish-friendly trash rakes are to be used, then the debris collected from those screens will be placed into the fish return system, since any viable fish must be returned to the water. If there are significant amounts of weed and other debris, this could cause blockages and increase the interaction of the fish with debris in the launder.

Most studies on fish in launders and bypass channels are on freshwater species, usually in relation to riverine blockages. The applicability of the values given for shear stresses to UK marine fish is unknown, but without any evidence from relevant species, at least these studies give some guidance on the forces and likely levels of damage involved.

There is a balance to be struck between rapid transit of fish through the launder, possibly with higher turbulence and shear stress damage, and slower transit times where the fish are exposed to the other stresses in the launder for a longer period.

6.2.4 Evidence scoring for fish return launders and discharge head design

Fish return launders and discharge head design

6.2.4 Evidence scoring for fish return launders and discharge head design

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Trials and tribulations of fish recovery and return. Turnpenny (2014b).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper. **Applicability of evidence** The paper reviews issues around fish return systems. The review is relevant to power station impingement in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, with the author covering basic design and operation. There is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**

6.2.4 Evidence scoring for fish return launders and discharge head design

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Fishway evaluations for better bioengineering: an integrative approach. Castro-Santos et al. (2009).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper. **Applicability of evidence** The paper reviews fishways around dams. The sections on fish passing along launders are relevant to power station impingement. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors suggesting that turbulence can impact on fish fitness. There is sufficient evidence to give confidence to the conclusions in the text.	**Medium (11)**
Effects of Fouling and Debris on Larval Fish Within a Fish Return System. EPRI (2012a).	Report	5	3	3	**Quality of information source** This is a report from a well-respected body. **Applicability of evidence** The paper reports on tests of larval freshwater fish in fish launders with differing simulated fouling and debris. The fish are freshwater and the fouling and debris artificial. The launder was only 8 m long. Fish were not stressed before exposure. The species do not occur in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**Medium (11)**

6.2.4 Evidence scoring for fish return launders and discharge head design

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Effects of distance and debris exposure on survival and injury of juvenile fish within a fish return system. EPRI (2013).	Report	5	3	3	**Quality of information source** This is a report from a well-respected body. **Applicability of evidence** The paper reviews reports on tests of several species of freshwater fish in fish launders, using differing simulated fouling and launder lengths. The fish are freshwater and the fouling and debris artificial. Fish were not stressed before exposure. The species do not occur in the UK. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**Medium (11)**

Drops in fish launders

6.2.4 Evidence scoring for drops in fish launders

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Mortality and injury rates for small fish passing over three diversion dam spillway models. Bestgen et al. (2018).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence on species not found around the UK. **Applicability of evidence** The paper is based on 3 freshwater fish species not found in the UK. The activities assessed are related to fish return systems, but the impact of fish falling from height is relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors inferring that the depth of the receiving water is important to fish survival. There is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**

6.2.4 Evidence scoring for drops in fish launders

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Fish passage in large rivers: A literature review. Linnansaari et al. (2015).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence on species not found around the UK. **Applicability of evidence** The paper is based on 3 freshwater fish species not found in the UK. The activities assessed are related to fish return systems, but the impact of fish falling from height is relevant to the assessment. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors inferring that the depth of the receiving water is important to fish survival. There is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**
Response relationships between juvenile salmon and an autonomous sensor in turbulent flow. Richmond et al. (2009).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence, on species not found around the UK. **Applicability of evidence** The paper is based on a freshwater fish species not found in the UK. The technology reviewed is suitable to improve our knowledge of fish return systems. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**

6.2.4 Evidence scoring for drops in fish launders

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Physical and ecological evaluation of a fish-friendly surface spillway. Duncan et al. (2018).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence, on species not found around the UK. **Applicability of evidence** The paper is based on a freshwater fish species not found in the UK. The technology reviewed is suitable to improve our knowledge of fish return systems. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**

6.2.5 Evidence review conclusions for fish return launders and discharge head design

Little research has been done on the importance of the various stages that make up a fish return system. For fish return systems to be effective, the launders ideally would not cause any additional damage to the fish, not increase the level of stress or lead to further exhaustion (Castro-Santos et al. 2009). This is not possible, so the design should introduce as little stress as possible. The system must be large enough to handle the largest fish caught at the station. If fish from the automatic raking system are to be released into the launder, the size of these fish could determine the width and depth of the launder required.

How to handle the debris and fouling in the launder is unclear. Experiments to date have been on small freshwater fish from the US. These showed that debris did not increase the mortality of young fish, but fouling of the launder did. If automatic fish-friendly trash rakes are to be used, they will add the debris to the fish launder.

Drops within the system are another potential source of injury or mortality. Freshwater fish survive short drops well, provided the receiving pool is deep enough. Many migratory freshwater fish pass up and down drops of a metre or more.

There are no relevant data on British marine fish and the likelihood of damage due to drops in fish launders.

It is not clear whether it is better for a fish to be rapidly washed down a launder back to sea, minimising the exposure time to the various stresses, or to pass more steadily down the launder. This, like most of the other issues addressed here, is a multifactorial problem. Technology such as the Sensor Fish could give insight into a fish’s experience passing through a launder. The Sensor Fish are being used effectively to investigate the impact on fish passage in other situations, for example in irrigation systems (Salalila et al, 2019).

6.2.6 Subject area scoring

6.2.6 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Debris in a fish launder will not affect survival?	3	1	1	**Quality of evidence base** Studies have been carried out in the US on freshwater species. No relevant UK studies were identified. **Applicability of evidence** No published data on British marine species were found. Using artificial debris, the US study did not find a relationship between debris and survival. **Degree of concordance** Not enough studies have been identified to judge the level of concordance.	**Low (5)**
How will the height of a drop impact on fish survival in a fish launder?	1	1	1	**Quality of evidence base** No studies on the effect of drops on British marine fish were identified. **Applicability of evidence** No data identified. **Degree of concordance** No studies found.	**Low (3)**

6.3 Fish lift pumps: ensuring fish friendliness for fish recovery systems

6.3.1 Introduction

Where impinged fish and other organisms return to the sea via fish launders, there must be sufficient slope on the fish launder to allow the free flow of the wash water and the organisms to their release point. With onshore systems, where the fish launder is short, the animals are normally recovered from the screens at a height above sea level that is enough to allow an adequate flow in the launder. With an offshore release point, which may be hundreds or thousands of metres from the screens, additional energy may be required to ensure sufficient flow in the fish launder. One method of gaining the additional energy required is to raise the impinged organisms to a higher starting point in the fish launder system. This additional lift could be provided using fish-friendly pumps. Fish-friendly pump types include Archimedes (a shrouded arch screw), helical and axial screw pumps.

Fish pumps have been used in the USA to remove fish from the forebay and return them to the environment. A review of studies was carried out by EPRI (2004). The authors found high survival rates of fish passing through the pumps, both in laboratory and field situations.

There is a range of literature looking at the survival of fish passing through pumps and turbine blades, but this is generally focused on freshwater or migratory species, and examines healthy fish passing irrigation, drainage and hydropower stations. Organisms entering the fish pumps in a fish launder experience a different environment, and in a different condition, from those generally tested passing the pumps.

A fish in a fish launder is likely to be:

- exhausted
- stressed
- damaged due to:
    - abrasion
    - screen impact
    - barotrauma
- in contact with other animals
- among other debris
- exposed to biocides

This may all impact on the survivability of fish entering a fish-friendly lifting system.

Solomon (2010) carried out a review of Archimedes screw pumps for the safe passage of eels. Solomon identified 2 main areas for damage to fish in a conventional Archimedes screw pump. The first is the entrance where collisions may occur with the blade leading edges. This is where an organism is most likely to get between the blade and the trough. The second is any gap between the blade and the trough along the length of the lifting trough.

The factors identified that affected fish survival are:

- the screw diameter and rotational speed
- the pitch of the screw
- the number of flights (blades). More blades resulted in more impacts with the leading edges
- the design of the leading edge at the entry point
- clearances within the system

Many of these potential impact areas have been addressed in new fish-friendly screw pump designs offered by commercial companies. These include modified leading edges, a shroud around the screw at the entry point, and the pump being designed to work slowly.

Shrouding the screw eliminates gaps between the blades and the trough in which it rotates. This 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) report on shrouded screws installed at Kortenhoef pumping station (FishFlow Innovations 2016), where negligible damage was found on fish passing through the system. Fishtek Consulting (2008) report on an Archimedes screw turbine on the River Dart in Devon, which again showed very little damage to fish passing through it.

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 2017). To date, this has formed best practice for screw pumps.

Several other technologies have been used in fish-friendly pumps such as spiral vane pumps, helical screw centrifugal fish pumps and axial pumps.

