The Sizewell C Project

9.70 Evaluation of Chlorination Dosing Options for Sizewell C

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Evaluation of chlorination dosing options for Sizewell C

(balancing biofouling efficacy and non-target species effects)

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Note on Editions:

Edition 2 recalculated TRO profiles using the revised TRO decay model presented in TR143 Ed.2. The new model parameters resulted in faster decay which resulted in a need to use higher initial dosing (e.g. option 2 - 0.68 vs. 0.5 mg l^{-1}) to keep the minimum concentration throughout the cooling water system above target values. Ed 2 also included a sensitivity study taking account of the range of experimentally observed TRO decay rates (TR143 Ed.2). The uncertainty in TRO decay rates gave roughly a factor of 2 (0.48 to 0.96 mg/l) difference in the possible initial dose concentration for Option 2.

Edition 3 included a new option of allowing TRO levels in the inlet tunnels to fall below 0.2mg l^{-1}.

Edition 4 reviewed the practicality of controlling intake TRO doses levels. It also included a consideration of residual risks with the proposed chlorination strategy that remained to be fully considered/mitigated.

Edition 5 includes the results of a full appraisal of options and reflects the proposed position on the chlorination strategy after consideration of the options by EDF Energy. At this stage the implications of the proposals had not been subject to consideration by EDF engineering.

Edition 6 includes the latest design information (Section 9) and final SZC chlorination policy after engineering optioneering studies.

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Executive summary

EDF Energy's policy for its existing UK fleet is that those stations where the cooling water system is exposed to a high biofouling risk should have the capability of maintaining a default regime of continuous, year-round chlorination to obtain 0.2 mg l^{-1} Total Residual Oxidant (TRO) in front of plant vulnerable to biofouling. Sizewell B is currently assessed as subject to a high risk of biofouling and operational practice is, therefore, to maintain the default regime. The detailed application of the EDF Energy policy, for example whether the entire cooling water (CW) system is dosed continuously or just critical plant, is dependent upon site specific issues such as the flexibility of the chlorination plant and station design. At SZB the current policy is to dose the entire CW system, including the inlet tunnels, throughout the year.

Based upon the known risk of biofouling at Sizewell, it would be necessary to dose critical plant at Sizewell C (the condensers and essential cooling water systems) during the growing season when seawater temperatures exceed 10 °C and also to have the flexibility to dose those systems at other times of the year based upon operational inspection and need. The chlorination policy for the other parts of the CW system has to be effective against any biofouling risk that would threaten the operation of the station whilst minimising toxicological effects on non-target species. In particular, Sizewell C will be fitted with a fish recovery and return (FRR) system to return impinged fish back to sea and the Environment Agency best practice screening guidelines are that, wherever possible, chlorination should be avoided before or within the FRR so as to minimise any loss of fitness for those fish returned to the marine environment. The toxicity of TROs to marine organisms is a function of the residual oxidant level and exposure time; for all species the higher the residual the shorter the time to achieve specific levels of mortality.

The need to minimise the abstraction losses of fish and crustacea whilst simultaneously ensuring that the SZC cooling water system is at low risk of biofouling involved a complex set of interrelated design decisions which meant that there was a more restricted set of design options available than at HPC where there is a very low biofouling risk. For example, selection of an intake design for SZC that would require chlorination to be applied at the intakes to reduce biofouling risk would significantly reduce the effectiveness of an FRR system due to the high chlorination doses that would be required and the long exposure time of abstracted biota due the location of the intakes at approximately 3km offshore. The chlorination strategy is, therefore, a more complex environmental issue for Sizewell C (SZC) than it was for Sizewell B (SZB) due to the length of the SZC CW tunnels and the potential significant increase in TRO exposure time, dependent upon chlorination system design, for organisms abstracted into the CW system. If EDF Energy needs to chlorinate before the FRR system, a reasoned ecotoxicological case would be required to depart from EA Best Practice.

During the period mid 2014 - mid 2016 studies were undertaken on potential chlorination strategies for SZC with the aim of meeting the required biofouling control of critical plant whilst minimising both operational risks and toxicological effects on non-target species. Version 5 of this report, dated October 2016, presented the recommendations for a chlorination strategy that reflected the design evolution of the plant up to that date. Between then and the submission of the SZC DCO application in May 2020, the chlorination strategy has been finalised and although it has subsequently been described in the SZC Environmental Statement and WDA permit application, this report (TR316) had not been updated to reflect the final design decisions. This report has now been brought up to date with the majority of the 2016 version being preserved as a record of the early design evolution and the factors of importance. The main change is the addition of Section 9 which describes the post October 2016 cooling water system design optioneering and the final chlorination strategy for SZC.

1 Introduction

EDF Energy's policy for its existing UK fleet is that stations exposed to a high biofouling risk should have the capability of maintaining a default regime of continuous, year-round chlorination to obtain 0.2 mg l^{-1} Total Residual Oxidant (TRO) in front of plant vulnerable to biofouling. Sizewell B (SZB) is currently assessed as subject to a high risk of biofouling and operational practice is, therefore, to maintain the default regime. The detailed application of the EDF policy, for example whether the entire cooling water (CW) system is dosed continuously, or just critical plant is dependent upon local issues such as the flexibility of the chlorination plant. At SZB the current policy is to dose the entire CW system including the inlet tunnels throughout the year.

Based upon the known risk of biofouling at Sizewell, at Sizewell C (SZC) it would be necessary to dose critical plant (the condenser, essential cooling water systems) during the growing season (when seawater temperature exceeds 10 °C) and also to have the flexibility to dose those systems at other times of the year based upon operational need. The chlorination policy for the other parts of the CW system has to be effective against any biofouling risk that would threaten the operation of the station whilst minimising toxicological effects on non-target species. In particular, Sizewell C will be fitted with a fish recovery and return system to return impinged fish back to sea and the EA best practice screening guidelines are that, wherever possible, chlorination should be avoided before the FRR system so as to minimise any loss of fitness for those fish returned to the marine environment.

The toxicity of TROs to marine organisms is a function of exposure concentration and exposure time; for all species the higher the concentration the shorter the time to achieve specific levels of mortality. The potential environmental effects of chlorinating the cooling water system include:

a. Effects of the heated, chemical discharge plume on the marine ecosystem including indirect effects; in particular the potential effect on SPA protected marine birds and SAC protected marine mammals via potential effects on their fish prey distribution. The size of the TRO plume is controlled by the TRO levels at the inlet to the condensers and subsequent decay in the outfall tunnels. The size of the chlorinated by product (CBP) plume is dependent upon the total chlorination input to the CW system and the inlet water quality.

b. The mortality of organisms (mostly eggs and larvae) entrained through the CW system where they experience the effects of pressure, temperature and TRO. Effects vary with species but for many species and life stages the initial TRO exposure concentration and the exposure duration are the determinant factors for most mortality; increased temperatures above an absolute threshold generally serve to increase mortalities. The TRO exposure profile along the whole CW circuit, whereby TRO concentration decreases after the initial dose due initial chemical demand and then subsequent slower decay, is therefore material to entrainment mortality. The earlier the point that chlorination is applied, the higher the initial dose required and the longer the exposure.

c. The additional mortality of fish impinged on the filtration screens and returned via the fish recovery and return system (FRR). A need to chlorinate the SZC inlet tunnels would mean that the EA Best Practice requirement to avoid chlorination upstream of FRR systems would be unworkable and fish that would be returned via the FRR system would be in chlorinated seawater from the intakes onwards and until they were discharged at the FRR outfall. Dependent upon TRO exposure levels, chlorination could reduce the effectiveness of the FRR in reducing impingement mortalities.

The purpose of this report is to evaluate a range of potential chlorination strategies for use at Sizewell C in order to best meet the required biofouling control of critical plant whilst minimising both operational risks and toxicological effects on non-target species. In particular, if EDF Energy needs to chlorinate before the FRR system, a reasoned ecotoxicological case will need to be made to depart from the EA Best Practice guidance.

1.1 Cooling Water systems design (at October 2016)

The existing Sizewell B power station uses chlorination to protect its cooling water (CW) system. SZB's existing Water Discharge Activity (WDA) permit allows for a maximum TRO discharge (measured prior to the discharge tunnel) of 0.3 mg l^{-1} throughout the year.

The cooling water systems of SZB and the proposed SZC are markedly different:

- Sizewell B has a 700 m long inlet and a 150 m long outfall both running in sub seabed culverts. The intake structure consists of two large simple 'velocity capped' intake heads, each initially leading to its own tunnel, which then join to form a single tunnel. Each head is octagonal, ~11.5 m across and is omnidirectional in terms of tidal flows. The structure sits ~1.5 m above the seabed and the intake aperture is 3 m high. The intake tunnel consists of nine square precast concrete caissons, each of which is 4.8 m wide (internal). Flow velocities in the inlet tunnel are approximately 2.5 m s^{-1}, giving a passage time through the tunnel of approximately 5 minutes.
- Sizewell C would have two 6m internal diameter, ~3.1km long inlet tunnels each of which will have 2 intake heads and one 8m internal diameter ~3.2km long outfall tunnel with 2 outfall heads. In October 2016 the intake head design for Sizewell C has not yet been developed and was in large part dependent upon the chlorination strategy, as this would of necessity also reflect the balance of operational benefit and potential for environmental harm being sought through that same strategy. SZC would have one or two dedicated FRR discharge tunnels dependent upon plot plan considerations. The length of the FRR tunnel(s) had not then been finalised but was considered likely to be approximately 300 metres. (The studies to determine the location of the SZC FRR outfall are described in BEEMS Technical Report TR333).

The average seawater transit time through SZB is approximately 10 minutes from intake to discharge. The SZB FRR system returns fish to sea via the CW seal pit and then the CW outfall. At Sizewell C the use of offshore intakes and outfalls means that the seawater transit time would be approximately 52mins (source EDF Energy). The exact transit time would be dependent upon the final location of the two SZC intake heads on each intake tunnel which would be located at two of the three potential locations on each tunnel described in the BEEMS Technical Report TR303. The final choice of location is subject to offshore geotechnical considerations but would only make a marginal difference to transit timing.

To minimise fish mortality due to impingement in SZC, EDF Energy proposes to install a Fish Recovery and Return system (FRR) that will provide a safe return of the more robust species directly into the marine environment. After being removed from the drum screens and band screens by a low-pressure wash, the impinged organisms will be returned to sea via a dedicated tunnel and inshore sea bed outfall (the tunnel length approximately 300m long).

Several elements of the cooling water system at SZC were considered for protection against biofouling. Potential chlorination dosing points are shown in the simplified schematic of the proposed SZC CW system shown in Figure 1 and tabulated below:

1. The intake heads.
2. The inlet tunnels - could be protected via a sufficiently high single dose at the intakes or via use of 1 or more dosing rings to achieve a TRO level at or above 0.2 mg l^{-1} throughout tunnels (in principle the forebay could also be independently dosed).
3. Dosing grids within the entrances to the drum and band screen wells. If not protected the screens could foul at Sizewell: the 'whiteweed' (hydroid and bryozoan furze) plus algae, given any light, could prosper in these high surface area, wetted and well-oxygenated areas. If chlorination was applied here, the screen wells would be dosed to achieve a TRO level of 0.2 mg l^{-1}. Dosing at this point would also chlorinate the FRR system.

4. The condensers - additional dosing point to ensure the required TRO level of 0.2 mg l^{-1} at the discharge from the condensers

5. Essential cooling water systems. These systems are fed independently from the forebay and would have their own dosing system to ensure a TRO level of 0.2 mg l^{-1} at the entrance to the vulnerable plant.

The cooling water outfall tunnel would not require additional dosing as it would both have a degree of resilience and be protected by the residual oxidants remaining in the system after dosing before the condensers.

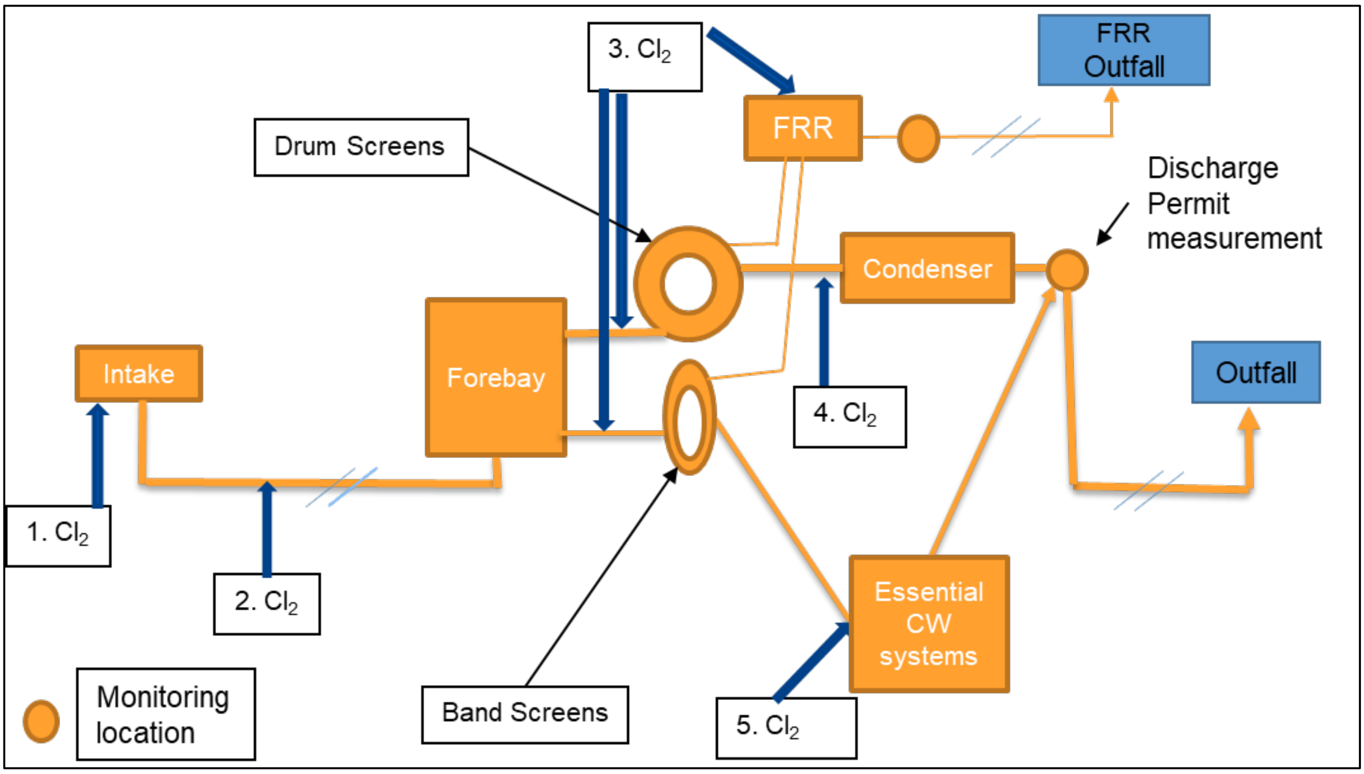

Figure 1 Simplified schematic of SZC cooling water system showing potential chlorination dosing points

By restricting TRO discharges to 0.2 mg l^{-1} the discharge plume arising from the main cooling water outfalls would be expected to have only minimal, short range ecological effects in the vicinity of the outfall head(s) (BEEMS Technical Report TR303).