A review of fish- and eel-friendly pumps has been provided by Solomon (2010) and Jackson (2014). The focus of the survival studies to date has generally been on freshwater fish, with particular reference to eels in light of the recent eel regulations.

This review could find no reports of the efficiency of fish-lifting technologies within fish return launders, and no indication of survival rates of UK marine species.

6.3.2 Documents reviewed

Fish injury and mortality at pumping stations: a comparison of conventional and fish-friendly pumps (Bierschenk et al. 2019)

In a study of drainage pumps at Köster in Germany, the effects on fish health of pump passages through 4 conventional and one ‘fish-friendly’ pump were investigated. All the pumps caused external fish injuries, leading to direct and delayed mortality. An increase in the speed at which the pump was run increased the damage for all pumps. There were significant differences between pump designs, in terms of mortality. The fish-friendly pump tested caught fewer fish, had a lower occurrence of injuries, but a higher proportion of blunt force damage than the conventional pumps.

Delayed mortality, which was after 72 hours in this study, increased mortality by 9% on average; for perch the increase was 34% over the immediate mortality rate.

The mortality figures are higher than a previous study referenced in the paper by Vis et al. (2013). The authors suggest that there may be differences in fish survival between the field trials and the manufacturers' trials.

Catch‐related fish injury and catch efficiency of stow‐net‐based fish recovery installations for fish‐monitoring at hydropower plants Pander et al. (2018)

This study looked at the impact of holding fish to examine the survival rate at a hydroelectric dam. The authors found highly species-specific variations. They found exposure time was the most influential factor determining catch-related mortality and sub-lethal injuries. After exposure time, higher current speed within the nets and larger biomass of fish within the nets resulted in greater fish damage.

Effects of pumping height and repeated pumping in Atlantic salmon (Salmo salar) (Espmark et al. 2016)

This study looked at the stress levels in farmed salmon moved either once or repeatedly over 3.6 and 5.2 m heights using a vacuum pump. Each pumping event lasted 25 to 30 seconds. There were no moving parts for the fish to impact within the pump, and fish were killed immediately, and a blood sample withdrawn. Fish that were pumped showed some physiological measures reflecting stress responses; there were no differences in the stress levels between fish pumped to different heights.

Comparison of damage to live v. euthanized Atlantic salmon (Salmo salar) smolts from passage through an Archimedean screw turbine (Brackley et al. 2018)

In a study that passed euthanised and live Atlantic salmon (*Salmo salar*) smolts downstream through an Archimedes screw turbine to test for external damage, the authors found that severe scale loss was 5.9 times more prevalent in euthanised turbine-passed fish (45%) than the live fish (7.6%). The patterns of scale loss that were consistent with grinding between the turbine helices and housing trough were observed in 35% of euthanised turbine-passed smolts.

This shows that the condition of the fish might be important as they passed through the Archimedes screw. If the fish are moribund from impingement, they may be more likely to be damaged.

Fish monitoring and live trials. Archimedes screw turbine, River Dart. Phase I Report (Kibel 2007)

In a study on the River Dart in the UK freshwater fish passing down an Archimedes screw were examined. A wide range of sizes of fish were observed. Injury rates were very low, with about 1.4% of smolts showing scale loss.

Fouling and antifouling in other industries–power stations, desalination plants–drinking water supplies and sensors (Henderson 2010)

This chapter reviews the main groups of fouling organisms found on large industrial intakes. It covers both active (fouling growth) and passive fouling (weed, debris, jellyfish or fish), including weed loads on power station screens.

Research into the fish-friendly screw pumps (Vriese 2009)

A trial examining the mortality caused by lifting freshwater fish using a modified Archimedes screw to lift the fish 1 m at 35 $m^3\ h^{-1}$ found no mortalities.

6.3.3 Review synthesis

Several types of pump have been shown to be fish-friendly under certain conditions. Most have been tested in fresh-water environments, often used for drainage purposes (Bierschenk et al. 2019), or as part of power generation systems (Kibel 2007).

Archimedes screws have been shown to be fish-friendly (Kibel 2007, Vriese 2009) but have mainly been assessed for downstream migration of fish through hydropower plants. No data on the behaviour of UK marine fish passing up an Archimedes screw in fish return systems have been found. The effectiveness of this technology is therefore untested for marine species.

Vacuum pump systems such as those tested by Espmark et al. (2016) are used for moving salmon stock from pen to pen in an aquaculture setting. These produced a small stress reaction in the fish, which did not vary with the height to which the fish were pumped.

The fish tested for survival passing through fish-friendly pumps have not had the experience of an impinged fish. The addition of the stressors of impingement could change the behaviour of the fish in relation to the pump and affect their chances of survival.

Fish-friendly pump systems within a fish launder will also have to handle a much larger proportion of trash than clean-water systems. The screening system concentrates up trash many times over its natural density. Power stations can impinge large quantities of weed, jellyfish, ctenophores and other debris, depending on their location:

1. A high percentage of the trash will wash off into the launder with the low power wash of the fish return system.
2. If the high-pressure wash water is also returned to sea via the same system, it will increase the level of trash further.
3. Finally, if the angled rake screen debris is also added, to protect the fish impinged on that system, then even more, larger trash will be in the system.

Weed and other debris loads can be large; when Fawley Power Station was sampled in 1973 (Henderson 2010), maximum weekly weed loads were estimated at 5,100 kg. Ctenophores (comb jellies) can be a significant part of the impinged mass during summer, particularly in the North Sea.

The survival factor that is of relevance here is not just the survival of a fish through the Archimedes screw, with or without debris, but the survival of the fish after it has had all the experiences from impingement up to that point (exhaustion, rapid pressure changes, screen impingement, biocides and handling) and then passes through the lift. Extension of the time during which the fish are exposed to stresses within the launder could be detrimental (Pander et al. 2018).

In summary, no Archimedes screw has been found operating in the marine environment. In freshwater environments, these systems have proved to have low mortality rates (Kibel 2007, Vriese 2009). No relevant survival studies were found where debris and fish were moved together.

6.3.4 Evidence scoring for fish lift pumps

6.3.4 Evidence scoring for fish lift pumps

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Fish injury and mortality at pumping stations: a comparison of conventional and fish-friendly pumps. Bierschenk et al. (2019).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence on freshwater species. **Applicability of evidence** The activities assessed are not power station-related but the data on fish survival through pumps are relevant. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**
Catch-related fish injury and catch efficiency of stow-net-based fish recovery installations for fish-monitoring at hydropower plants. Pander et al. (2018).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence on freshwater species. **Applicability of evidence** The activities assessed are not power station-related, but the data on fish survival are relevant. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**

6.3.4 Evidence scoring for fish lift pumps

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Effects of pumping height and repeated pumping in Atlantic salmon (*Salmo salar*). Espmark et al. (2016).	Paper	5	3	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence on freshwater species. **Applicability of evidence** The activities assessed are not power station-related, but the data on fish survival through pumps are relevant. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (13)**
Comparison of damage to live v. euthanized Atlantic salmon (*Salmo salar*) smolts from passage through an Archimedean screw turbine. Brackley et al. (2018).	Paper	5	5	5	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence on species found in the UK. **Applicability of evidence** The activities assessed are not directly power station-related, but the data on fish survival through an Archimedes screw are relevant. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**

6.3.4 Evidence scoring for fish lift pumps

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Fish monitoring and live trials. Archimedes screw turbine, River Dart. Phase I Report. Kibel (2007).	Report	3	3	3	**Quality of information source** This is a report based on direct empirical evidence on freshwater species found in the UK. **Applicability of evidence** The activities assessed are not directly power station-related, but the data on fish survival through an Archimedes screw are relevant. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**Medium (9)**

6.3.5 Evidence review conclusions for fish lift pumps: ensuring fish friendliness for fish recovery systems

In some of the proposed new nuclear build (NNB) power stations in the UK, the fish return system is some distance from the screens. In this case, raising the fish in the launder may be required to create sufficient slope to transport the fish back to sea. This additional lift could be provided using fish-friendly pumps. Fish-friendly types of pump include Archimedes, helical and axial screw pumps.

At NNB sites, Archimedes screws have been suggested for lifting the fish. There is a range of literature looking at the fish survival of passing through pumps and turbine blades, but this is generally focused on freshwater or migratory species, and is focused on healthy fish passing irrigation, drainage and hydropower stations.

In the right circumstances, Archimedes screws (shrouded screws) are fish-friendly, but the evidence for this in marine species is limited.

No studies on UK marine species were found. It is unclear how marine species will survive the experience, particularly post-impingement.

The effect of marine trash in the screw system is unknown. Power stations can impinge large quantities of weed, jellyfish, ctenophores and other debris, depending on their location. If this is also in the return system, then it will also have to be lifted by the Archimedes screw.

Survival studies are needed to investigate:

- the survival of suitable UK species
- the presence of realistic levels of trash
- the effect of pre-stressing the fish (by impingement, pressure changes)
- the time taken to clear from the trash pit through the screw to the higher launder
- potential effects of crushing or smothering by large debris loads

6.3.6 Subject area scoring

6.3.6 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Are fish lift pumps fish-friendly in a fish return system?	1	1	1	**Quality of evidence base** No studies on the fish lift pumps on British marine fish were identified. **Applicability of evidence** No data identified. **Degree of concordance** No studies found.	**Low (3)**

6.4 Biofouling control, implications for fish return systems

6.4.1 Introduction

The use of biofouling control in power station cooling water systems, and the potential impacts, have been reviewed by several authors (Henderson, 2010, Khalanski and Jenner 2012). To improve organism survival in the fish return system, it is recommended that biocides be applied downstream of the filter screens (Environment Agency, 2005, Bruijs and Taylor, 2012). Environment Agency (2010a) assumed that fish within a recovery system would not be exposed to biocidal treatments during passage through the plant. The document states that it would be permitted if a suitable ecotoxicological risk assessment showed that no harm would result to the fish.

In an onshore intake, even where fouling of the filter screens is an issue, it is possible to limit the exposure of fish and other organisms captured in the fish return system to these biocides by introducing the biocides into the system close to the filter screens. If the wash water used for the fish return system does not contain biocides, the exposure time of the organism will be short, limited to the time it takes for the animal to become impinged. At onshore intakes, the fish launders are normally accessible and all cleaning and maintenance is manual.

With offshore intakes, particularly with fish return systems that return the fish to sea several hundred metres from shore, cleaning and maintenance is more difficult.

If fouling is prevalent in the intake culvert, to protect the cooling water flow to the station, biocides may be introduced close to the intake structure. If this is the case, organisms will be exposed to biocides for the entire time they are exposed to the station. As wash water is taken from the CW intake system, water in the fish return system will also contain biocides.

Efficient clearing for the fish and debris from the screens is important in power stations. Stations have been shut down when screens become blocked (Henderson 2010). In the marine environment, blocking can occur from a wide range of materials, from seaweed, white weed (*Sertularia* sp.), jellyfish, starfish and fish. The risk of debris backing up from the fish return systems and reducing the efficiency of the main CW screens must be avoided.

If the fish return system is in a tunnel hundreds of metres long, this may also become fouled. If this occurs, blockages may become more likely. Since the good operation of the system is critical to the operation of the plant, the station may require some form of biofouling control within the fish return system.

As discussed in section 0, fouling can impact on the survival of animals within the system. The Environment Agency (2010a) report did not envisage that it would be necessary to chlorinate the return system 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 chlorination may be necessary.

Developing robust estimates of the impacts of biocide treatments on the organisms within a fish return system is problematic. It is obviously preferable to use existing data where possible, to save costs and in order to comply with Home Office licensing requirements to minimise unnecessary lethal testing on animals.

To show, by an ecotoxicological assessment, that organisms are not harmed by adding biocides to the return system, testing should ideally include cover a wide range of variables such as:

- all relevant species
- cover the range of life stages and sizes of the organisms that will be in the return system at the site
- test relevant biocidal concentrations
- cover a relevant temperature regime for the species
- cover a relevant salinity regime for the species
- have similar exposure times to animals within the system
- record instant mortality
- record latent mortality
- investigate sub-lethal effects
- test for behavioural abnormalities
- test fish in the condition in which they will enter the return system (post-impingement)

To carry out this testing on the full range of animals caught at a coastal power station in the UK would be impractical.

If the testing cannot be done fully, the question then arises which species to concentrate on. The ideal list of species to test, and the species feasibly available to test are not likely to be the same. The choice of species could vary from site to site and will depend on several factors, including which:

- species are of conservation concern at the site?
- species have statutory protection?
- fish are caught in large numbers?
- species survive the impingement process at a level to make any additional mortality from the return system significant?
- fish are available at suitable sizes for testing?

No papers have been found that give methods suitable for assessing all the factors involved in the exposure of impinged fish to biocides. There have been many studies looking at biocide toxicity (chlorine in particular) at various levels, but these tend to be simple dose-related tests. The impacts of chlorination in a fish return system are multifactorial, with the animals already stressed and potentially injured before being exposed to biocides.

6.4.2 Documents reviewed

Chlorination chemistry and ecotoxicology of the marine cooling water systems in Operational and Environmental Consequences of Large Industrial Cooling Water Systems (Khalanski and Jenner 2012)

The amount of biocide present is often measured as the total residual oxidant (TRO). In this chapter, the authors review the complexity of chlorine chemistry in seawater, and present a review of experimental data on residual oxidant toxicity. They discuss how the acute toxicity of chlorine depends on exposure time. They give values for zero mortality level of total residual oxidant (TRO) chronic toxicity of 0.02 mg l^{-1}. For times lower than 2 hours, they give values of 0.06 mg l^{-1} at 10 minutes and 0.04 mg l^{-1} at 30 minutes. They suggest that some studies have shown that short-term exposures to TRO concentrations of 1 to 10 µg l^{-1} still show lethal or sub-lethal effects. Finally, they suggest that there is no practical chronic toxicity threshold for marine biota.

Cooling water management in European power stations: Biology and control of fouling (Jenner et al. 1998)

Diagram used as Figure 11 below.

6.4.3 Review synthesis

Power plants using continuous chlorination normally try to maintain levels of TRO of over 0.2 mg l^{-1} in the system to prevent fouling. This can be done either by injecting the biocide at high levels early in the system (at the intake or forebay), and allowing it to reduce by chlorine demand as it passes through the system (Figure *11*), or by injecting lower amounts at several points in the circuit.

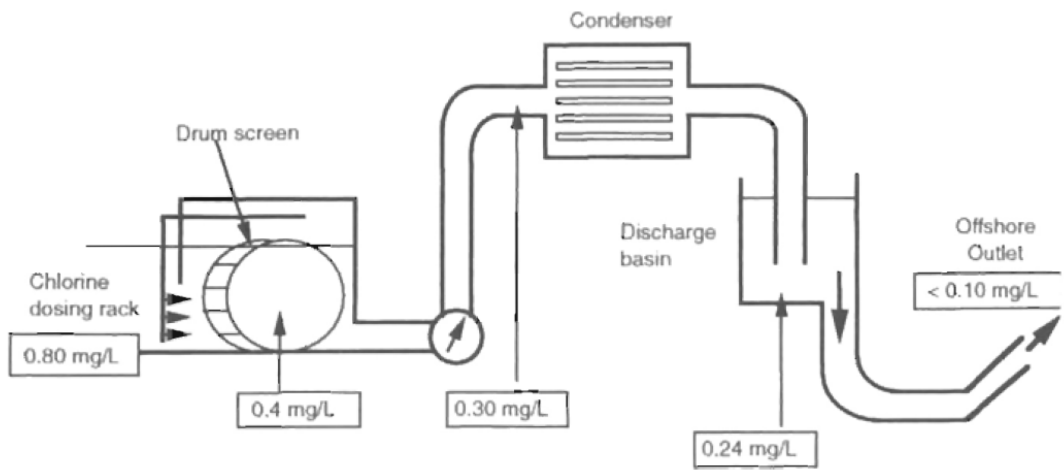


Figure 11: Decay of TRO at the Penly nuclear power station for a chlorine dosage of 0.8 mg l^{-1} (From Jenner et al. (1998)

No studies of chlorine or other biocide impacts have been found that cover the range of environmental and biological conditions that are relevant to biocide toxicity within fish launders.

Since the chemistry of chorine and other halogen-based biocides is complex, the amount of biocide present is often measured as total residual oxidant (TRO). This combines a range of chlorinated and brominated products that are produced when biocides are added to sea water. Chlorine demand is defined as the difference between the level of chlorine added and the residual chlorine at the end of a specified period. This varies considerably with environmental conditions.

Toxicity studies on chlorine are difficult. Khalanski and Jenner (2012) assert that it is not possible to measure TRO levels below 0.01 mg l^{-1} and only specially-designed protocols can produce accurate data in the range of 0.01 to 0.05 mg l^{-1}.

There have been many laboratory experiments looking at individual dosage of biocides on various species. These give useful information in general, but are not relevant to multifactorial situations such as those found in the fish launder of a return system. Given the number of interactions that are possible between the environment, the biology and the biocide, it is probably impossible to carry out laboratory experiments that cover a meaningful range of factors.