Appendix F provides schematic drawings of the HPC pump house to help visualise the layout of the system and the cooling water flows within it.

1.2 SZC design assumptions used in this report (design at October 2016)

Inlet tunnels

Two, each approximately 3.1km long, diameter 6m, flow rate approximately 66$m^3 s^{-1}$, approximate flow velocity 2.3 m s^{-1}

Outfall tunnel

Length approximately 3.2km, diameter 8m, flow rate approximately 132$m^3 s^{-1}$, approximate flow velocity 2.6 m s^{-1}

FRR tunnel

Length and discharge location to be finalised (designed to avoid fish re-entrainment into SZB intake and to minimize contact with SZB outfall TRO plume). For the purpose of this report it has been assumed that the FRR tunnel length would be approximately 300m with an internal diameter 0.8m and a flow velocity of approximately 0.5m s^{-1}.

Forebays

Time to flush each forebay approximately 5 minutes (Sizewell C would have 2 forebays; 1 for each reactor).

Cooling water transit times (Source EDF SA, CNEPE)

Time from intake head to forebay: 1500 s (25 minutes)

Time from intake to inlet to drum screens: 1740 s (29 minutes)

2 Ecotoxicological considerations of chlorination.

The sensitivity of fish to TRO exposure concentrations following chlorination of seawater is species and life stage dependent. Sensitivity to exposure duration will also vary between species and life stages. Based on operational experience and some limited experimental data on dead and live sprats at Dungeness power station Turnpenny (1992) suggested that pelagic and demersal fish could remain longer in fish return systems (60 minutes) compared to epibenthic species (15 minutes) which less actively resist passage through the system. (The experiments showed that 60% of dead sprats were cleared in 8.5 minutes and 60% of live sprats were cleared through the system per hour, implying that approximately 95% could be cleared in 3 hours). No experimental data are available for species other than sprat; in particular dependent upon the design of the forebay, it is possible that eels could take a protracted time to leave the forebay. Based on data from Turnpenny (1992) and the proposed SZC cooling water system design, the time taken for a fish to pass through SZC and to be returned to sea via the FRR tunnel is predicted to be in the approximate range of 1 – 3.5 hours. (Table 1). These estimates provide a rough indication of potential fish transit times; in practice transit times at SZC will be design, species and seasonally dependent. Improved estimates of fish residence times in the screen wells and in the drum screen/FRR mechanisms could only be obtained by experiments on the operational system or a close analogue.

Table 1. Estimated transit times for impinged fish through the SZC FRR system

Stage	Typical minimum time minutes	Mean time minutes	Maximum time (95% clearance) minutes
From intake to forebay	29	29	29
Time in forebay/screen well	15	60	180
Drum screens to FRR discharge (minimum – timings design dependent)	10	10	10
Total time	**54**	**99**	**219**

The toxicological effects of chlorinated seawater have been investigated for a range of fish species. These studies can be divided into two main types: studies including a combined evaluation of seawater chlorination together with elevated temperature and pressure such as might occur during power station entrainment; and studies for which the focus is chlorination effects in the wider environment. The larger species of fish will be processed through the fish return system and will be subjected to different potential stresses compared to smaller species, larval forms and eggs that pass through the entire system.

All of the original species data and source references used for the assessment are provided in Appendix B. The data include a range of fish species and life stages exposed to chlorinated seawater with or without additional stressors included in the experimental protocol. A number of species are not from UK waters and so provide only a potential indication of likely sensitivity to chlorination for related indigenous species. The available data cover a range of exposure comparisons and therefore assessment of the impact of the likely TRO exposure time predicted for Sizewell C based on these data has a high degree of uncertainty. Data points shown in Figure 2 represent TRO exposure concentration and exposure time combinations resulting in 40-60% mortality of the exposed species when assessed at least 24 hours after the initial exposure period. (The 40-60% mortality represents how the experimental data were reported and is not intended to imply that this is an acceptable level of mortality). The exceptions to this are the data point shown for European eel elvers which represents a TRO concentration and exposure time not shown to result in any mortality of exposed elvers (0.47 mg l^{-1} for 60minutes, Turnpenny, 2000). There was also 100% survival for glass eel after 15 minutes exposure at 0.15 to 0.49 mg l^{-1} TRO in EMU studies (BEEMS Technical Report TR273) but to avoid confusing the information presented this data point is not shown on the graph.

Survival is likely to be high for species such as eel for which a threshold effect concentration of 0.2 to 0.3 mg l^{-1} TRO is indicated (Turnpenny, 2000). Epibenthic fish species that are predicted to transit the system more rapidly are also likely to survive better than other groups of species.

The box indicated on Figure 2 shows the worst-case potential exposure time for fish returned via the FRR system assuming dosing at SZC takes place in the intakes with the objective to maintain a target residual TRO concentration of ≥0.2 mg l^{-1} from the intakes to the discharge from the condensers.

The data summarised in Figure 2 indicate that:

- TRO levels >0.3 mg l^{-1} could cause 50% mortality within 10 minutes exposure for some fish species
- At a constant TRO level of 0.2 mg l^{-1} for an exposure time equivalent to the mean expected SZC transit time of 100 minutes (Table 1) there could be approximately 50% mortality for bass, cod, sole, plaice and mullet i.e. many of the species that the FRR was designed to benefit. At a fixed TRO level the only way to mitigate this mortality would be to reduce the exposure time. This could be done by not chlorinating before the drum screen.
- There would be 0% mortality for glass eel and 1+ eels (1-2yr old eels) at TRO levels of 0.2 mg l^{-1} from exposures of up to the predicted maximum transit time of 3.5h. At 0.3 mg l^{-1} 1+ eel mortality is likely to start to increase at exposure times of greater than 2.25h.

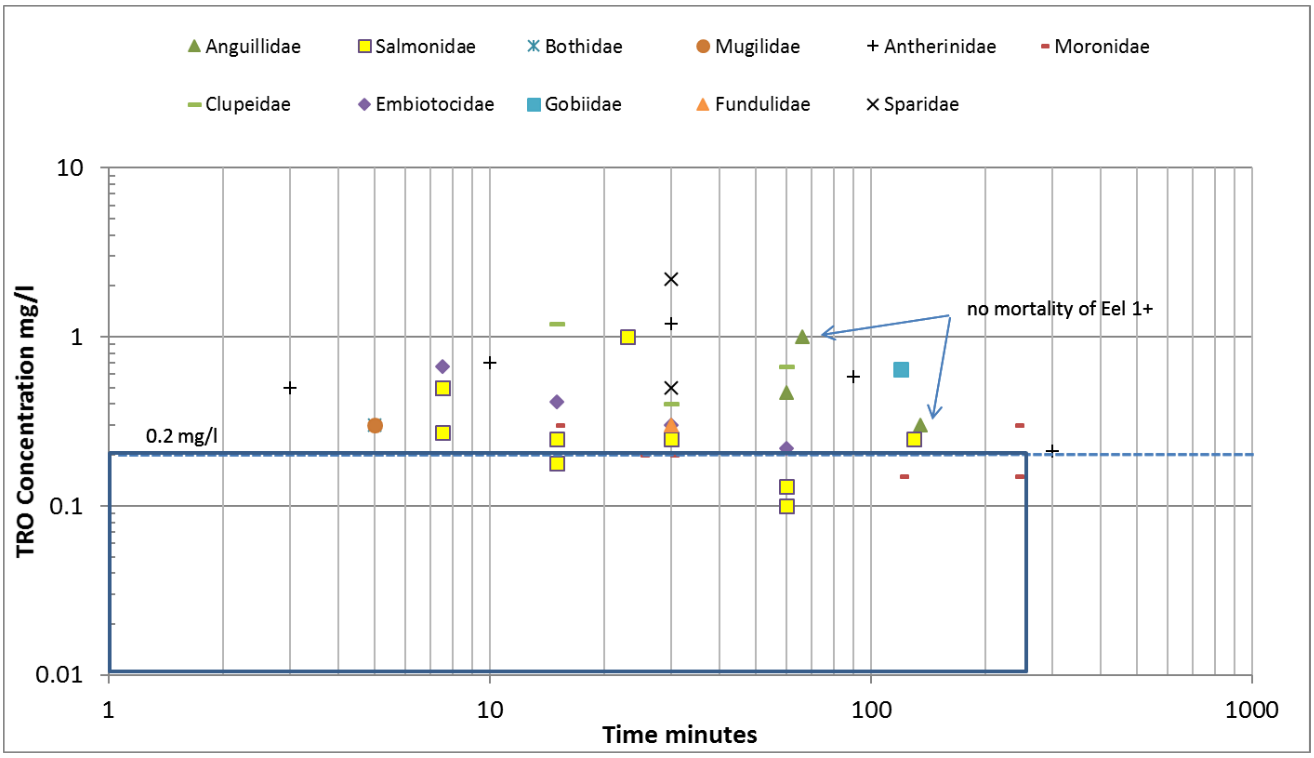

Figure 2. Plot of TRO concentration and exposure time resulting in approx. 40-60% mortality of exposed fish species except where otherwise indicated. The large box represents the maximum exposure period for fish discharged via the FRR systems assuming that chlorination is applied near to the SZC intakes.

Based on these data any dosing strategy intended to maintain a TRO residual of 0.2 mg l^{-1} from the intakes to the discharge from the condensers would be expected to produce significant mortality (≥50%) for many impinged fish species that the FRR is intended to benefit. One exception would be for eels where the available experimental data indicates that they would not suffer increased mortality at TRO levels of 0.2 mg l^{-1} for the maximum predicted residence time within the SZC CW system.

Ideally additional dose-exposure data are needed to refine these estimates and in particular if more complex systems such intermittent dosing were proposed.

For total chlorine additions around 0.4mg l^{-1} (i.e. typical as dosed levels against Sizewell water quality rather than residual levels) the resulting bromoform concentration is expected to be around 15 µg l^{-1} within 15-30 minutes of the addition of chlorine (Jenner et al., 1997 and BEEMS Technical Report TR217). Animals entrained within the cooling water will therefore be exposed to bromoform and potentially other chlorination by-products. Bromoform is unlikely to represent a major issue in terms of food chain effects as, although it has the potential to bioconcentrate, the exposure period to the highest bromoform concentrations is brief and depuration is rapid with a half-life in the tissues of organisms of 3-5 hours reported for species such as Japanese flounder (Libuchi *et al*., 2011).

3 Potential Dosing Strategies

The way that chlorination is applied in the CW system will have a major bearing on the TRO exposure that those organisms in the system experience. If it is considered necessary to protect the intakes, inlet tunnels and forebay from biofouling, then a TRO level of ≥. 0.2 mg l^{-1} will need to be maintained throughout the CW system. The simplest engineering approach would be to apply a large dose at the intakes that, after decay in the system, would be sufficient to maintain TRO levels at 0.2 mg l^{-1} until the discharge from the condensers. At the other end of the spectrum chlorination could be applied at multiple places along the CW system to minimize any exposure to TRO levels above 0.2 mg l^{-1} and in particular to avoid exposure to levels above 0.3 mg l^{-1}. However, multiple chlorination points in the inlet tunnels would create maintenance problems for EDF Energy that, given the depth of the tunnels, would require a capability to dry the tunnels down for any required repairs to the chlorination pipework and nozzles. EDF Energy has no operational experience of dosing long tunnels in this manner; indeed maintaining dose levels in SZB's much shorter and shallower inlet tunnel has presented issues of chemistry control that would become very much more acute with longer tunnels.

Certain plant design assumptions can be made:

a. The risk of biofouling at Sizewell requires chlorination of critical plant and therefore it can be assumed that EDF Energy will require the ability to chlorinate in front of the condensers such that the TRO level in the discharge is maintained at a continuous level of 0.2 mg l^{-1} throughout the year. By setting a TRO level of 0.2 mg l^{-1} at the discharge from the condensers the worst-case level at the outfalls is readily determined (i.e. the necessary chemical plume modelling for WDA permit purposes is not dependent upon the detailed chlorination policy for the whole CW system).

b. Dependent upon design, the FRR system itself may need to be protected, probably by injection of chlorine into the drum screen wells. The FRR tunnel will be short and if it is chlorinated the recovered fish would be exposed to TRO decreasing from an initial level of 0.2 mg l^{-1} to approximately 0.1 mg l^{-1} for approximately 10 minutes in the tunnel (BEEMS Technical Report TR333).

c. The longest period of potential TRO exposure would be for fish travelling through chlorinated inlet tunnels and the forebays before being recovered by the FRR system (45minutes to 2¼h representing >95% of the CW transit time). The dose strategy for this section of plant therefore provides the main scope for optimization.

The potential dosing options for the cooling water system are listed below:

1. Seasonal dosing. Where feasible, limit chlorination to when it is required during the annual cycle i.e. during the biological growth season when seawater temperatures exceed 10 °C.