6.4.4 Evidence scoring for biofouling control in fish return systems

6.4.4 Evidence scoring for biofouling control in fish return systems

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Chlorination chemistry and ecotoxicology of the marine cooling water systems in Operational and Environmental Consequences of Large Industrial Cooling Water Systems. Khalanski and Jenner (2012).	Chapter of book	5	5	5	**Quality of information source** This is a chapter of a book by a well-respected publisher. **Applicability of evidence** The chapter reviews the complexity of biocide chemistry. **Strength of conclusion** The conclusions of the study are clearly documented, with the authors giving ranges of dose *vs*. concentration of biocides. There is sufficient evidence to give confidence to the conclusions in the text.	**High (15)**

6.4.5 Evidence review conclusions for biofouling control, implications for fish return and recovery and fish risk assessment protocols

The use of biofouling control in cooling water systems is common in power stations. To improve organisms' chances of survival in the fish return system, it is recommended that biocides are applied downstream of the filter screens. If fouling is prevalent in the intake culvert, with the long intake and discharges tunnels proposed at some NNBs, it may be necessary to chlorinate at the intakes to protect water flow into the station. If this is the case, fish in the fish return system will be exposed to chlorine for the entire time in the station from entering the intakes, via the screens, and in the launder before returning to sea. Even where this is not the case, the biofouling will have to be controlled in the fish launder. If the launders are long and have offshore discharges, biocides may be required.

No data on survival of UK marine species in chlorinated fish return systems were identified. Laboratory studies are of limited use as they do not include the full range of stressors the fish are exposed to in a fish return system.

Tests could be carried out at existing power stations that have fish return systems. Onshore systems with release points for the return system close to the station would be easier to test than sites with offshore return points. These systems would allow some of the factors to be examined together. The inshore sites would not have the long passage time of the proposed offshore intakes or the potential pressure impacts. They would have impacts from screens and fish launders, and chlorination could be applied to the fish return system relatively easily.

6.4.6 Subject area scoring

6.4.6 Subject area scoring

Confidence criteria	Quality of evidence base	Applicability of evidence	Degree of concordance	Comments/justification	Overall confidence (Total score)
Biocides in the fish return system will not impact fish survival.	5	3	3	**Quality of evidence base** There is extensive literature on biocides and chlorine in particular. **Applicability of evidence** No data on survival of UK marine species in chlorinated fish return systems were identified. Laboratory studies are of limited use as they do not include the full range of stressors the fish are exposed to in a fish return system. **Degree of concordance** High levels of confidence in chlorine as a single factor, much lower confidence in the synergetic effects within a fish return system.	**Medium (11)**

7 Monitoring protocols

For monitoring protocols to be useful, the questions to be answered must be defined. The protocol for studying whether an intake impacts a single protected species or a species of conservation concern is different from the protocol to study the impact of the intake on the overall population.

Fish and crustacean populations are highly variable, with high within- and between-year variation. For the results of an impingement and entrainment monitoring programme to give robust estimates, the programme needs to sample at a high enough frequency and for a long enough time to capture the natural variation of the site and the species concerned.

The factors affecting impingement work over several different time scales. Local factors that have been shown to influence impingement and entrainment include:

Over a day:

- day or night
- tidal height
- salinity

Over weeks or months:

- seasonality
- spring neap cycles
- temperature
- migration events

Over years:

- prior recruitment
- previous site history (recovery or pollution events)
- climate change

There are also several factors that work at larger scales and are known to correlate with certain species' capture rates, such as the North Atlantic Oscillation and the sun spot cycles (Henderson 2007, Henderson et al 2011).

On top of these variations, power stations do not operate consistently year-to-year. The station must respond to electrical demand, undergo maintenance and respond to other regulatory issues, all of which can affect the amount of water abstracted, and therefore the number of organisms caught.

Given the range of factors that can impact the number of animals captured at a station, a good monitoring programme must have some or all of the following features:

- cover all the species present – note that species of concern vary through time

- cover the entire seasonal pattern
- cover the tidal ranges of the station
- sample both day and night time captures or have an estimate of 24-hour capture
- sample for long enough to understand 'normal' impingement at a site

If species that are rare or of conservation concern are the issue of interest, then sampling may continue all year, but may be more highly focused on particular months of the year when the organisms in question are present. Migratory fish often have quite distinct periods when they will be in the vicinity of a coastal power station.

If the focus is on the overall captures of the site, the samples should be spread more evenly throughout the year (BEEMS 2011, Matson et al. 1988). Murarka and Bodeau (1977) analysed several sampling patterns and concluded that stratified random sampling was the most efficient for estimating the annual catch of a station, suggesting that around 40 samples were needed a year. It should be noted that true random sampling is, in practice, impossible on power stations, because of issues with access to the site, and the necessary involvement of site staff. Generally, sampling is difficult on weekends and bank holidays, and can be impossible during station outages.

The US Electric Power Research Institute (EPRI) has produced some guidance information on monitoring for the US regulatory situation over the years. This may be useful for general reference, but would require care in transferring to UK situations.

If the aim of the sampling regime is to examine between-year variations or long-term trends, then it is possible that regular sampling is a better option, as it allows more powerful time series methods to be used (for example, Henderson and Corp, 1997, Henderson and Magurran 2014, Henderson and Henderson 2017).

For each sampling occasion, data should be collected on the site for the day, including temperature, salinity, number of pumps operating/volume of water abstracted, and the times of the samples. When recording the data from individual samples, the data should be recorded sample by sample and not grouped into a single larger sample. Estimates of 24-hour catches are best done post-sampling, so an individual sample's data should be maintained over the time period for which they were taken. By using a sample pattern of 6 hours of hourly samples combined with an 18-hour bulk sample, both total daily catch and analysis of variations due to tidal cycles or weather can be examined. In addition, shorter-term sampling is better for finding and analysing small or delicate organisms; this allows adjustments to be made to the larger bulk for the loss of small organisms.

When sampling the impingement, the number of fish caught can be large, and sub-sampling is common (BEEMS 2011). It is impossible to give a method of sub-sampling that would work at all intakes, but in general there are 2 methods; sub-sampling temporally, for example only sampling for 30 minutes in the hour, or reducing the volume of the collected sample by division, for example only sorting 50% of the sample. Temporal sub-sampling is only suitable for shorter-term samples (hourly or less). For longer-period bulk samples, just taking half a day's sample is not suitable, without fully understanding the tidal and diurnal factors and how they could influence the catch. In this instance, reducing the sample by division is a better option. A decision on how to handle rare and large fish is often needed in a divisional sub-sample; it is common to have a separate data class for animals taken from the entire sample even when dividing the sample. This helps with rare species, when the frequency of occurrence can be low, and sub-sampling may mean missing a species altogether.

All fish should be counted and weighed or estimated by sub-sampling. Standard lengths should be taken for at least 200 individuals of each species. If sampling over 24 hours, the animals measured should include individuals from both day and night periods. Standard to total length ratio data for each species should be collected over the sampling project for conversion purposes. Individual length-weight data can be informative if time allows, depending on the aims of the survey (Henderson and Seaby, 2005, Henderson et al 2011).

Invertebrates are normally counted and weighed, unless important at the site. An example of a species that might be measured is the lobster (*Homarus gammarus*), as it is commercially valuable.

Weed and trash data can be valuable, and is best separated into categories such as green weed, brown weed, white weed, plastic, ctenophore, jellyfish, terrestrial. All sites will be different.

There are numerous other pieces of data that may be required depending on the survey aims. These might include sex ratio, condition, biological samples, swim bladder condition, or vitality at point of capture.

7.1.1 Documents reviewed

Methodology for the measurement of impingement (BEEMS 2011)

This document gives recommendations for the sampling effort to estimated annual losses due to impingement and entrainment. The authors suggest that 40 sampling occasions per year is common in US studies, and suggest this as a minimum sampling effort. They suggest that tidal and diurnal biases can be avoided by working over 24 hours, and that longer-term bias is eliminated by the randomisation of the samples. This approach has been followed during the recent studies relating to new nuclear build (NNB) sites. They discuss how sampling patterns and efforts might vary depending on the aims of the study.

Reliability of impingement sampling designs: An example from the Indian Point Station (Mattson et al. 1988)

Analysis of 4 years of daily sampling at Indian Point Power Station on the Hudson River, USA allowed several sampling designs to be tested. 3 sampling regimes were analysed:

1. random
2. seasonally-stratified (3-month periods)
3. empirically-stratified (based on trends in daily impingement variation).

For all regimes, the precision of the estimate improves logarithmically for each design as more days in the year were sampled. Precision went up in order of sampling design from 1 to 3. By randomly sampling from within the data, the authors were able to get an estimate of reliability of the 2 stratified methods. They found that the 95% confidence limits around the estimation enclosed the true mean for 93 to 95% of the time when the sampling effort reached 20 to 30% of the available days. For the ongoing sampling, an effort of 110 days a year was chosen, with the samples stratified in 4 seasonal strata.

Sampling designs and methods for estimating fish-impingement losses at cooling-water intakes (No. ANL/ES-60) (Murarka and Bodeau 1977)

This report examines a range of sampling protocols for impingement. The authors model impingement to look at how many samples are needed to get to a certain level of confidence given different levels of variation in a species. They show that compared to a simple random sampling scheme, stratified systematic random sampling schemes yielded better estimates of fish impingement numbers.

The role of climate in determining the temporal variation in abundance, recruitment and growth of sole (Solea solea) in the Bristol Channel (Henderson and Seaby 2005)

Community level response to climate change: the long-term study of the fish and crustacean community of the Bristol Channel (Henderson et al. 2011)

These papers are examples of the use of a long-term data set gathered using impingement data. The authors use a short, regular 6-hour sample, always from high water to low water, taken midway between springs and neaps. The site is unusual in having very little difference between day and night captures, due to the extremely high sediment loads. Light does not penetrate more than a few centimetres into the water. After initial intensive study, the regular sampling was designed to be sustainable over a long period.

7.2 Monitoring and assessment protocols for fish recovery and return facilities

Fish entering a station equipped with a fish return system can have 4 possible fates. They may be returned to sea via the fish return system, they may be washed into a trash basket for disposal, captured on the coarse trash screens and removed via a rake system, or if they are small, pass through the station and back to the sea.

To represent the 24-hour catch of the station, all possible fates must be quantified. To understand the mortality caused by the station, the condition of fish returning to sea needs to be assessed.

Sampling for fish mortality within the fish return systems should be carried out as late in the system as practicable. For general monitoring on site, this should be just before the fish leave the site in the fish launders. For experimental studies on the factors influencing mortality, ideally sampling would take place after the return to sea.

Some of the advantages and disadvantages for the 2 sampling locations are outlined below.

From within the launder on site	**From return release point**
Pro - safe – working with a controlled environment	Con - working in open water
Pro - not very weather-dependent	Con - highly weather-dependent
Pro - lower cost	Con - higher cost
Con - additional capture mortality	Pro - lower additional capture mortality
Con - not full station experience for organisms	Pro - full station experience for organisms

The collection methods are largely determined by the location that has been decided upon for sampling.

For end of return systems, some form of large net or cage is appropriate.

For sampling from within the launder, either a purpose-built sampling area can be provided, or nets can be fitted within the launder to collect fish. Purpose-built sampling locations are preferable, as they can reduce the possible collection mortality due to nets within the launder, and allow larger samples to be collected.

Survival studies

Factors that impact on mortality rates include the environmental condition at the time of capture, the size of the fish, the station's operational status, and the population health.

With the current state of knowledge of mortality rates, it is suggested that all species be observed to look for mortality. Some species are assumed to have 100% mortality (for example, clupeids) but these assumptions are made on old-fashioned screen systems, with many features that may not reach best practice on a new screening system. For understanding impingement mortality in the future, all data gathered will be useful.

Survival studies should be over several days. In the US, 96 hours has become the standard length of trial. Much of the mortality will occur either immediately or within a few hours, but some fish can take a long time to succumb to the damage caused by impingement. It is impractical to carry out a survival study on every animal impinged at a station, so decisions will have to be made on species to be tested, the number to test, size ranges and how to simulate the post-fish return system environment.

No survival studies have been found for British marine species on similar intakes to those proposed at the NNB power stations in the UK.

Focus should be given initially to the top 20 or so species impinged at a site. This will normally include over 95% of the numbers and biomass of the animals caught. There are several studies that show that mortality can happen over much longer periods (Olla et al. 1997, Varsamos et al. 2006, Turnpenny 2014b, Teffer et al. 2017), but the testing needs to be practical on an industrial site. Where the opportunity arises, survival of other species should be tested. If there are species that are of concern (rare or protected), these should be tested whenever they are caught, as they will tend to be less frequent than other species. Survival studies must be tied to other data, such as date, water temperature, salinity and initial fish condition, as well as station-dependent variables such as pumping rate, chlorination. Survival tests should include the full range of animals caught, and cover the full seasonal pattern. It is possible that the time of year will affect the mortality rate. 96 hours is a reasonable balance between cost and difficulty of keeping animals alive and observing latent mortality.

New methods that may give additional insight are presented by Wu et al. (2015), which allow the real-time monitoring of fish stress. This appears to be suitable for laboratory-based studies of some of the stressors involved in fish impingement and entrainment.

A second system allows the level of predation to be examined (Halfyard et al. 2017), with tags that activate once they have been eaten. These could be used to understand the fate of fish released from a fish return system.

Documents reviewed

Survival studies

Capture severity, infectious disease processes and sex influence post-release mortality of sockeye salmon bycatch (Teffer et al. 2017)

In this study, the authors found that the stress of biopsying and gillnet entanglement on returning Stuart River salmon significantly increased the mortality of the salmon several days post-treatment. For the biopsied animals, mortalities occurred 10 to 15 days after release into the river. Mortality of net-entangled animals occurred 5 to 10 days after release. Increasing the length of the gill net entanglement increased the mortality rate. The female fish died more frequently and faster than the male fish. The study also examined a range of pathogens in the fish, at capture and at death. The authors found that some species of pathogen increased in relation to the amount of stress the salmon had experienced, suggesting that these infectious agents are related to the mortalities.

New methods

Fish stress become visible: A new attempt to use biosensor for real-time monitoring fish stress (Wu et al. 2015)

The development of new biosensors opens possibilities to examine the individual’s experience of the process. These are not yet suitable for field trials.

Evaluation of an acoustic telemetry transmitter designed to identify predation events (Halfyard et al. 2017)

This is an interesting development that may allow the estimation of increased predation after release of fish. The tag used was activated by the digestion process in a fish. This could give an insight into the level of predation experienced by fish being released from a fish return system.

7.2.1 Evidence scoring for monitoring protocols

Survival studies

7.2.2 Evidence scoring for survival studies

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Capture severity, infectious disease processes and sex influence post-release mortality of sockeye salmon bycatch. Teffer et al. (2017).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper and based on direct empirical evidence on freshwater species not found in the UK. **Applicability of evidence** The activities assessed are not power station-related, but the data on the length of time needed in fish survival experiments are relevant. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**Medium (11)**

7.2.2 Evidence scoring for new methods

Document	Piece of evidence	Quality of information source	Applicability of evidence	Strength of conclusion	Comments/justification	Overall confidence (total score)
Fish stress become visible: A new attempt to use biosensor for real-time monitoring fish stress. Wu et al. (2015).	Paper	5	3	1	**Quality of information source** This is a peer-reviewed paper of a new method to monitor stress in real time. **Applicability of evidence** The method might in future allow studies of fish as they experience stressors to happen in real time. Different stressors could be applied in sequence to see if they are synergistic. **Strength of conclusion** The conclusions of the study are clearly documented, but the technology is still being developed.	**Medium (9)**
Evaluation of an acoustic telemetry transmitter designed to identify predation events. Halfyard et al. (2017).	Paper	5	3	3	**Quality of information source** This is a peer-reviewed paper. **Applicability of evidence** The technology might allow the predation of fish post-impingement to be measured directly. **Strength of conclusion** The conclusions of the study are clearly documented, there is sufficient evidence to give confidence to the conclusions in the text.	**Medium (11)**

7.2.2 Evidence review conclusions for monitoring and assessment protocols for fish recovery and return facilities

Monitoring protocols for estimating the catch of an intake are reviewed. It is important that the reason for the monitoring is defined before sampling patterns and efforts can be decided. A minimum sampling regime is suggested that covers entire seasonal pattern, includes all the species present, samples both day and night time capture and has an estimate of 24-hour capture, covers the tidal ranges of the station, and samples for long enough to understand the 'normal' impingement at a site. Monitoring of species of concern might require higher sampling frequency at the times of the year when they are present.

The methods used in survival studies of fish captured by intakes are reviewed. No survival studies have been found for British marine species on intakes similar to those proposed at the NNB power stations. Some general guidance is given on species selection, length of study and environmental conditions that might vary the results.

Some new technologies are examined that would give insights into a fish's experience. The Sensor Fish is a promising system for measuring the conditions experienced by an animal as it passes through a system.

7.3 Monitoring and assessment protocols for fish deterrent effectiveness

7.3.1 Introduction

Fish deterrent systems tend to be bespoke, with installations designed for each intake. As such, the results from one site might not be reliably reproduced at a second site, even though the general layouts are similar. Therefore, to ensure the level of protection is suitable, if a fish deterrent system has been fitted to an intake, the efficiency should be evaluated once the station is operating. Many of the factors outlined in section 7.2 on monitoring apply to the sampling for fish deterrent efficiency.