2. Apply a single dose at the intakes sufficient to maintain a TRO level of 0.2 mg l^{-1} at the discharge from the condensers

3. Use multiple dosing points along the inlet tunnels to minimize peak TRO levels (particularly to minimise any exposure to levels ≥0.3 mg l^{-1}) and to maintain TRO levels between the intakes and the condenser as close as possible to 0.2 mg l^{-1}. (options 3.1, 3.2 and 3.3)

4. Apply a single dose at the intakes which would only be sufficient to protect the intakes and an initial section of the inlet tunnels. This could be accomplished by dosing at the intakes to achieve an initial TRO level of 0.2 mg l^{-1} and then allowing the TRO level along the inlet tunnels to fall below this threshold.

5. Maintaining TRO levels of 0.2 mg l^{-1} for critical land-based plant only (e.g. the condensers and essential cooling water systems) and not dosing before the drum screens or the FRR system i.e. not dosing in the intakes, inlet tunnels and the forebays.

6. To introduce intermittent chlorination to reduce TRO exposure time for organisms within the CW system and, by operating the chlorination systems asynchronously in the 2 reactors, to reduce the size of the TRO discharge plume. (This option could be combined with any of options 2-4 and some variants of option 5)

Options 2 to 4 are only required if it is considered necessary to protect the intakes, inlet tunnels and forebays from biofouling.

For options 2 to 5 TRO concentrations have been calculated using the formulations for demand, decay and dilution derived in BEEMS Technical Report TR143 ed. 2. In the case of TRO in the discharge tunnel, no additional dilution occurs until after discharge. It should be noted that the initial concentration is that shown at T_0 as demand is factored into the model. As the experimental studies to evaluate demand and decay of TRO in Sizewell seawater showed some seasonal variability this has been factored into the model calculations by deriving a fit that takes account of all of the experimental runs. In the figures 3 -12 the blue lines show the modelled TRO levels and the green lines the minimum TRO level required.

3.1 Option 1: Seasonal dosing

Macrofouling organisms only start to grow rapidly when seawater temperatures are above 10°C. Water temperatures are less than 10°C at Sizewell in the approximate period December to March.

3.1.1 Potential Benefits of seasonal dosing

Reductions in impingement mortality.

Examination of the BEEMS SZB impingement monitoring data (measurement period February 2009 – January 2011 described in BEEMS Technical Reports TR120 and TR196) shows that.

a) Most fish impingement occurs in winter when the Sizewell inshore area is used by over wintering juvenile fish. 76% of the annual fish impingement catch by number was caught in the period December to March.

b) Approximately 70% of the total annual catch consists of pelagic species (e.g. sprat, herring, anchovy). The FRR is not expected to reduce the impingement mortality for such species which are damaged by contact with the drum screen mesh.

c) Approximately 65% of the annual non-pelagic impingement occurs in the period Dec – March

This would imply that a policy of not chlorinating before the FRR system when temperatures are below 10°C could have a substantial benefit for some non-pelagic species. In particular, the following frequently impinged species would benefit:

Table 2. Percentage of annual impingement taken in December - March

Species	% of annual impingement in December - March
Bass	97%
Cod	89%
Mullet, thin lipped	99%
Flounder	44%
Whiting	51%

With exposure to TRO levels of a maximum of 0.2 mg l^{-1} from the intakes to the condensers, based upon the currently available evidence, it is expected that these species could suffer an additional 50% impingement mortality compared to the scenario where no chlorination is used during December to March. Mortality would be greater if the TRO levels were higher.

Reductions in entrainment mortality

The use of seasonal dosing would reduce entrainment mortality in winter. However, although most biological productivity is outside the winter months, a reduction in the TRO exposure time over winter could reduce the risk of entrainment mortality on herring and sprat larvae and upon juvenile gobies and sprat (BEEMS Technical Report TR315).

3.2 Option 2: Single Dose to achieve a TRO of 0.68 mg/l at the intakes.

A single dose is applied to achieve a TRO level of 0.68 mg l^{-1} inside the intakes. No further dosing is required at the forebay (red lines at 25 minutes or at the drum screens at 29 minutes)

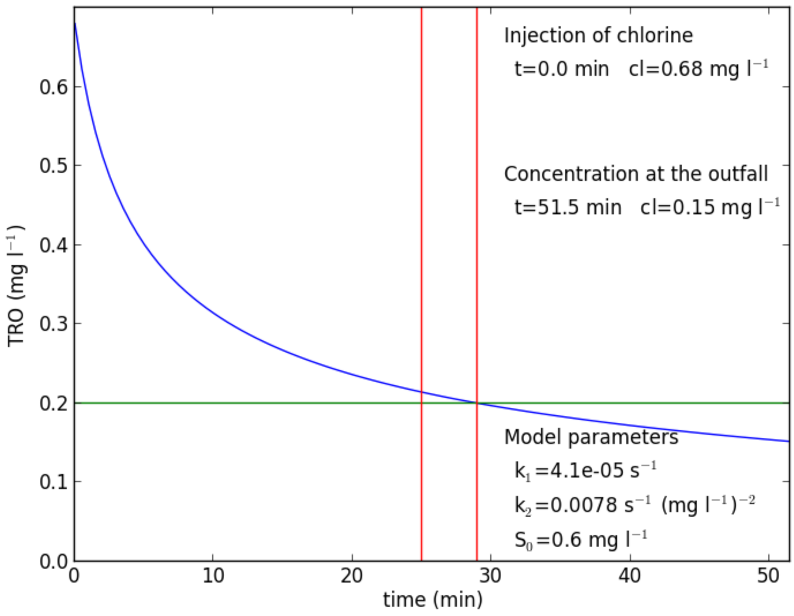

Figure 3 Option 2 - one dose at the intake heads

This scenario provides the required TRO level at the condensers, it is the simplest to implement, but has the disadvantage of exposing entrained fish to the highest TRO levels; in particular levels above 0.2 mg l^{-1} would be experienced for 29 minutes and above 0.3 mg l^{-1} for approximately 10 minutes.

As a worst-case assumption for modelling purposes we have assumed that eventually all of the dosed oxidant becomes chlorinated by-products and thus this scenario contributes a total input of 0.68 mg l^{-1} chlorine towards formation of CBPs.

3.3 Option 3.1: dosing at the intakes and at 1 location in the inlet tunnels – intermediate ring dose at 1584 metres along the inlet tunnels

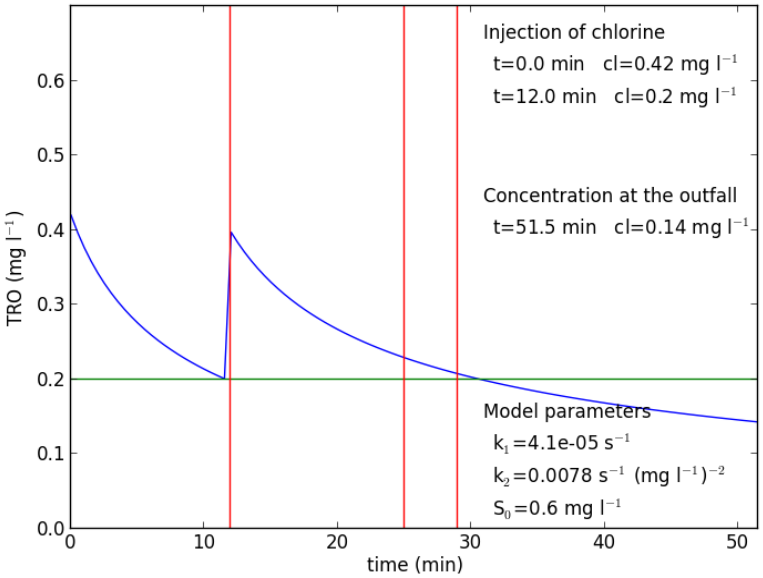

Figure 4 Option 3.1 with 2 dose points

By using a ring dosing at 1584 metres into the inlet tunnel, the initial concentration is reduced by a third compared with Option 1, but still leads to 2 periods of five minutes of exposure above 0.3 mg l^{-1}. Total TRO addition is 0.62 mg l^{-1}.

3.4 Option 3.2: 3 dose locations - initial, 1 ring at 1320 metres from the start of inlet tunnel, and at forebay

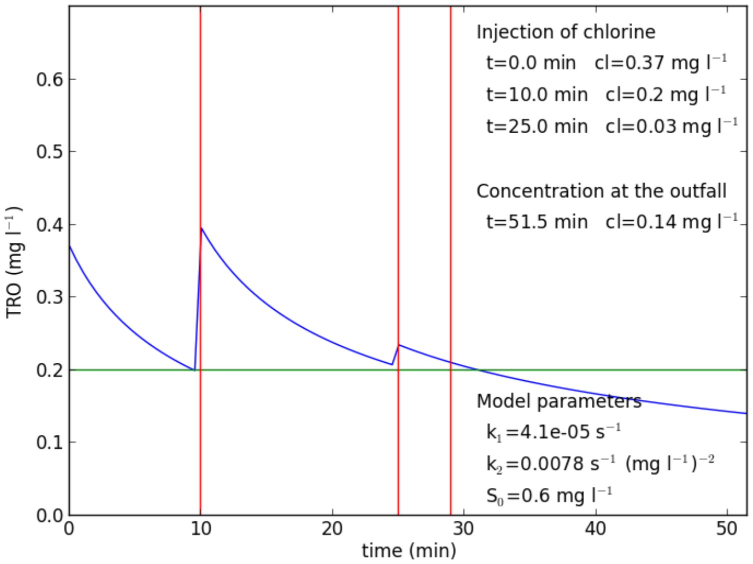

Figure 5 Option 3.2 with 3 dose points

The initial concentration is 0.37 mg l^{-1} with subsequent additions of 0.2 mg l^{-1}, and 0.03 mg l^{-1}. The TRO exposure is above 0.3 mg l^{-1} for a total of 8 minutes. The total TRO is 0.6 mg l^{-1}. i.e. 12% less than the contribution of chlorine to CBP formation compared to Option 1.

3.5 Option 3.3: 4 dose locations - initial, 2 rings at 924 and 2046 metres from the start of the inlet tunnel, and at forebay

In addition to dosing at the inlet of the tunnel, this scenario would require additional dosing at 924 and 2046 metres along the inlet tunnels and at the drum screen.

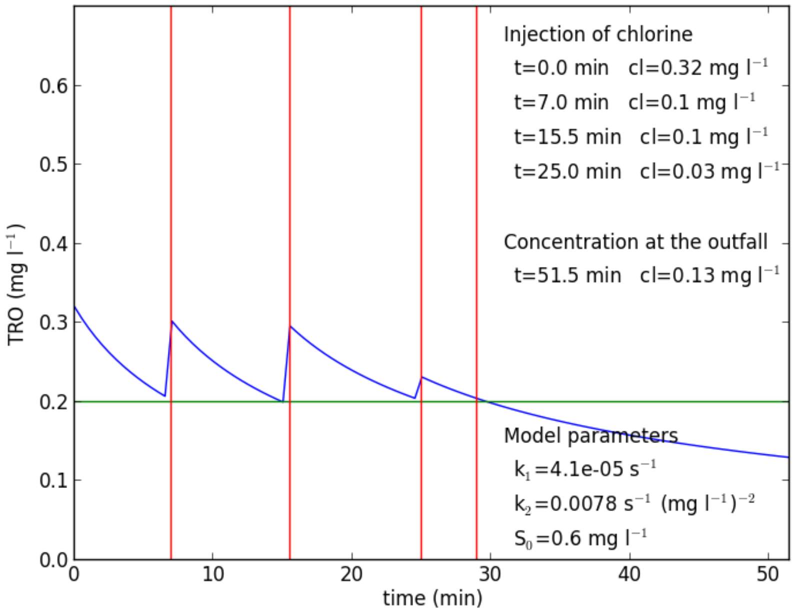

Figure 6 Option 3.3 with 4 dose points

This scenario results in dose levels beneath 0.3 mg l^{-1} almost immediately. The total TRO which is converted to CBP is 0.55 mg l^{-1} as a worst-case assumption for modelling purposes. The scenario produces the lowest maximum values of TRO exposure. Additional rings would progressively reduce the peak TRO exposure but not decrease the total CBP.

As would be expected increasing the number of dose points along the inlet tunnels permits a worthwhile reduction in the peak and mean TRO exposure levels that approaches the target TRO level of 0.2 mg l^{-1}. Further reductions could only be accomplished by allowing the residual to either drop below 0.2 mg l^{-1} for sections of the inlet tunnels or by introducing yet more dosing points. However, inspection of Figures 3 - 6 shows that the law of diminishing returns applies to the addition of further dosing points because of the need to maintain minimum TRO levels of 0.2 mg l^{-1}.

3.6 Option 4: Single dose to achieve a TRO level of 0.2mg l^{-1} at the intakes, no further dosing until after the drum screens.

This strategy assumes that the inlet tunnels do not present a high risk of sufficient biofouling to cause unacceptable hydraulic problems in the CW system and that most benefit would be achieved by protecting the intake itself and the initial tunnel sections with the highest TRO level. At Sizewell B there is operational experience when the inlet tunnel dosing hoses became fractured and the seaward end of the tunnels became unprotected for several years. Inspection of the undosed tunnel sections revealed only limited biofouling by soft bodied organisms and only small mussel colonies. There is, therefore, operational support at Sizewell for a more restricted tunnel dosing strategy and this has been modelled in Figure 7. It should be noted that the degree of biofouling that can be tolerated in the SZC inlet tunnels has yet to be confirmed by the EDF engineers.

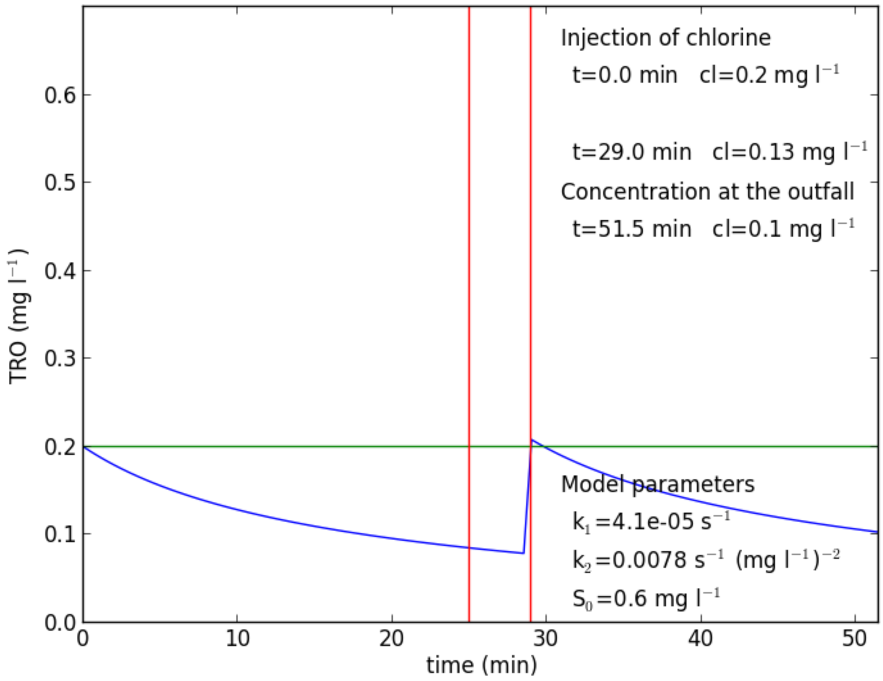

Figure 7 Option 4 with a single dose at the intakes and then dosing at (or after) the drum screens.

This scenario maintains protection for critical plant but results in a much reduced TRO exposure profile for impinged and entrained organisms. Even allowing for dosing of the FRR system, for impinged fish the TRO exposure would always be less than 0.2 mg l^{-1} and less than 0.1 mg l^{-1} for 70 minutes out of the mean transit time of 90minutes.

3.7 Option 5. Not dosing before the drum screens

For impinged fish the largest portion of the transit time through SZC would be the time spent in the inlet tunnels and forebay before recovery from the cooling water system on the drum screens. According to Table 1 this might represent 89-209 minutes out of a total transit time of 99 -219 minutes. Operational experience at Sizewell B together with the proposed use of larger tunnels at Sizewell C (6m diameter v 4.8m at SZB) indicate that it may be acceptable to not chlorinate the SZC inlet tunnels. Biofouling of the forebays is considered unlikely to represent a significant risk, however if the forebays were unchlorinated the trash racks would be at enhanced risk and may require regular maintenance to remove attached organisms. Chlorination of the drum screen wells would provide protection for the large operating surfaces of the drum screens themselves and would also chlorinate the FRR system which, dependent upon design, may be required during the growing season to prevent macro fouling of any exposed large surface area components in the system.

For option 5 chlorine dosing would therefore be:

a. to the drum screen wells; and

b. at the inlets to the condensers.

This option has been modelled in Figure 8.

If feasible, in order to protect impinged fish, it would be desirable not to chlorinate at the drum screen but only at the inlet to the condensers. This may be practical outside of the growing season i.e. when water temperatures are <10°C.

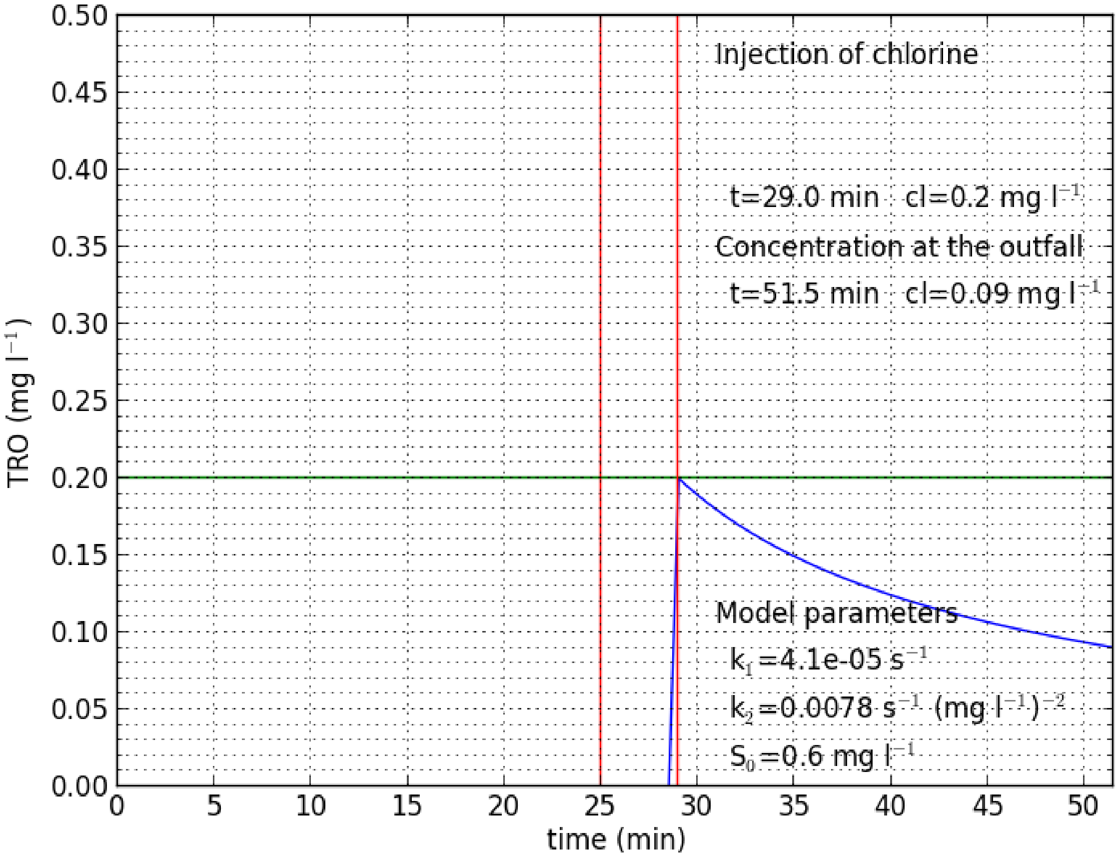

Figure 8 Option 5 – single dose before the condensers to achieve a TRO level of 0.2 mg l^{-1} in front of the condensers

Sensitivity tests have been run on option 5 in Appendix E. Using the measured variation in TRO decay parameters at Sizewell, the predicted TRO level at the outfall varied between 0.05 and 0.13 mg l^{-1} with an expected value of 0.09mg l^{-1} if all the decay data are fitted to one equation.

3.8 Option 6. Use of an intermittent chlorination regime

Semi-continuous dosing strategies have been used at some power stations (i.e. 30 minutes on and 30 minutes off was adopted at Flamanville in 1997, Jenner et al. 1998) and this would mean that fish would be exposed to residuals below 0.2 mg l^{-1} for some percentage of the transit period. Jenner et al. 2003 describes the results of a 4-year trial of an intermittent chlorination regime (referred to as ‘Pulse Dosing’) at the E.ON power station ‘Maasvlakte’ between 1999 and 2003. The chlorination interval was selected based upon the recovery time for mussels i.e. the time taken for mussels to resume filter feeding after detecting that the seawater chlorination had stopped. The authors found that the recovery time was site specific and depended upon the TRO levels, the local water quality and the water temperature. Experiments at Massvlakte showed that mussels recovered in about 10 minutes which explained why a previous dosing regime of 4h on and 4h off had been ineffective at biofouling control. The study results demonstrated that the intermittent chlorination regime was effective, but it does cast doubts on whether the Flamanville 30min on, 30min off regime would be effective at Sizewell. With a suitable design of the on/off phasing, an intermittent dosing strategy could reduce the exposure time of impinged species that are returned via the FRR system; as a theoretical best-case half of the organisms could experience low TRO levels. (In practice, dependent upon the design of the dosing system, there would be TRO exposure from at least the forebay onwards due to variable fish residence time in the forebay). Again, with the available data it is difficult to evaluate what the potential gains in terms of increased FRR effectiveness might result from the introduction of such a system. Intermittent dosing would also reduce entrainment exposure for most species and the size of the TRO discharge plume. Dependent upon the adopted control system it could be possible to combine intermittent dosing with options 2 to 4 and option 5.

4 Operational dosing control issues

After initial chlorination, the reduction in TRO levels in the CW system is a function of an initial instantaneous demand and then a relatively slow decay term. Both the demand and decay parameters vary with the properties of the seawater (e.g. organic content) and at present there is insufficient site-specific information to determine whether there is any seasonal pattern in the parameters at Sizewell or whether the measured variability just represents short term temporal fluctuations. The relationship between the TRO levels at the drum screens and at the intakes is not linear and is governed by a differential equation. Without knowledge of the equation parameters it is not simple for the operator to determine what the applied dose actually is; in particular, it is not just a simple volumetric calculation. This understanding bears directly upon the operator’s ability to control residual levels with any confidence from a position any great distance downstream from the injection point: these difficulties increase rapidly with increasing intake tunnel length to the point where control becomes unstable and impractical.

Appendix B presents the calculated TRO levels that would have to be applied at intakes under Option 2 to achieve a TRO level at the discharge from the condensers of 0.2mg l^{-1} using the measured range of TRO decay parameters at Sizewell. Under these conditions the initial TRO level would be in the range of 0.45 to 0.98 mg l^{-1} with an intermediate value from pooling of all data of 0.68 mg l^{-1}.

The question again arises over how the operator would control the residual oxidant level at the intakes. It is not feasible to fit suitable instrumentation at the intake, nor to take separate pumped water samples from the vicinity of the intake head for analysis on shore. The operator would therefore have to control the initial dose by an iterative process to achieve a TRO level at the condensers of 0.2 mg l^{-1} with a 29 minute lag in the feedback control system. If, as expected, there are substantial temporal fluctuations in TRO decay parameters this could result in an unstable control system. Control over options 3 and 4 would be even more problematical (Appendix C). It is not considered that such a system would be operationally viable.

5 Evaluation of chlorination options

Each of the 6 chlorination options have been evaluated in Appendix A in terms of:

a. Biofouling risk
b. Operational risk
c. Environmental impact

In terms of environmental impact, the most beneficial option would be not to chlorinate the main CW system until the inlet to the condensers thereby ensuring that the FRR system was unchlorinated. However, the risk of biofouling of the FRR system itself is uncertain and EDF Energy may require the ability to chlorinate the system via the pumping station screen wells if no chlorination is applied to the inlet tunnels and forebays (Option 5).

Seasonal chlorination (Option 1: not dosing when seawater temperatures are < 10 °C) produces an environmental benefit for all options and, where feasible, should be part of the strategy for Sizewell C. Over the lifetime of the station the effectiveness of this mitigation could be expected to reduce as sea temperatures increase but the measure would always offer a worthwhile environmental benefit. By linking the onset of chlorination to seawater temperature it would seem unlikely that the chlorination regime would cease to be effective in the future. The maximum benefit would be obtained if the entire CW used such a regime but on operational risk grounds that is unlikely, and we have assumed that the critical plant would be dosed continuously throughout the year.

Option 6, use of intermittent dosing has some operational experience but not within EDF Energy. With a suitably high pulse repetition frequency it would appear to offer effective biofouling control and reduced environmental impact. Dependent upon where it was applied in the CW system, intermittent dosing could reduce TRO exposure in the inlet tunnels, entrainment exposure to TROs and with suitable design could reduce the size of the discharged TRO plume at the outfalls. However, with any option that dosed the inlet tunnels the theoretical reductions in TRO exposure may not be realised if impinged fish have long residence times in the forebay/FRR mechanism. The chlorination dosing parameters for SZC would have to be determined by experiments on the operational plant and it is not clear at this stage whether such a system would offer sufficient benefits to justify its likely cost and operational complexity. An alternative approach, suitable for controlling biofilm development only and which may thus have application in protecting critical plant during the colder months, is to couple the dosing systems to Redox monitors which measure both local TRO levels and biofilm thickness, essentially providing a feedback system allowing for optimum dosing. Such an approach has not yet been proven on UK plant but it is an opportunity that may be explored. The feasibility of these approaches could only be determined at a later stage and cannot, therefore, be included in a pre-construction environmental assessment of SZC.

There are then 2 distinct chlorination strategies dependent upon whether it is considered necessary on biofouling risk grounds to dose the inlet tunnels:

5.1 Seasonal dosing of tunnels with a dose applied at the intakes.

If tunnel dosing is required on biofouling risk grounds then seasonal dosing should be combined with Option 2 (a single dose at the intakes sufficient to maintain TRO levels at or above 0.2mg/l throughout the system up to the inlet of the condensers). In practice, on risk management grounds, a chlorination point in front of the condensers would be retained to ensure that there was always a capability to dose critical plant. Option 2 represents the simplest chlorination policy and has proven operational performance within the existing EDFE UK fleet (with relatively short inlet tunnels). When dosing is applied it would produce the largest environmental effects and would mean that the FRR effectiveness in the growing season would be substantially reduced for most species. However, most of the species that the FRR would benefit would be impinged in the winter when seasonal dosing was not applied so this strategy could still produce environmental benefits.

Options that rely upon complex dosing control within the inlet tunnels (options 3 or 4) could produce some reductions in environmental impact compared with option 2. However, the dosing control would be so poor that they cannot be recommended as viable options (see section 4 of this report). Neither EDF Energy nor its partners in France or overseas have operational experience of operating and maintaining a system for chlorinating 3km inlet tunnels with dosing points along the tunnel. Such tunnels and their associated intakes elsewhere are not dosed.

Based upon Sizewell B operational experience it is considered a high risk to assume any of options 2-4 could be kept continuously operational for a 60 year period. Given the depth and length of the tunnels, such systems would be complex to maintain, likely to be unreliable and subject to safety risks for maintenance staff.