There are several factors that must be considered if the survey's aim is to look at the efficiency of the fish deterrent system, and some should be decided upon before the trial to avoid bias.

For example, if the test is going to involve discrete periods when the deterrent is on and off, then the following must be decided:

1. Setting length and pattern of the on- and off-period of the deterrent to avoid bias - matching tidal height, day/night and other short-term variations.
2. Consider resident fish in the system – are large numbers of fish resident in the system? How long to clear these fish?

3 How to treat the periodic arrival of shoals of pelagic fish. The numbers of animals caught can be dominated by the arrival of a shoal of fish in the vicinity of the intake. How this is to be analysed should be determined before the experiment.

4 How measurement of reduction is undertaken. Is the test designed to find the reduction for a single species, representative species or all species?

Deterrence can act in different ways at different points in the cooling water system. A deterrent could deter fish away from the intake altogether, or it can deflect them into a bypass channel or fish return system. Monitoring of effectiveness should include the fish impinged on the screens and the fish passing through as well as those entering the bypass or other safe route.

In most cases, the analysis should be carried out over a short period of intensive work. To get sufficient data to make the measurement statistically significant, generally the periods of the year when most fish are present are likely to give the most useful results. If the reduction is required for a migratory species, obviously the sampling must be carried out at the period of highest risk to that species.

It is possible for the efficiency of the deterrent system to vary over the year. Different-sized fish have differing sensory and swimming abilities. For example, if a small fish is deterred by a system, but its avoidance reaction does not occur until it is in a stream of water that is entering the intake faster than it can swim, it will still be impinged. If the same animal were large, then it may be able to escape.

Given the possibility of seasonal variations and the relatively-untested nature of fish deterrence over the lengths of time the NNB intakes are expected to be in operation, it may be advisable to test them at different points in the year, and to test them over a longer period.

Some questions that were not answerable from the literature at present were:

- do fish deterrent systems age badly – is there a drop in efficiency as loudspeakers or lights become fouled or worn?
- what percentage of the time are all units in a system working, after one year, 5 years, 50 years?
- do fish become acclimatised to the system?
- what is the environmental impact of adding noise to the marine environment?
- what will happen if the system fails to meet the required reduction?

The number of samples needed to judge whether a system is working or not very much depends on the natural fluctuations in catch at a site. If a site catches consistent numbers of fish from day to day, and the difference required to meet the specification is small, relatively few paired samples would be needed. If the samples are highly variable and the difference required to meet the specification is large, many paired samples may be needed.

To give an indication of the amount of sampling required, trials of a fish deterrent system at Hinkley Point in Somerset were designed to have 22 days of sampling (Turnpenny et al. 1994). As the location of the speakers was moved half way through the survey, the final length of the survey was 42 days of sampling (19 test days, 23 control days). For each sample day, the deterrent system was switched on or off 18 hours before the 6 hours of sampling were carried out. The results showed an increase in fish catches for 'sound on' days of 47% and 58% in the 2 halves of the survey.

At Hartlepool (Turnpenny et al.1995), the sampling effort was programmed to test a trial fish deterrent system for 30 days (15 control and 15 experimental). Again, the sound projectors were moved, and the trial extended. The final trial lasted 44 days. The sound system ran a day on/day off pattern through most of the trial. The 2 trials analysed total fish, some individual species and 2 groups of species. The smallest-detected significant difference between the control and the experimental catch rates was when they varied by around 35%. The highest difference observed that was not significant was 54%. Interestingly, the effectiveness was observed to decrease the longer the trial went on.

Maes et al. (2004) studied the fish deterrent system at Doel Power Station in Belgium. The trial consisted of 15 48-hour trials between October 1998 and October 2001, all in winter, except for one June sample in 2000. The deterrent system was always active on the first day and off on the second. The trial shows how the variability of the species over the year can affect the ability of the trial to detect significant reductions. This sampling effort could detect a significant 37% decrease in flounder, but a 75% reduction in mullet was not significant.

Transit and residence time of fish within the system

Transit time is the time the water, and anything in the water, will take to travel from the intake to the screens. It can be estimated by putting some obvious neutrally buoyant object into the intake and observing the time between release and recapture at the screen. Not all objects put into the system will arrive at the same time, as objects will get caught in eddies, for example. The arrival pattern is often a left-skewed curve, with a long tail of objects arriving, having been delayed in the system. The longer the system, the wider the spread of arrivals.

The residence time is related to the transit time, but applies to active organisms. If a fish swims actively against the current or moves into any slower or stationary water in the system, it will take longer to arrive at the screens than a passive object. Some species such as conger eel (*Conger conger*) can live within the system and effectively have an infinite residence time.

At Hinkley Point B the residence time of the system has been assessed in several ways. Henderson and Holmes (1987) used marked shrimp (*Crangon crangon*) to calculate the transit and residence times of the system. For Hinkley B shrimp this was about one hour. In 1993, Turnpenny et al. (1994) used salt water-conditioned rainbow trout (*Oncorhynchus mykiss*) to see how long more active swimming species took to arrive at the screens. They introduced 25 fish on each of 2 days into the cooling water (CW) system. 24 and 32% arrived at the screen in the first hour, and after 5 hours 64 to 76% had been recaptured. No other fish were subsequently recaptured.

Turnpenny et al. (1994) used a further method to estimate the rate of clearance from the screens using sprat shoal ingresses. It was assumed that since sprat are shoaling animals, most of the fish would be captured by the intake in a relatively short time. By looking at the decline in the sprat numbers on the screens, after the peak ingress of sprat, an exponential decline was calculated. This indicated that the system cleared about 60% of the fish every hour, giving a 95% clearance in 5 hours.

At Doel, Maes et al. (2004) used goldfish (*Carassius auratus*) as an obvious marker. This station has a 540 m pipe from the intake to the screen. By releasing 246 goldfish, measuring between 7 and 23 cm in total length, into the cooling water inlet the study found that 69% of the fish were recaptured after 20 minutes, and 80% after one hour.

7.3.2 Evidence review conclusions for monitoring and assessment protocols for fish deterrent effectiveness

Monitoring approaches of fish deterrent systems is reviewed here. Many of the features of the fish impingement monitoring assessment also apply to monitoring of fish deterrent systems. The additional factors that need to be considered are discussed. The sampling effort required to find differences in capture rates is examined.

Transit and residence times are discussed, and some methods of measuring or calculating them for a site are indicated.

8 Fish population considerations

It is possible to consider many different species to see what size of population should be used in the environmental impact assessment. In this section, 5 important species are chosen to illustrate the issue.

Migratory fish populations are often localised around the British coastline. Shad (Jolly et al. 2012, Gerard et al. 2017) and salmon (Griffiths et al. 2010) in the Bristol Channel will generally come from the Severn Estuary population.

For the resident species found around the coast, there is good evidence that local populations exist. Whiting in the Bristol Channel and Severn Estuary form a meristically-distinct sub-population (Potter et al. 1988) which, for stock assessment purposes, is part of the much larger International Council for Exploration of the Seas (ICES) Celtic Sea stock in map area Division VIIf. For sprat, Henderson and Henderson (2017) state that the meristic and seasonal distribution studies indicate that the Bristol Channel and Severn Estuary hold a local population. Potter and Claridge (1985) report that the mean number of fin rays and vertebrae of Bristol Channel sprat differs from that of other British west coast sprat populations. Fox et al. (1999) show that the Thames and Blackwater hold a separate herring spawning population from the main Downs breeding stock.

Genetic studies have increased our level of understanding of how the marine species' populations are structured. Hauser and Carvalho (2008) state that these studies have "contributed to the discovery of extensive genetic population structure in many marine species, overturning the notion of large, essentially homogenous marine populations limiting local adaptation and speciation." In this paper, they review the size of the estimated effective population sizes and find that they are 2 to 6 orders of magnitude smaller than census sizes that are usually used in assessing impacts.

In recent genetic studies on the cod in the Skagerrak, Norway, Jorde et al. (2018) suggest that coexisting cod come from 2 separate populations. Roney et al. (2018) study 2 spatially adjacent (<10 km) populations of cod that are distinguished by differences in genetics and life history from inner- and outer-fjord populations in Norway. The authors suggest that spatial mismatches exist between management and biological units. Similar findings have been found for the New England stock of cod (Cadrin et al. 2014), where it is suggested that the stock is managed as 3 stocks. Rogers et al. (2017) shows that a spatially-structured model with local population dynamics had better predictive ability than assuming a homogeneous population.

Considerations should be given in assessments as to whether there are distinct locally important populations contributing to the wider species populations of fish, as there is evidence for such local populations within marine and estuarine species.