5.2 Not dosing before the drum screens

If it is not considered necessary to dose the inlet tunnels, the preferred strategy on risk grounds would be to chlorinate seasonally at the drum screens and to dose continuously at the condensers (Option 5 + Option1).

This strategy assumes that the intakes and inlet tunnels do not present a high risk of sufficient biofouling to cause unacceptable hydraulic problems in the CW system. At Sizewell B after upstream elements of the inlet tunnel dosing pipes failed, the seaward end of the tunnels became unprotected for several years. Inspection of the undosed tunnel sections revealed only limited biofouling by soft bodied organisms and only small mussel colonies. There is, therefore, operational experience at Sizewell that the tunnels themselves are at low risk of fouling.

Subject to engineering confirmation that such a degree of biofouling can be tolerated in the SZC inlet tunnels, not dosing the intakes, inlet tunnels and forebay with seasonal dosing of the drum screen wells and continual dosing of the condensers and essential cooling water systems is considered the preferred chlorination strategy for SZC.

6 Implications of the SZC chlorination policy to the intake head design

The Environment Agency’s guidance for screening at intakes and outfalls (Environment Agency 2005, 2010) recommends that power station intakes should be designed to reduce abstraction of fish and crustacea by the use of velocity capped heads, the avoidance of tidal velocities adding to intake velocities and where possible by reducing velocity into intake surfaces to less than or equal to 0.3m/s. These design principles are embodied in the low velocity side entry (LVSE) intakes that EDF Energy are installing at Hinkley Point C. These intakes were designed using the principles described in EA guidance after substantial optimisation via computational fluid dynamic (CFD) modelling and subsequent design verification via physical modelling.

These very large and highly engineered intake structures are designed to reduce the abstraction of fish and crustacea per cumec ($m^3 s^{-1}$) compared with the earlier intake designs such as that fitted at the HPB by:

a. limiting the exposure of the intake surfaces to the tidal stream and in so-doing reduce the risk of impingement for fish swimming with the tidal stream. i.e. they reduce the cross-sectional area of the intake presented to the prevailing tidal directions by mounting the head orthogonally to the tidal flow;
b. reducing vertical velocities which fish are ill equipped to resist by means of velocity caps on the intakes.
c. reducing intake velocities into the head to a target velocity of 0.3 m s^{-1} over as much of the length of the intake surface as practical during all tidal states in order to maximise the possibility of most fish avoiding abstraction.

(BEEMS Scientific Position Paper SPP105). The HPC LVSE design is the first example of this technology to be constructed worldwide as far as EDF Energy is aware.

EDF Energy's policy is that the design of SZB should replicate HPC wherever possible to maximise supply chain and construction efficiencies which would imply that the HPC LVSE design should be used for SZC. Environment Agency 2005, 2010 offer no guidance on the performance that would be expected from LVSE intakes as the necessary modelling studies had not been undertaken. EDF Energy therefore claimed no quantified reduction in impingement losses at the time of the HPC DCO application from the use of LVSE intake heads.

When considering what intake designs should be adopted for SZC EDF Energy had to consider the different biofouling environment at Sizewell compared with Hinkley Point. The HPC LVSE heads are very large (approximately 44m long by 10m wide) to reduce velocities into the intake surface in order to comply with EA guidance. To achieve the low flow velocities, LVSE designs use a large surface area intake and a complex system of internal baffles in order to linearise the flow field across the face as much as possible. The risk associated with such designs is their vulnerability to biofouling; in particular the disproportionately large surface area available to potential biofouling organisms inside of an LVSE intake head compared with that available in existing, simpler designs (e.g. the omnidirectional capped intakes at SZB) presents a potential hazard for the operation of Sizewell C. At Hinkley Point C chlorination of the cooling water system will not be required unless environmental conditions at the site change substantially in the future and, in order to reduce the residual risk of settlement from colonising species such as *Sabellaria*, copper based sheet will be plated onto the vertical bars across the intake apertures. The problem for the operator is that the efficacy of such measures in complex LVSE structures and particularly the longevity of anti-biofouling efficiency is unknown. If the structures did start to biofoul, their design with internal baffling could present serious, possibly insuperable maintenance issues.

At Sizewell the biofouling risk is much greater than at Hinkley Point and if HPC LVSE intake heads were selected it was considered at the time of version 5 of this report (October 2016) that chlorination dosing points would have to located inside of the intake heads. The viability of such an approach would then be subject to the environmental impact issues that are predicted from option 2 in section 3 of this report i.e. to protect an LVSE intake head a chlorine dose would have to be applied at such a level to create high levels of mortality for impinged fish, thereby reducing the FRR efficiency to the point where for most species its benefits would be questionable.

Given the risk of biofouling of the HPC LVSE design, and the lack of performance predictions for LVSE heads at the time, EDF Energy therefore proposed not to fit LVSE intakes and instead fit 'simple' omnidirectional velocity-capped heads of a similar design to Sizewell B which are much more readily maintained and much less likely to biofoul.

In October 2016 the provisional impingement mitigation strategy for SZC consisted of:

a. Acoustic fish deterrents at each of the SZC intakes (but feasibility studies on their viability at SZC had not yet been undertaken);

b. An FRR system with chlorination applied just before the drum and band screens which would partially reduce the FRR effectiveness compared with an unchlorinated system due to TRO toxicity in the FRR system; and

c. SZB type capped intakes with no measures to reduce tidally induced high intake velocities.

Subsequent to the release of version 5 of this report, EDF energy re-examined each of these measures in turn in order to finalise the design for the SZC cooling water system and the impingement mitigation measures. The results of this work are described in Section 9.

7 TRO discharge source term to be used for chemical plume modelling

The TRO level at the outfalls for the preferred chlorination option 5 is shown in Figure 8 and is 0.09 mg l^{-1} within a range of 0.05 to 0.13 mg l^{-1} (Appendix E). For TRO plume modelling purposes, a precautionary discharge source term of 0.15 mg l^{-1} is therefore appropriate.

8 Proposed chlorination policy for Sizewell C (at October 2016)

Subject to engineering feasibility and risk studies by EDF Energy, the recommended chlorination policy for SZC was:

a. Maintaining a TRO level of 0.2mg l^{-1} at entrance to critical land-based plant (condensers and essential cooling water systems) throughout the year.

b. Intake heads, inlet tunnels and the forebays not to be chlorinated because of the impracticality of operational control of the chlorination dose in the intakes and inlet tunnels and so as not to compromise the FRR system effectiveness.

c. Velocity-capped intake heads of a similar design to Sizewell B to be employed at Sizewell C. Such intake heads are much more readily maintained and much less likely to biofoul than the LVSE intake heads planned for Hinkley Point C.

d. In order to protect the drum screens and FRR system, chlorinate the drum and band screen wells but only in the growing season when seawater temperatures exceed 10 °C.

e. Apply for a WDA discharge permit for TRO (measured before the discharge tunnel) of 0.2mg l^{-1} throughout the year.

In addition, as post commissioning opportunities:

f. EDF Energy to consider the operational feasibility of only chlorinating critical land-based plant (e.g. at the inlet of the condensers and in front of essential cooling water systems) when seawater temperature exceeds 10 °C.

g. EDF Energy to consider the operational feasibility of maintaining an intermittent dosing regime on critical plant when seawater temperatures are below 10°C, potentially mediated by biofilm monitors.

It was concluded that this policy includes all proven methods to reduce TRO mortality to impinged and entrained organisms at Sizewell. In particular, the policy should maintain the effectiveness of the FRR system when chlorination is applied.

9 Post 2016 cooling water system design optioneering and finalisation of the SZC chlorination strategy

After October 2016 EDF Energy engineers undertook a through and extensive review of the proposed cooling water system for SZC in order to determine the acceptability of the proposed chlorination strategy and whether any design improvements could be made that would increase the fish impingement mitigation performance of SZC.

9.1 Acceptability of not chlorinating the intakes, intake tunnels and forebays

After consideration of operational experience at Sizewell B and other stations and the reduced risk resulting from the larger diameter of the proposed SZC intake tunnels, EDF Energy engineers decided that the biofouling risk was sufficiently low to allow the use of unchlorinated SZB type intake heads with the planned intake tunnels and forebays at SZC.

9.2 Improvements to the proposed Intake head design

The use of the SZB omnidirectional intakes would offer no additional impingement mitigation at SZC over the that provided by the SZB intakes and so EDF Energy undertook an extensive set of Computational Fluid Dynamics (CFD) modelling studies to determine if a modified version of the HPC LVSE intake heads could be used at Sizewell without incurring an unacceptable biofouling risk. These studies were successful, and it was found that, with improved nose piece designs (longer and ramped) on the ends of the heads facing into the tidal flow and other design optimisations, the hydrodynamic flow past the heads would be improved to the extent that heads of the same size as those planned for HPC could be designed without many of the complex internal baffles that offered at least the same predicted performance as the HPC heads. Without these internal baffles, EDF Energy's engineers decided that these modified LVSE intakes would not require chlorination at the heads, thereby avoiding chlorinating the entire cooling water system. This meant that all of the impingement mitigation benefits of the LVSE intakes could be realized without sacrificing most of the planned benefits of the FRR system due the high levels of TRO exposure that abstracted fish would experience if the intake head were chlorinated.

9.3 Improvements to the FRR design

Since 2016, elevation levels have been confirmed that allow a simplification of the FRR design compared with HPC. At HPC due to the large tidal range the FRR systems uses an Archimedes screw to raise the fish to a higher elevation to allow discharge back to see under gravity. The HPC design also requires quite long onshore gutters to transfer the fish to a single FRR discharge tunnel that is shared by both reactors.

For SZC, EDF Energy engineers have confirmed that elevation of the debris recovery building (an integral part of the FRR system) is sufficient to allow discharge of fish directly back to see without the need for an Archimedes screw or long onshore gutters. Each FRR system will discharge to sea directly from the debris recovery building via separate tunnels, each of internal diameter 0.65m.

9.4 Acceptability of not chlorinating the FRR system

The final stage of design optimization was to determine whether it would be possible to avoid chlorination of the FRR system. In October 2016 the recommended chlorination strategy was to chlorinate at the drum screen wells. In addition, the flushing water used to improve flow in the FRR fish gutters after the drum screens was designed to be fed from a chlorinated source.

This study therefore consisted of two parts:

a. Determination of whether it was acceptable not to dose at the screen wells in front of the drum or band screens

b. Determination of whether an unchlorinated flushing water supply could be provided to the FRR fish gutters.

After careful consideration EDF Energy engineers decided that under the current biofouling conditions that chlorination would not need to be applied in the drum screen wells.

The flushing water supply was also successfully rerouted to ensure that the gutters were flushed with unchlorinated seawater. This modification meant that even if the drum screens had been chlorinated at the drum screen wells, that the TRO levels in the HCB building would have been reduced by dilution from 0.2 mg l^{-1} to 0.14 to 0.12 mg l^{-1} dependent upon loadings within the fine filtration system.

The successful conclusion of these studies means that the chlorination will not be applied before the SZC drum or band screens and that the subsequent addition of flushing water will not subsequently increase TRO levels within the FRR system (waste stream H).

In line with the strategy adopted at HPC, the chlorination dosing points in the screen wells before the drum and band screens will still be installed as a precaution but these would not be used unless there is a required change to the SZC chlorination strategy and a variation to the Water Discharge Activity (WDA) permit has been obtained from the Environment Agency.

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Appendix A Evaluation matrix for SZC chlorination dosing options (At October 2016)

Option	Option	Description	Biofouling risk	Operational risk/cost	Environmental risk	Finding
1	Seasonal dosing for inlet tunnels and forebay (EDFE would have the option to continuously dose critical plant)	Apply dose when incoming seawater temps exceed 10°C	Good/moderate – reflects local OPEX and ecological understanding on biofouling risk	Good/Moderate; advantage of winter period allowing for oxidant plant maintenance; prescribed TRO level less effective at lower temperatures	Good (when dosing off); avoids oxidant exposure to FRR-related biota over key winter months	Apply where feasible
2	Single dose at entrance to inlet tunnels	Single Dose to 0.68 mg/l TRO at the tunnel inlets	Good; full system protected	Moderate/poor; will require constant high dose towards inlets; difficult to maintain associated pipework; chemistry control not difficult	Poor; largest FRR impact, high entrainment impact; non-compliant with good practice	Least desirable on environmental impact grounds (could be mitigated by combination with option 1)
3.1	Minimise TRO levels within the CW system - maintaining a minimum level of 0.2mg l^{-1}.	2 dosing locations along tunnel lengths – initial and dosing ring at 1584 metres	Good; full system protected	Poor; will require constant high dose towards inlets; difficult to maintain associated pipework; difficult chemistry control	Moderate/poor; high FRR impact, high entrainment impact; non-compliant with good practice	Ruled out due to poor environmental impact + plant complexity+ poor chemistry control
3.2		3 dosing locations – initial, dosing ring at 1320 metres from the start of each inlet tunnel, then at drum screens	Good; full system protected	Poor; will require constant high dose towards inlets; difficult to maintain associated pipework; difficult chemistry control	Moderate/poor; high FRR impact, high entrainment impact; non-compliant with good practice	Ruled out due to moderate/poor environmental impact + plant complexity + poor chemistry control
3.3		4 locations – initial, 2 rings at 924 and 2046 metres from the start of each inlet tunnel, then drum screens	Good; full system protected	Poor; will require constant high dose towards inlets; difficult to maintain associated pipework; difficult chemistry control	Moderate/poor; high FRR impact, high entrainment impact;non-compliant with good practice	Ruled out due to moderate/poor environmental impact + plant complexity + poor chemistry control
4	Reduced dose levels in the inlet tunnels	Maintain residual of 0.2mg l^{-1} at tunnel inlets, no further dosing until after the drum screens	Moderate; tunnel partially protected; drum screens and FRR may be at risk	Poor; will require constant high dose towards inlets; difficult to maintain associated pipework; difficult chemistry control	Moderate; moderate entrainment impact; moderate FRR impact; non-compliant with good practice	Ruled out due to plant complexity + poor chemistry control providing uncertain or no benefit
5	Not Dosing before drum screens	In 2016 it had not yet been determined if it was possible to avoid chlorinating at the drum screen and so, subject to further investigation, it was assumed that the drum screens would be chlorinated.	Moderate; tunnels considered resilient, drum screens and FRR may be at risk	Good/moderate; limited pipework requirement; limited plant capacity required	Good if seasonal dosing applied at drum screens; no FRR impact. When dosing is applied at the drum screens this option produces the lowest TRO exposure for impinged fish. Entrainment impact still present but reduced from full system chlorination; compliant with good practice	Apply

6	Use of an intermittent chlorination regime	Choose from family of possible regimes for macrofouling (tailored via experiment) or microfouling (empirical trial or feedback driven)	Good/moderate; Depends how applied – would probably need a high duty cycle – to be determined by experiment on site	Moderate; requires plant that can be turned on/off for short periods; useful facility out of season on critical plant if continual dosing strategy chosen	Would reduce environmental impact in sections of plant when dosing off. Most environmental benefit at or after drum screens	Consider options to apply in combination with other options post station commissioning.

Appendix B Literature data on fish mortality following exposure to chlorinated seawater

B.1 Fish species sensitivity to chlorine toxicity

Table 3 Chlorination effects upon survival of different fish species (where chlorination is in combination with other factors these are indicated in the affect column)

Species	**Common name**	**TRO concentration (mg/l)**	**Exposure duration (minutes)**	**Effect**	**Reference**
Pleuronectes platessa	plaice larvae	0.05	460[1]	50% mortality	Alderson 1970
Pleuronectes platessa	plaice larvae	0.075	175[1]	50% mortality	Alderson 1970
Psedopleuronectes americanus	Winter flounder larvae	2.5	15[2]	50% mortality	Ward et al 1976
Pleuronectes platessa	European plaice yolk sac	0.06	29[3]	46% mortality	BEEMS TR 297
Pleuronectes platessa	European plaice yolk sac	0.13	24[3]	60.9% mortality	BEEMS TR 369
Pleuronectes platessa	European plaice yolk sac	0.14	24[3]	67.01% mortality	BEEMS TR 396
Solea solea	Common sole post larvae	>0.2	10[3]	96.6% mortality	Bamber and Seaby 1994
Clupea harengus	Atlantic Herring (post larvae)	0.4	60[4]	43h LC50	Dempsey 1986
Dicentrarchus labrax	European sea bass yolk sac	0.2	30[3]	62% mortality	BEEMS TR 282
Dicentrarchus labrax	European sea bass yolk sac	>0.2	10[3]	50% mortality	Bamber and Seaby 1995
Gadus morhua	Atlantic cod yolk sac	0.2	24[3]	89.4% mortality	BEEMS TR 281
Gadus morhua	Atlantic cod yolk sac	0.2	24[3]	48.4% mortality	BEEMS TR 392
Anguilla anguilla	European Eel (Elver)	0.47	60[3]	0% mortality	Turnpenny 2000
Anguilla anguilla	European Eel (glass Eel)	0.2	15[3]	20% mortality	BEEMS TR 273
Anguilla anguilla	European Eel (glass Eel)	0.2	24[3]	0% mortality	BEEMS TR 395
Anguilla anguilla	European eel 1+ group	0.2 0.3	Pulsed – any duration Pulsed – approx. 2.25h (read from constructed dose exposure curve)	0% mortality 24h after pulsed exposure	Emberton and Turnpenny 1981

Note: 1 continuous dose to maintain specified residual throughout exposure period; 2 it has not been possible to confirm exact dosing regime ; 3 continuous dose to maintain specified residual during exposure period followed by period thereafter up to 24 hours in clean water before final mortality is assessed.

Table 4 Chlorination effects upon survival of different fish species (where chlorination is in combination with other factors these are indicated in the affect column)

Species	Common name	TRO concentration (mg/l)	Exposure duration (minutes)	Effect	Reference
Menidia menidia	Atlantic silverside	0.58	90[2]	50% mortality	Engstrom and Kirkwood, 1974
Menidia menidia	Atlantic silverside	0.58	90[2]	50% mortality	Engstrom and Kirkwood, 1974
Menidia menidia	Atlantic silverside	1.2	30[2]	50% mortality	Engstrom and Kirkwood, 1974
Brevoortia tyrannus	Atlantic menhaden	0.22	60[2]	50% mortality	Fairbanks et al., 1971
Brevoortia tyrannus	Atlantic menhaden	0.7	10[2]	50% mortality	Fairbanks et al., 1971
Brevoortia tyrannus	Atlantic menhaden	0.21	300[2]	50% mortality	Engstrom and Kirkwood, 1974
Brevoortia tyrannus	Atlantic menhaden	1.2	30[2]	50% mortality	Engstrom and Kirkwood, 1974
Morone saxatillis	striped bass larvae (72h old)	0.3	15[1]	60%	Burton et al, 1979
Morone saxatillis	striped bass larvae (72h old)	0.15	120[1]	62%	Burton et al, 1979
Morone saxatillis	striped bass larvae	0.2	1440[1]	LC50	Morgan and Prince 1977
Morone saxatillis	striped bass larvae	0.15	<240[1]	20% mortality	Hall et al 1983
Morone saxatillis	striped bass larvae	0.3	240[1]	100% mortality	Hall et al 1981

Note: 1 continuous dose to maintain specified residual throughout exposure period; 2 it has not been possible to confirm exact dosing regime ; 3 continuous dose to maintain specified residual during exposure period followed by period thereafter up to 24 hours in clean water before final mortality is assessed

Table 5 Chlorination effects upon survival of different fish species (where chlorination is in combination with other factors these are indicated in the affect column)

Species	Common name	TRO concentration (mg/l)	Exposure duration (minutes)	Effect	Reference
Alosa oestivalis	Blueback herring	0.67	60[2]	50% mortality	Engstrom and Kirkwood, 1974
Alosa oestivalis	Blueback herring	1.2	15[2]	50% mortality	Engstrom and Kirkwood, 1974
Cymatogaster aggregata	shiner perch juv	0.22	7.5[3]	LC50 elevat 7.5	Stober et al., 1980
Cymatogaster aggregata	shiner perch juv	0.41	60[3]	LC50 elevat 7.5	Stober et al., 1980
Cymatogaster aggregata	shiner perch juv	0.302	15[3]	LC50 elevat 3.2	Stober et al., 1980
Cymatogaster aggregata	shiner perch juv	0.175	30[3]	LC50 elevat 3.2	Stober et al., 1980
Gobiosoma bosci	naked goby	0.08	120	LC50	Roberts et al., 1975
Oncorhynchus gorbuscha	Pink Salmon	0.5	7.5[3]	50% mortality	Stober and Hanson 1974
Oncorhynchus gorbuscha	Pink Salmon	0.25	15[3]	50% mortality	Stober and Hanson 1974
Oncorhynchus tshawytscha	Chinook salmon	0.25	130[2]	mortality threshold	Holland et al 1960
Oncorhynchus tshawytscha	Chinook salmon	1	23[2]	mortality threshold	Holland et al 1960
Oncorhynchus tshawytscha	Chinook salmon	0.5	7.5[3]	50% mortality	Stober and Hanson 1974
Oncorhynchus tshawytscha	Chinook salmon	0.25	30[3]	50% mortality	Stober and Hanson 1974
Oncorhynchus kisutch	Coho Salmon	0.27	7.5[3]	LC50 elev 7.3	Stober et al., 1980
Oncorhynchus kisutch	Coho Salmon	0.179	15[3]	LC50 elev 7.3	Stober et al., 1980
Oncorhynchus kisutch	Coho Salmon	0.129	30[3]	LC50 elev 7.3	Stober et al., 1980

Note: 1 continuous dose to maintain specified residual throughout exposure period; 2 it has not been possible to confirm dosing regime; 3 continuous dose to maintain the specified residual during exposure period followed by period thereafter up to 24 hours in clean water before final mortality is assessed

Appendix C Sensitivity of Option 2 to the TRO decay model parameters

The TRO demand and decay model used in this report was fitted to data from 4 laboratory experiments (BEEMS report TR143 ed. 2). There was considerable variability between the experiments and this was considered to be due to changes in the biology of the seawater at Sizewell over the several months in which sampling took place. The contribution of this experimental variability to model predictions was therefore evaluated here to test the sensitivity of Option 2 to using different fits of the model. Instead of using all the experimental data for the fit only one of the experiments was used at a time resulting in four model fits.

The results in Figure 9 show initial concentrations of TRO in a range of 0.45 to 0.98 mg/l. As expected the model fitted to all the data (Figure 8) has an intermediate value of 0.68 mg/l which was therefore used in for option evaluation in the main text. Despite the variation around required target residual the concentration of TRO entering the environment does not vary much and is between 0.15 and 0.18 mg/l (Table 7).

Table 6 Option evaluation: Model fitted to data from different experiments.

Parameter	m	n	k_1 (s^{-1})	k_2 ($s^{-1}(mg/l)^{-2}$)	S_0 (mg l^{-1})	Injection of chlorine (mg/l)	TRO conc. at the outfall (mg /l)
Experiment 1 (5L)	1	2	2.6×10^{-5}	4.7×10^{-3}	0.47	0.45	0.15
Experiment 2 (2L)	1	2	5.7×10^{-5}	26.0×10^{-3}	0.36	0.58	0.18
Experiment 3 (2L)	1	2	3.5×10^{-5}	4.5×10^{-3}	0.7	0.64	0.15
Experiment 4 (2L)	1	2	9.2×10^{-5}	16.0×10^{-3}	0.77	0.98	0.16
All data	1	2	4.1×10^{-5}	7.8×10^{-3}	0.60	0.68	0.15

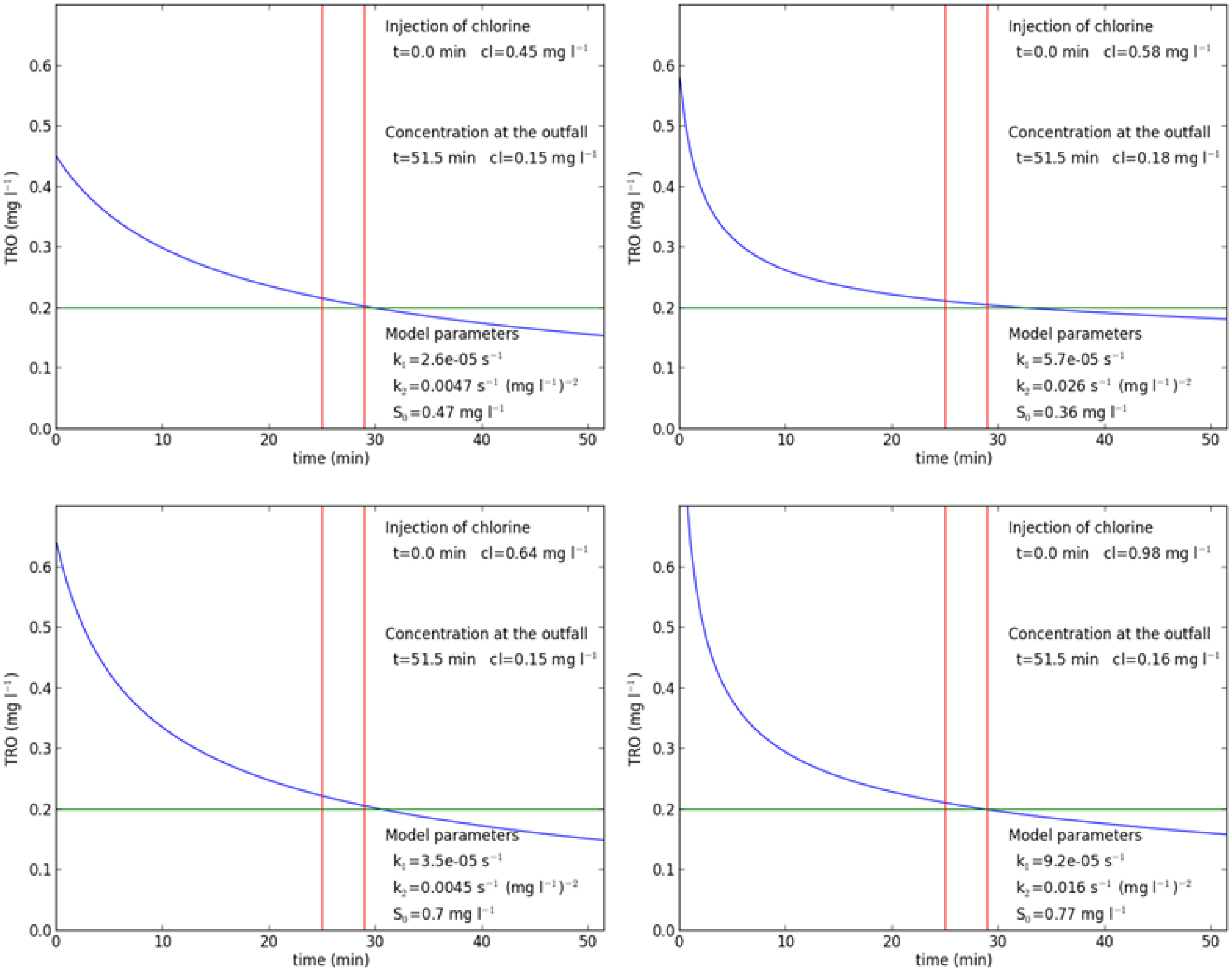


Figure 9 Four versions of Option 2 derived using modelling based on the 4 available experiments (TR 243 Ed.2). In each case the initial dose was chosen so as to guarantee a TRO value of at least 0.2 mg l^{-1} throughout the inlet tunnel and through the condenser.

Appendix D Sensitivity of Option 4 to the TRO decay model parameters

The TRO demand and decay model used in this report was fitted to data from 4 laboratory experiments (BEEMS Technical Report TR143 ed. 2).

Figure 10 show the calculated TRO concentrations at the SZC drum screens and at the outfall for an initial residual of 0.2 mg l^{-1} close to the intakes. The residual at the drum screens varies between 0.03 – 0.11 mg l^{-1} and at the outfall between 0.06 and 0.14 mg l^{-1}. The model fitted to all the data (Figure 8) has an intermediate value of 0.07 mg l^{-1} at the drum screen and 0.1 mg l^{-1} at the outfall.