9 Conclusions and recommendations

9.1 Conclusions

This report concludes a series of reviews on measures to protect biota that may help inform consideration of proposals for turbine condenser cooling water systems for nuclear power stations, particularly the planned new build nuclear power stations in the UK. An initial scoping report (Environment Agency 2018) briefly reviewed information on 14 topic areas to determine the information sources available since a previous review was published in 2010 (Environment Agency 2010a). Subsequently 3 topics identified as of high concern were reviewed fully (Environment Agency 2019). These 3 topics were: fish behavioural deterrents, the approach of international regulators, and fisheries impact assessment methods. The findings of that review are briefly summarised within this current report.

This report reviews and examines in detail the following 12 remaining topics covered in the scoping report relating to 4 areas of cooling water use, and assesses the confidence that can be placed in the existing evidence. The topics are as follows:

Intakes - design and location:

1. optimising cooling water intake siting to minimise impacts on aquatic biota
2. intake head designs
3. approach/escape velocity

Passage through the station – excluding screening:

4. cooling water system tunnels: pressure change effects
5. forebay and screen well design, including hydraulic conditions
6. cooling water systems downstream of fine screens

Screening and survival:

7. onshore screening, including fish recovery facilities
8. fish return launders and discharge head design
9. fish lift pumps: ensuring fish-friendliness for appropriate fish recovery and returning dependent species
10. biofouling control

Monitoring protocols:

11. monitoring and assessment protocols for fish recovery and return facilities
12. monitoring and assessment protocols for fish deterrent effectiveness

The review has reached the following conclusions.

Intakes - design and location:

- **Optimising cooling water intake siting to minimise impacts on aquatic biota**: The decision on whether an intake near shore or further from shore is preferable requires site-specific data. The balance between different locations may be decided based on which of the fish in the community is of greatest concern. We do not have the data to resolve the differences in density of these fish in coastal waters in the UK. Arguments made based on reducing the impact of the intake should be based on high-quality site-specific studies.
  For individual-based models (IBMs), we conclude that they are not yet robust enough to predict the capture rates of an intake from a model alone. IBMs may help if the decision on where to place the intake is based on one or two of the well-studied species. The knowledge gained by building IBMs and comparing them to the behaviours of animals in the environment is valuable.
- **Intake head designs**: A Low Velocity Side Entry intake (LVSE) is an elongated, rectangular, capped intake which is orientated with its long axis aligned with the local currents. No direct evidence of the likely efficiency of this type of intake at reducing fish entrapment was found. Using fish swimming ability to estimate the capture of fish at an LVSE intake, the reductions in impingement are predicted to be about 16% from a given baseline for the species that respond to the water velocities (Hinkley B data was used as the baseline). This intake type will not provide a reduction in entrainment rates. The NNB cooling water intakes are likely to be several times larger than the Hinkley B intakes, so actual catches at a site will potentially increase.
  No studies were found on the effect of water being drawn into the side of a long intake such as the LVSE intake. An applied study that investigated a side-drawing intake would help to give confidence in using swimming ability as a proxy for the vulnerability to capture.
- **Approach/escape velocity**: Approach velocities influence the likelihood of a fish being able to escape an intake. The lower the velocity, the higher the proportion of the fish that can escape. However, just because a fish is theoretically able to escape, does not mean that it will. Several studies suggest that even after escape there are sub-lethal impacts on fish that have been stressed by prolonged swimming efforts. Shoaling fish lose coherence and have lowered avoidance responses to predators. Some studies have shown higher predation rates on stressed fish. Few studies have been carried out on UK species.

Passage through the station – excluding screening:

- **Cooling water system tunnels: pressure change effects:** Rapid pressure changes in fish can cause injury as gases within the body expand. This is known as barotrauma, and is related to the depth from which a fish is raised. Few studies on barotrauma were found on species that are caught at UK intakes. Barotrauma is not always a mortal injury. Cod have been shown to recover well after suffering a burst swim bladder, particularly when the fish was able to return to depth soon after the injury. Fish with barotrauma injuries can show sub-lethal behaviour

and physical changes, with damage to the eyes and digestive tract common, along with a loss of equilibrium and buoyancy control impacting foraging behaviour, predator avoidance, increased stress levels and potentially-increased infection risks resulting in latent mortality. Barotrauma is only one part of the stress on an animal passing through a power station, and other stresses experienced by the fish will probably be synergetic.
Moving intakes into deeper water would increase the likelihood of barotrauma on fish caught at the station.

- **Forebay and screenwell design, including hydraulic conditions:** Water entering the forebay is normally moving rapidly and can be highly turbulent. The Environment Agency report (2010a) indicated that energy dissipation throughout the system should be kept at or below 100 Wm^{-3}. This is probably not a practical level in an intake forebay. Turnpenny (2014a) suggests that the US Department of Energy's (USDOE) 'environmentally friendly' turbine programme shear stress fish injury threshold of 1,600 Nm^{-2} was appropriate. This value could be too high for marine species; there is only one data point below 774 Nm^{-2} for a fully-marine species and that is for the sole, generally considered a hardy species. At shear stresses of 1,920 Nm^{-2}, sole, whiting and bass all showed high levels of damage and mortality. Herring were found to be unable to withstand the lowest shear stress tested. No data were found related to shear stress for most British marine fish.
  The effects of turbulence could increase the number of times a fish encounters a solid object within the system. No data were found related to turbulence and injury for British marine fish.
- **Cooling water systems downstream of fine screens:** Little work has been published on entrainment survival in the UK in recent years. Survival on entrained animals in power stations is difficult to measure. Longer intake and outfall pipes increase the length of exposure of the organism to the potentially-harmful effects of the power station cooling systems, particularly to the warmed water present in the tunnel after the condensers. This could increase mortality rates in entrained animals. Sub-lethal effects were found in young fish that had been thermally stressed. Investigations into the actual experience of an animal passing through a station, and its impacts, are needed. New technologies such as the Sensor Fish could give insights into the pressure, temperature and mechanical experience of an entrained animal.

Screening and survival:

- **Onshore screening, including fish recovery facilities:** Once a fish enters the forebay of a station with an offshore intake it cannot generally escape. Automatically-raked bar screens in the forebay, in front of the main travelling screens, are common at newer direct-cooled power stations. If a fish is too large to pass through the rake screen it will die, unless it is captured and released. Fish-friendly rake systems are sold by several companies. No published evidence could be found for fish-friendly rake systems for UK marine species. This is an area that needs research.

- **Fish return launders and discharge head design:** Little research has been done on the importance of the various stages that make up a fish return system. The system must be large enough to handle the largest fish caught at the station, including those from the fish-friendly rake system.
  The effects of debris within the fish return system on injury and survival rates are unknown for British marine fish.
  Physical drops within the system are a potential source of injury or mortality. Freshwater fish survive short drops well, provided the receiving pool is deep enough. There are no relevant data on British marine fish and the likelihood of damage due to drops in fish launders.
- **Fish lift pumps: ensuring fish-friendliness for appropriate fish recovery and returning dependent species:** In some of the proposed NNB stations the fish return system is some distance from the screens. In this case, raising the fish in the launder may be required to create a slope that can transport the fish back to sea. This additional lift could be provided using fish-friendly pumps. At NNB sites, Archimedes screws have been suggested for lifting the fish. There is a range of literature looking at the survival rates of fish passing through pumps and turbine blades, but this is generally focused on freshwater or migratory species, and on healthy fish passing irrigation, drainage and hydropower stations. No studies on the survival of UK marine species passing through fish lift systems were found. It is unclear how marine species will survive the experience, particularly post-impingement. Studies are needed on fish survival rates which examine the conditions that will be found in a working fish return system.
- **Biofouling control and fish return systems:** Biofouling control in cooling water systems is common in power stations. If fouling is prevalent in the intake culvert, with the long intake and discharges tunnels proposed at some NNB stations, it may be necessary to chlorinate at the intakes to protect water flow into the station. If this is the case, fish in the fish return system will be exposed to chlorine for the entire time in the station. Even where this is not the case, the biofouling will have to be controlled in the fish launder. If the launders are long and have offshore discharges, biocides may be required.
  No survival studies of UK marine species in chlorinated fish return systems were identified. Laboratory studies are of limited use as they do not include the full range of stressors the fish is exposed to in a fish return system. Experiments on existing stations are suggested.

Monitoring protocols:

- **Monitoring and assessment protocols for fish recovery and return facilities:** Monitoring protocols are reviewed. The reason for the monitoring needs to be defined before sampling patterns and efforts can be decided. A minimum sampling regime is suggested, and guidance given on the data to be gathered during samples. Monitoring of species

of concern might require higher sampling frequency at the times of the year when they are present.
Survival studies are reviewed. No survival studies have been found for British marine species on intakes similar to those proposed at the NNB sites. Some guidance is given on species selection, length of study and environmental conditions that might vary the results.