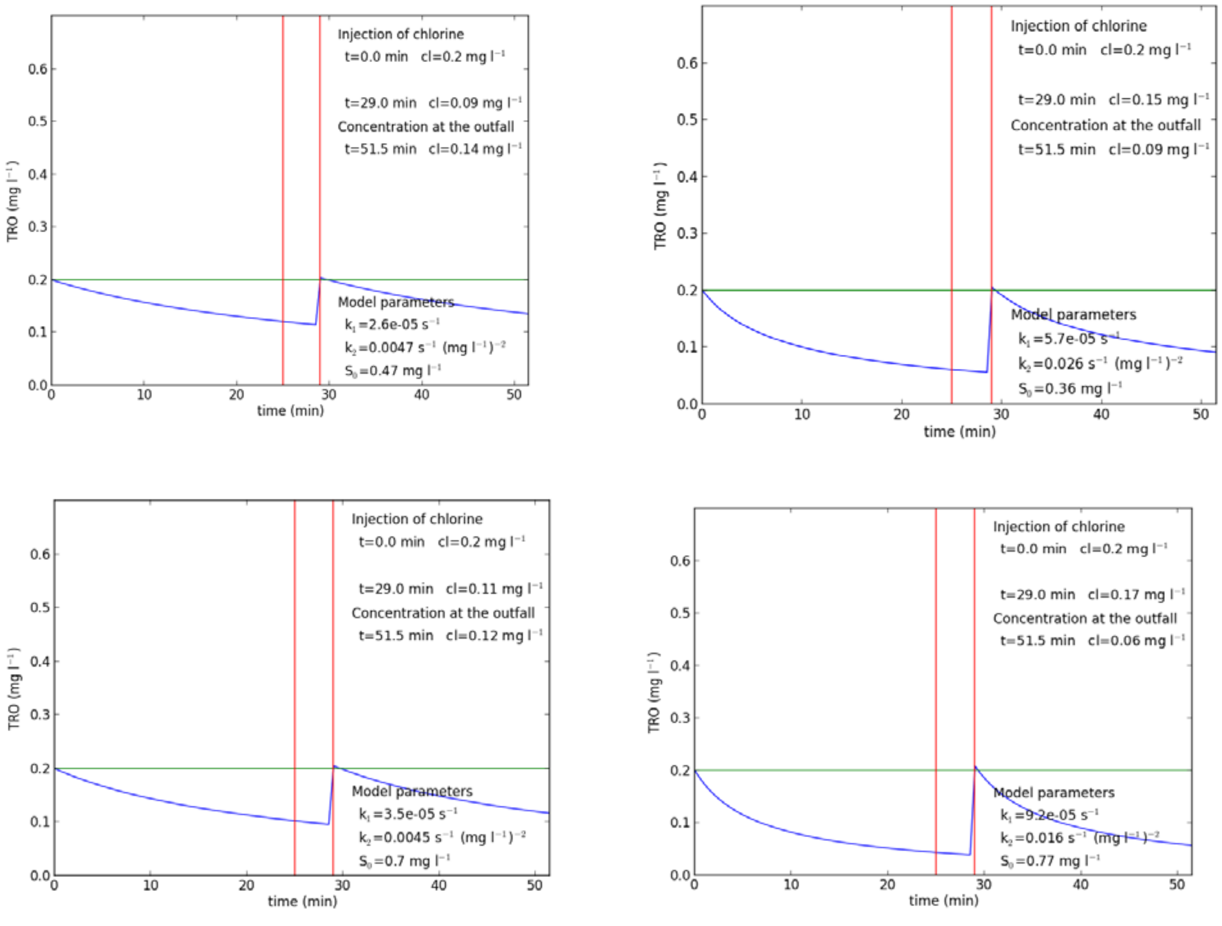


Figure 10 Calculated TRO dose profiles for Option 4 (Dose of 0.2mg l^{-1} near to the intakes) with different measured TRO decay parameters

In terms of dosing control under option 4, the first monitoring point after the initial dosing point near to the intake heads would be at the drum screens where the calculated TRO level would be 0.03 – 0.11 mg l^{-1}. At 0.03 mg l^{-1} the level would be close to the detection limits of available analytical methods and therefore subject to measurement errors. If the operator selected the 'mean' value of 0.07 mg l^{-1} as a control target under conditions when the actual TRO level for a 0.2mg l^{-1} dose would be 0.03 mg l^{-1} , the applied dose at the intakes would be 0.5 not 0.2 mg l^{-1} (Figure 8). In terms of fish impingement mortality this is an undesirable dose profile but the potential effects are mitigated by the rapid demand loss which means that fish in the inlet tunnels would only experience residual oxidant levels above 0.3 mg l^{-1} for approximately 2 minutes and above 0.2 mg l^{-1} for 5 minutes (Figure 8). Inspection of Figure 1 indicates that such levels may not substantially effect fish survival. Use of a TRO control target of 0.07 mg l^{-1} at the drum screens would, therefore, seem a reasonable starting point for a control strategy. However, this would need further optimization supported by the collection of more data on how TRO decay parameters change in Sizewell seawater in both the short term and on a seasonal basis.

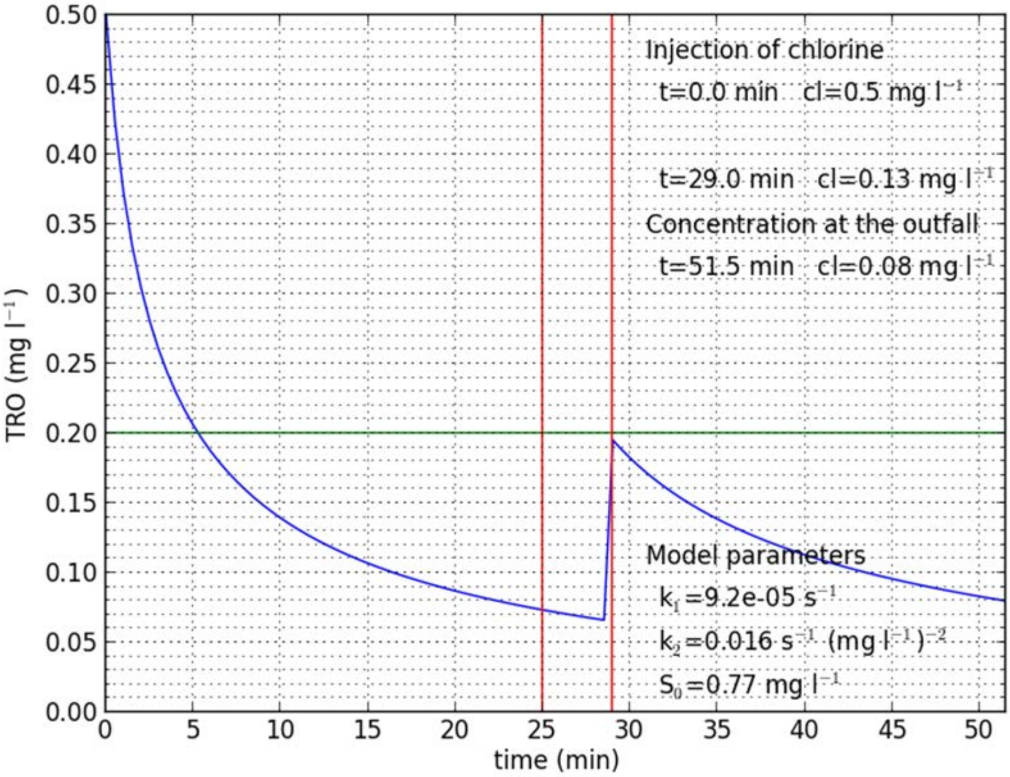


Figure 11 Worst case initial TRO dose level with a fixed dosing control target of 0.07mg l^{-1} at the drum screens

Appendix E Sensitivity of Option 5 to the TRO decay model parameters

The TRO demand and decay model used in this report was fitted to data from 4 laboratory experiments (BEEMS Technical Report TR143 ed. 2).

Figure 12 show the calculated TRO concentrations at the outfall for an initial residual oxidant level of 0.2 mg l-1 at the drum screens. The residual at the outfalls varies between 0.05 – 0.13 mg l^{-1}. The model fitted to all the data (Figure 8) has an intermediate value of 0.09 mg l^{-1} TRO at the outfall.

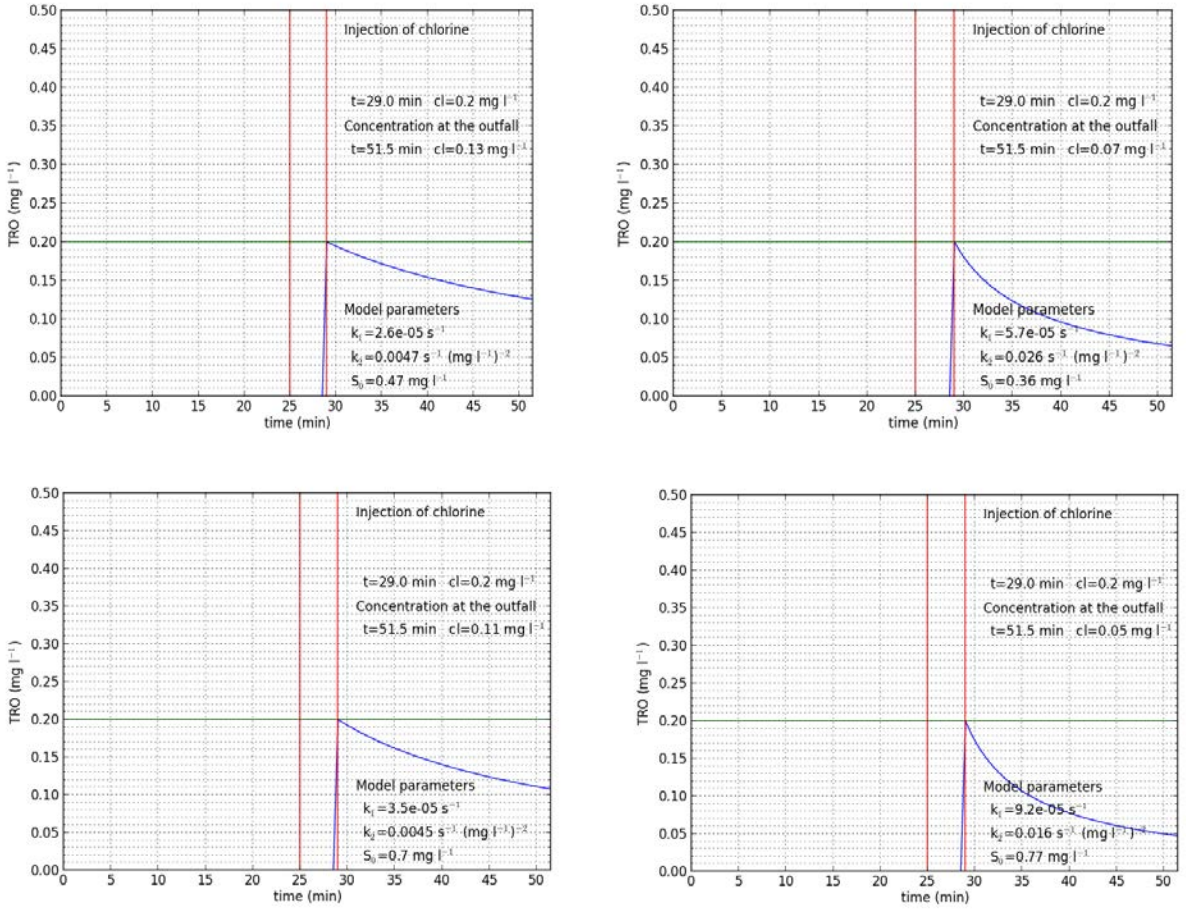
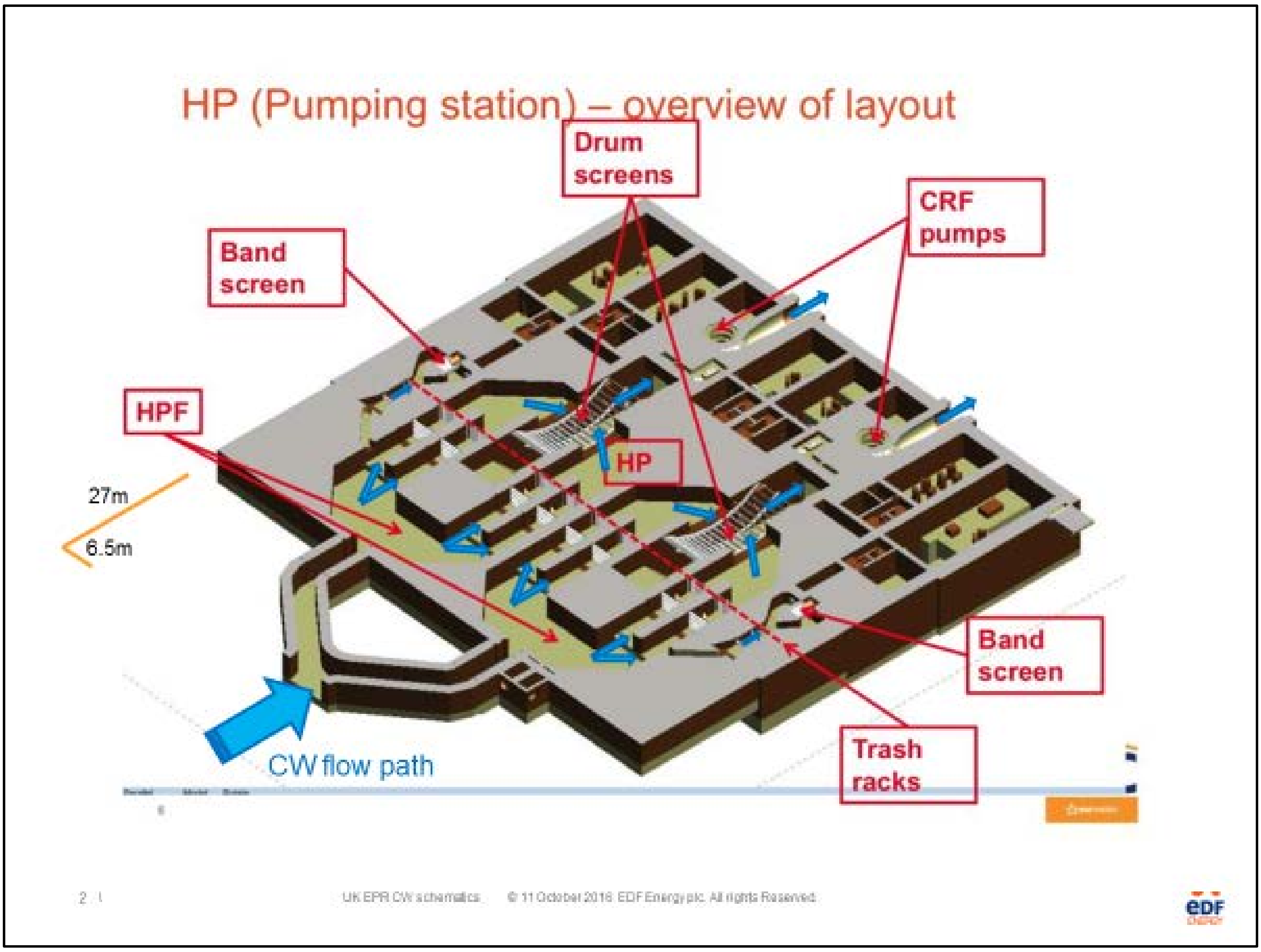