- **Monitoring and assessment protocols for fish deterrent effectiveness**: Monitoring of fish deterrent systems is reviewed. Many of the features of the fish recovery and return monitoring assessments also apply to the monitoring of fish deterrent systems. The additional factors that need to be considered are discussed. The sampling efforts required to find differences in capture rates are examined.
Transit and residence times are discussed, and some methods of measuring or calculating them for a site are indicated.

9.2 Recommendations

This review looked at a wide range of issues relating to large-scale industrial intakes. Some of the subject areas are specific to these types of intakes (for example, intake head design) and are unlikely to be researched by the academic community. Other areas overlap with similar issues in other fields, (for example, barotrauma in fishing), and, where this is the case, re-analysis of the existing literature may be informative.

There are many stressors potentially experienced by a fish as it passes through an intake system. There is more information available on these effects (for example, bypass systems, fish lift, handling) on the migratory fish species, particularly the salmonids, than on the fish species from the inshore community. It is unclear how the marine and estuarine species differ in their tolerance to these types of stresses.

It is recommended that the evidence for the topics discussed within this review is developed and expanded upon, by carrying out the following activities, or gaining further insight from the published literature:

- Investigations into the LVSE intakes to corroborate whether the proposed intake would behave as predicted in terms of fish capture reductions. A study investigating a side-drawing intake would help give confidence in the use of swimming ability as a proxy for the vulnerability to capture.
- A study on the lethal and sub-lethal impacts of single and multiple exposures to the stressors involved in escape and entrapment by an intake on relevant fish species would help understand the direct and indirect effects of cooling water abstraction. Fish undergo a series of stressors during impingement and entrainment, and the relationships between them are not understood.
- Shear stress testing is required to understand the amount of damage that could be caused to fish by turbulence in the cooling water system of a power station. No data were found related to shear stress for most British marine fish.

- The effects of turbulence could increase the number of times a fish encounters a solid object within the system. No data were found related to fish behaviour, turbulence and injury for British marine fish.
- Investigations into the actual experience of an animal passing through a station, and its impacts, are needed. New technologies such as the Sensor Fish could give insights into the pressure, temperature and mechanical experience of an entrained animal, and should be investigated.
- No published evidence could be found for fish-friendly rake systems for UK marine species. This is an area that needs research.
- The effect of debris within the fish return system and its effects on injury and survival are unknown for British marine fish.
- There are no relevant data on British marine fish and the likelihood of damage due to drops in fish launders. Experiments into the height of drop that marine fish can withstand, and the effects of the depth of the receiving pool, are needed to give guidance on fish launder design.
- No studies on UK marine species passing through fish lift systems were found. It is unclear how marine species will survive the experience, particularly post-impingement. Studies on fish survival are needed, which examine the survival rates of fish in the conditions that will be found in a working system.
- No survival studies on UK marine species in chlorinated fish return systems were identified. Laboratory studies are of limited use, as they do not include the full range of stressors the fish is exposed to in a fish return system. Experiments on existing stations are suggested.

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List of abbreviations

BAT	Best available techniques
BEEMS	British Energy Estuarine and Marine Studies
CCGT	Combined cycle gas turbine
CEGB	Central Electricity Generating Board
CW	Cooling water
CWS	Cooling water systems
EALP	Equivalent area of lost production
EAV	Equivalent adult value
EIA	Environmental Impact Assessment
EMU	Entrainment mimic unit
EPRI	Electric Power Research Institute
ETM	Empirical transport model
FRR	Fish recovery and return systems
HPC	Hinkley Point C
HPF	Habitat production foregone
IBMs	Individual-based models
ICES	International Council for the Exploration of the Sea
LED	Light emitting diode
LVSE	Low Velocity Side Entry
PTM	Particle tracking model
NNB	Nuclear new build (UK Programme)
SONGS	San Onofre Nuclear Generating Station
SDT	Signal detection theory
TRO	Total residual oxidant
USEPA	United States Environmental Protection Agency

Glossary

Abiotic	Devoid of life, sterile, not derived from living organisms.
Allostasis	The process of achieving stability (statis) through change in the body through physiological or behavioural change.
Approach/escape velocity	The minimum velocity (speed of swimming) which will allow for the fish to swim away from the pumped water intake current.
Barotrauma	Injury or mortality to fish (and other aquatic organisms) caused by pressure changes; these changes may be the result of, for example, turbine or pump operation, or from rapid ascent to the surface. Rupturing of the swim bladder (in fish species with a closed swim bladder) is the most common effect, though other forms of injury may also occur.
Bathymetry	The measurement of depth of water in oceans, seas or lakes.
Benthic	Relating to or occurring at the bottom of a body of water.
Biocide	A chemical additive designed to kill biota causing fouling in the cooling water system.
Biofouling	The accumulation of microorganisms, macroorganisms, plants, algae or animals in or on underwater pipes and other structures.
Biota	The animal and plant life of a particular region, habitat or geological time period.
Biotic	Resulting from, or relating to, living organisms.
Clupeids	Pelagic fish of the Clupeidae family, which includes herrings, sprats, shads, and sardines.
Cyprinids	Freshwater fish of the Cyprinidae family.
Diadromous fish	Fish species that spend part of their lifecycle in fresh water and part in salt water.
Epibiotic	Living on the surface of living plants or animals, usually parasitically.
Empirical transport model	A model system of the transport of fish in cooling waters based on measurements or observations.
Equivalent area of lost production (EALP)	This concept allows 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.

Equivalent adult value (EAV)	This concept puts catches via entrapment into the context of adult populations by estimating the likely future adult value of a juvenile fish had it avoided entrapment. This allows the biological value of fish at different ages to be compared
Entrainment	The passage of organisms through a cooling water system
Entrapment	Situations where fish and shellfish are unable to escape from the cooling water intake. They must go on to be impinged or entrained.
Fish return launder	A trough or chute through which fish are returned from the screens of a cooling water system to the water body.
Fishway	An engineered fish ladder or pass system to allow fish to travel up or downstream in a channel separated from the turbine or other man made obstacle.
Forebay	An artificial pool of water, forming a reservoir, in front of a larger body of water, which may be natural or man-made.
Habitat production foregone (HPF)	The cost of replacing the production lost (‘foregone’) by producing new, equivalent habitat; restoration that replaces the lost production.
Hormesis	A biphasic dose response of an organism to a chemical where low dose is beneficial and high dose is toxic.
Ichthyoplankton	The eggs and larvae of fish, which are mainly found in the upper 200 m of the water column.
Impingement	The physical contact of a fish with a screen or other barrier structure as a result of intakes that do not allow the fish to escape.
Meristic	Meristic features are countable structures of fish such as fin spines and rays, gill rakers, or lateral line scales, for example.
Moribund	Being in the state of dying, approaching death.
Motile	Of organisms, capable of motion.
Necropsy	Surgical examination after death.
Operculum	A flap covering the gills of bony fish.
Osmolality	The relative concentration of a substance in a fluid (water).
Pelagic	The open water zone of ocean or lake waters, not the bottom or near shore zones.

Periphyton	Freshwater organisms (such as algae, cyanobacteria) attached to or clinging to plants and objects protruding above the bottom sediment.
Photic	Relating to light.
Photic zone	The part of the ocean or lake water column where the penetration of light is sufficient to ensure that the rate of photosynthesis is greater than the rate of respiration of phytoplankton, enabling plant life forms to grow.
Physoclist	A teleost fish lacking a duct between the air bladder and the alimentary canal.
Phytoplankton	Mostly microscopic, single celled photosynthetic organisms that live suspended in water.
Propagule	A part of an organism which may grow to form a complete organism, usually to aid dispersal of plants.
Rheotaxic	The ability of an organism to orientate itself with respect to the water current, usually to face the current.
Screenwell	A vertical recess for the travelling screen which is installed in the cooling water intake system.
Shear stress	The force acting parallel to the cross section. In this case it is the force of the flowing water acting on the surface of the fish or other organism.
Smolts	Young salmon at the stage before they migrate out to sea from freshwater habitats. They spend time in brackish waters of river estuaries.
Spawning stock biomass (SSB)	The combined weight of all individuals in a fish stock that are capable of reproducing.
Strain rate	An index of physical force experienced by fish when subjected to shear stresses in their environment.
Sub-lethal effects	Effects on an organism which are below, often just below a lethal effect which would cause death.
Total residual oxidant	The concentration of total oxidant chemicals remaining in the water at any given or measured time. A dose of oxidant will decline with time leaving a residual concentration of oxidants in the water.
Tropic levels	The position an organism occupies in a food chain. The level is the number of steps from the start of the chain.
Turbidity	The cloudiness and lack of transparency of a fluid caused by the presence of suspended particulates, especially very fine particulates.

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