Figure 12 Calculated TRO dose profiles for Option 5 (target residual of 0.2mg l^{-1} at the drum screens) with different measured TRO decay parameters

Appendix F HPC Pumping station CAD schematics

The following diagrams provide slices through the HPC pump station in order to aid understanding of the layout and cooling water flow.
Notes:

a. the very much larger tidal range at Hinkley than at Sizewell means that the HPC drum screens are much bigger (approx 27m diameter) than those that will be designed for Sizewell C (approx. 14m diameter)
b. that the scale bars provided are approximate.



HP (Pumping station) – overview of layout

2

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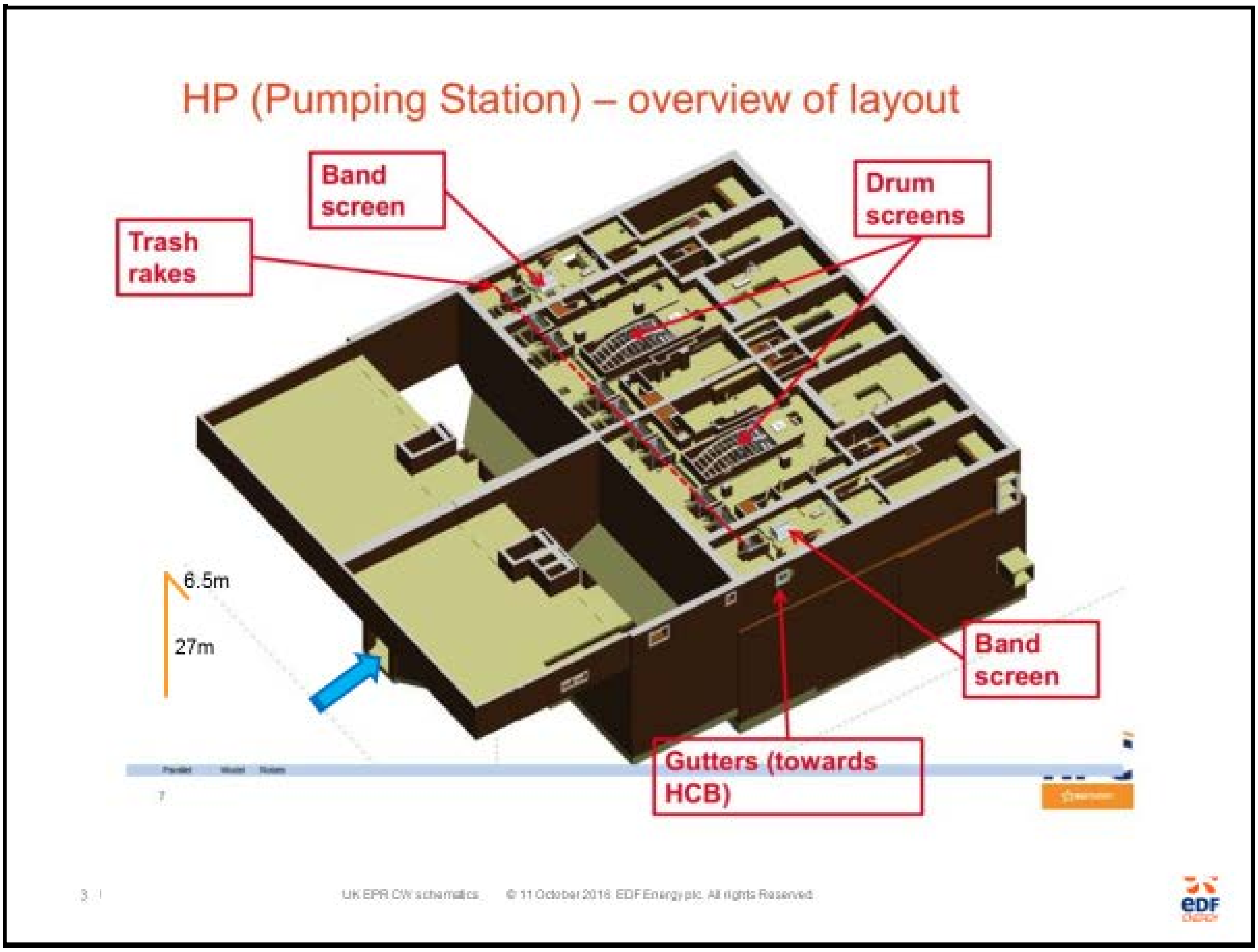
Low level slice through the HPC pump station



HP (Pumping Station) – overview of layout

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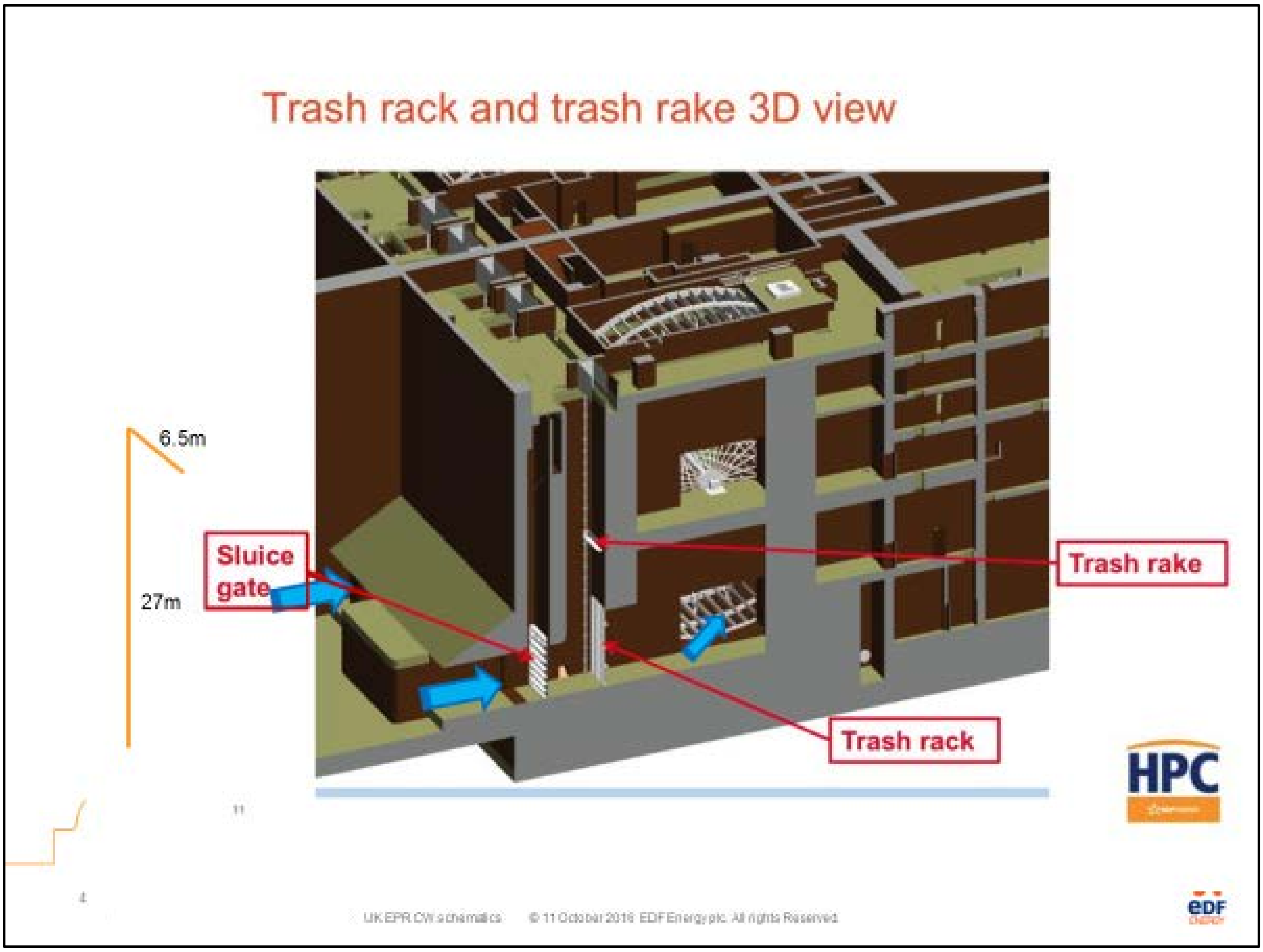
High level slice through HPC pump station



Trash rack and trash rake 3D view

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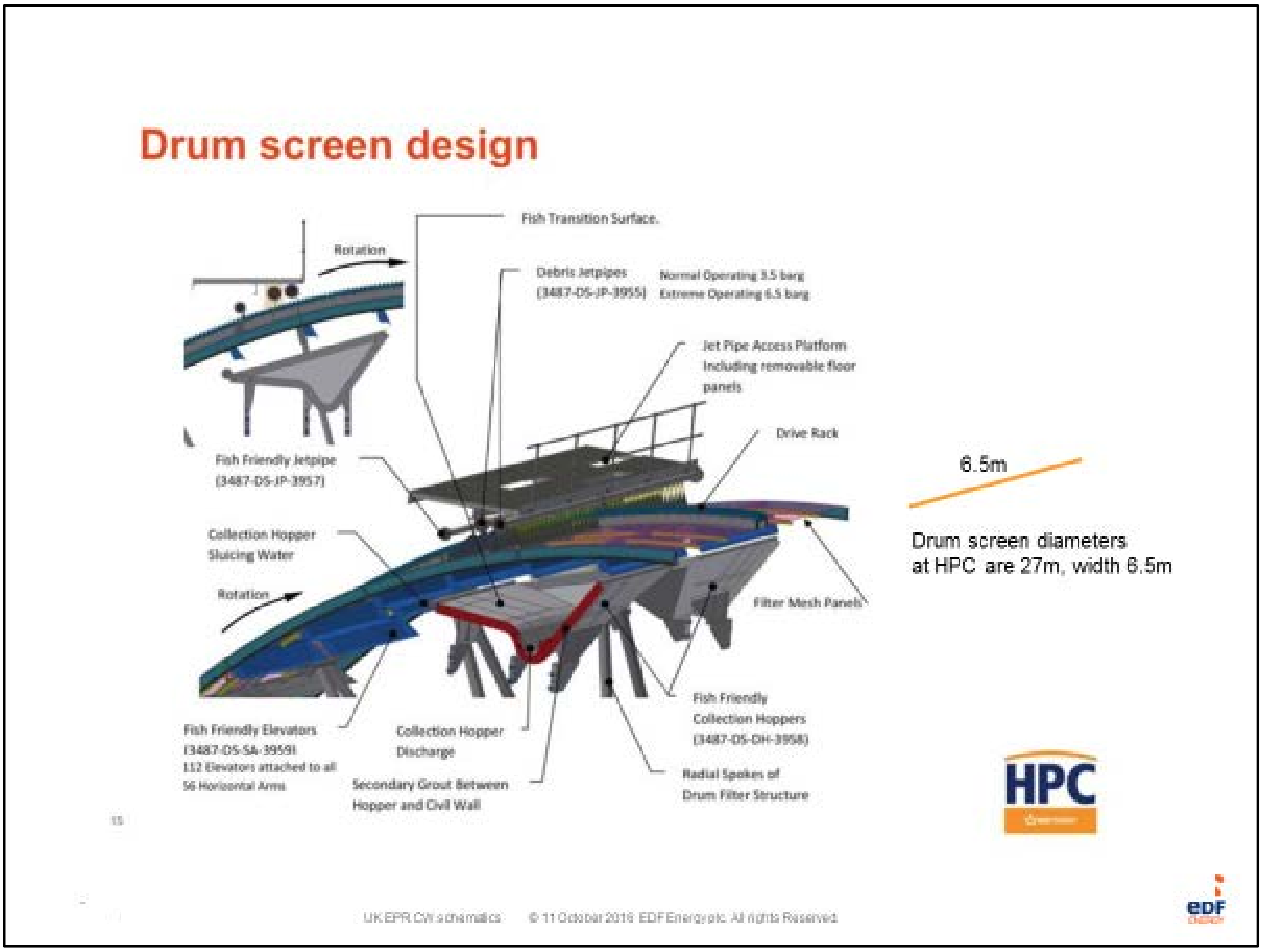
Vertical slice through HPC pump station



Drum screen design

Drum screen diameters at HPC are 27m, width 6.5m

15

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HPC drum screen design